Effect of High-Beta versus Gamma Binaural Beat Exposure on Immediate and Delayed Recall

Etienne Grobler

Author: GRBETI001

A dissertation submitted in fulfilment of the requirements for the award of the degree of Master of Arts in Research Psychology

Department of Psychology

ACSENT Laboratory

University of Cape Town

COMPULSORY DECLARATION

This work has not been previously submitted in whole, or in part, for the award of any degree. It is my own work. Each significant contribution to, and quotation in this dissertation from the work, or works of other people has been attributed and has been cited and referenced.

Signature: Signed by candidate Date: 30 October 2024

Supervisor: Dr. P. Njomboro

Word Count: 51220

Acknowledgements

All of this started with an idea much grander than what is presented to you today. A shot in the dark if you will. The University of Cape Town and the incredible team at the Psychology Department noticed that what I was proposing was somewhat off the beaten track and allowed me to take on this project under their guidance. The journey that would eventually lead to the completion of this thesis would not have been possible without the unlimited support, guidance, and encouragement offered in abundance by key individuals. Acknowledging you all here is merely an attempt to express my deepest gratitude and thanks. Dr. Progress Njomboro, none of this would have been possible without your guidance and insights. Often when my ideas or theories would become a bit wild, you were there to refocus and restate the purpose. The highest amount of appreciation I am capable of goes towards your patience and dedication and the hours spent throughout this project. I would also like to thank everyone at the Psychology Department at UCT for always being willing to shine a light in the dark during stressful times. In addition a very special thanks to Milton Gering and Kyra Scott for teaching me the ways of statistics. Without your willingness to share your knowledge on the subject of statistical analysis during the course work, I would most probably only have been able to report on averages using a calculator. I would be amiss if I did not mention a few special classmates, Nadine Upton and Amy Gribble. You both know why you deserve an honorary mention. Those all over the world who were always willing to offer a helping hand: Dr. Cheneal Puljević from the University of Queensland, Assoc. Prof. Andrey Chetverikov, Dr. Lars-Erik Christer Johansson, and Prof. Paul Hamilton from the University of Bergen, thank you. To the people who participated in this study, none of this would have been possible without you. Thank you. To the folks that had to deal with me throughout this experience daily, my friends and family… I cannot express how much I appreciate your limitless support and understanding, despite not always knowing what I am going on about. Rachel, you are an irreplaceable light to hold trust in. My inspiration, my guidance, my home. Lastly, I look up to the stars so you will forever see, that the best parts of you still live in me.

Table of Contents

List of Figures

List of Tables

Abbreviations

Terminology:

BB: Binaural Beats

BFDA: Bayesian Factor Design Analysis

GG – E: group exposed to Gamma frequency binaural beats during encoding

GG – ER: group exposed to Gamma binaural beats during encoding and recall

HBG – E: group exposed to High-Beta binaural beats during encoding

HBG – ER: group exposed to High-Beta binaural beats during encoding and recall

Measures and Procedures:

95% HPD: 95% Highest Posterior Density

elpd_loo: Expected Log Pointwise Predictive Density

emmean: Estimated Marginal Mean

LOO-CV: Leave One Out – Cross Validation

looic: Leave One Out Information Criteria

MCMC: Markov Chain Monte Carlo

mcse: Monte Carlo Standard Error

mean ppd: mean Posterior Predictive Distribution

n_eff: Effective Sample Size

p_loo: Predicted Standard Errors

rhat: Potential Scale Reduction factor

Abstract

In this study, I investigate the effect of binaural beats on immediate and delayed recall. Binaural beat exposure within the Gamma frequency band has been linked to alterations in neural connectivity and increased attention during working memory tasks, while stimulation in the Beta frequency band has been associated with increased memory performance. However, there is a lack of direct comparison between the effects of exposure to High-Beta versus Gamma binaural beats on immediate and delayed recall performance. This study employs a Bayesian approach and a between-groups 3 (exposure condition) x 2 (task presentation format) x 2 (timing of exposure) experimental design to examine the effects of both High-Beta and Gamma binaural beats on immediate and delayed recall performance in 75 participants. The results show that exposure to binaural beats resulted in mixed effects, with exposure to Gamma binaural beats only having a significant impact on immediate recall when combined with visual presentation, and exposure to High-Beta binaural beats during encoding and recall potentially interfering with recalling semantic information such as story themes after a delay. Comparatively, High-Beta binaural beat exposure did not significantly improve memory performance, while exposure to Gamma binaural beats only showed a significant improvement in memory performance when participants recalled information from the auditory memory tasks. These results have important implications for research and clinical work focused on cognitive improvement.

Keywords: Bayesian analysis, binaural beats, memory, immediate recall, delayed recall

Effect of High-Beta versus Gamma Binaural Beat Exposure on Immediate and Delayed Recall

Chapter 1: Introduction

The ability to encode and recall information from memory is a complicated and multifaceted process. In the context of modern cognitive neuroscience, opposing ideologies are emerging towards the processes involved in forming and recalling memories and how these processes can be improved. However, modern research into modulating neural activity through Auditory Beat Stimulation (ABS) suggests that exposure to certain frequencies can influence and potentially improve cognitive functions such as memory. Synchronising neural activity using binaural beats has shown the potential to improve cognition without medications. Both Beta and Gamma band binaural beats have been suggested to entrain the brain and alter neural activity, influencing cognitive functions such as attention and memory. However, research has been limited in exploring if exposure to High-Beta or Gamma binaural beats affects encoding and retrieval differently, and if the combination of binaural beat exposure and the format in which information is presented has any significant effects on memory.

This thesis presents an investigation into the effects High-Beta and Gamma binaural beats had on participants' ability to perform immediate and delayed recall memory tasks. The purpose of this study was to expand the current knowledge of how these binaural beat frequencies impact recall performance and comparatively explore their potential to improve memory. I also examined how factors such as the timing of exposure and the presentation format of the memory tasks contribute to this effect. I analysed the results by using a Bayesian approach to statistical inference which allowed for a more nuanced understanding of how the combination of these factors immediate and delayed recall.

Chapter 2 focuses on the theoretical background of the study. I present varied findings from prior research that explored Beta and Gamma band binaural beats and their influence on memory performance. I discuss other factors in the literature reported to influence the impact binaural beats have on memory performance such as the importance of the time-of-day effect when conducting memory tests, participant comfort, and binaural beat masking. I also present the steps I took in designing this study to control for these potentially confounding variables that may result from these factors. I conclude the literature review by highlighting the gaps in the current literature on binaural beats and memory justifying the significance of this investigation. I conclude Chapter 2 with the rationale behind the research questions and present the hypotheses.

In Chapter 3, I present the rationale behind using Bayesian Inference analytical methods I adopted in this study. I discuss that Bayesian analysis is a reiterative framework recognized for its adaptability in assimilating prior knowledge into current enquiries. I conclude Chapter 3 by describing the procedures and methods employed in the investigation, using the "Modulation through Auditory Beat Stimulation" (MABS) application specifically built for this experiment for presenting the memory tasks and binaural beats, and the experimental procedure.

Chapter 4 presents the results of this study. I began this inquiry by examining if the presentation format of the memory tasks had an impact on recall performance. In a follow-up analysis to address my second hypothesis, I introduced the High-Beta and Gamma binaural beat exposure conditions and comparatively investigated if the interaction between binaural beat exposure and the presentation format of the immediate and delayed memory tasks (auditorily or visually) influenced recall performance. To address my third hypothesis, I examined the effect the timing of exposure to binaural beats had on immediate and delayed recall performance. I contrasted the results of each digit span, target word, and story theme-based memory tasks from the single exposure (during encoding alone) and dual exposure (during both encoding and recall) conditions against the results obtained from the group not exposed to any binaural beats. I concluded the investigation by addressing my fourth hypothesis, where I directly compared the overall results from the groups exposed to High-Beta binaural beats to those exposed to Gamma binaural beats. By using the group not exposed to any as the reference, the analysis aimed to determine if there was a significant difference in the effect High-Beta binaural beats had on memory versus the effect of Gamma binaural beats, relative to the no-exposure group.

In Chapter 5, I address each hypothesis separately and discuss the findings from each analysis along with their implications. I argue that the potential for improvement or interference in the memory process may be dependent on a combination of binaural beat frequency, the timing of exposure, and the type of information being processed (i.e. numerical, linguistic, or semantic). I also propose that encoding and retrieving distinct types of information is underpinned by distinct neural activity, basing this on the Encoding Specificity Principle, early-stage perception findings, and supporting evidence from existing studies. To conclude this thesis, I present my conclusions and acknowledge the limitations of this study in Chapter 6. I provide suggestions on ways future research could overcome these limitations, and propose directions for future research to expand on my findings. I conclude this thesis with a summary statement on the significance of this study and provide practical implications for the findings.

Purpose and Rationale of the Study

Brainwave synchronization using auditory beat stimulation (ABS), also known as entrainment, presents a potentially less invasive and cost-effective intervention for addressing compromised cognitive functioning associated with neurological changes. ABS through binaural beats has demonstrated consistent promise in therapeutic applications for various conditions including pain management, anxiety and attention-deficit/hyperactivity disorder (ADHD), and has shown potential to enhance cognitive functions in healthy individuals (Gola et al. 2013). ABS serves as a practical, non-invasive intervention method utilizing auditory stimuli to synchronize predominant brainwave activity across cerebral hemispheres (Engelbregt et al., 2019). These brainwaves represent synchronised electrical pulses of neural communication (Breus, 2018; Derner et al., 2018) and play an integral role in regulating emotional and cognitive functioning (Basu & Banerjee, 2023; Buzsáki, 2006; 2020; Garcia-Agribay et al., 2019a; Jurvanen, 2020; Shekar et al., 2018).

However, existing literature on ABS using binaural beats presents a complex picture with disparate outcomes and related implications, particularly in cognitive domains such as attention and memory. Most studies differ on which frequency band optimally impacts memory performance. (Beauchene et al., 2017; Borges et al., 2023; Colzato et al., 2017; Garcia-Agribay et al., 2019a; 2019b; Ortis et al., 2008). These disparities are examined in systematic reviews such as the work by Basu and Banerjee (2023) and Huang and Charyton (2008), highlighting that different studies attribute significant effects on memory performance predominantly to Beta, Gamma, and Theta band frequencies.

To my knowledge, there is limited research on how binaural beats influence memory encoding and retrieval of presented information, in terms of numerical, linguistic, or thematic content and how this information is presented (i.e., visually and audibly). Although the influence binaural beats have on memory has mostly been focused on the potential to enhance performance, there is a significant gap in understanding how exposure to binaural beats influences memory when individuals are exposed while encoding presented information, and when they are recalling the information. Specifically, there is a lack of research comparatively investigating how exposure to binaural beats from different frequency bands impacts encoding and recall as distinctive cognitive processes.

The purpose of this study was to investigate whether exposure to High-Beta and Gamma binaural beats impacts the encoding and retrieval processes differently and whether immediate and delayed recall performance was influenced by the presentation format of the memory tasks. I used a comparative approach where participants would perform visually and audibly presented memory tasks, across two testing rounds. Comparisons of the results obtained from the participants in the groups exposed to binaural beats were then compared with the group that did not have any exposure to any type of binaural beats as the control. This approach had four main advantages in comparing participant performance: (1) whether the effects of Gamma vs. High-Beta binaural beats on immediate and delayed recall differed significantly, (2) whether exposure to binaural beats impacted the encoding and retrieval processes differently, (3) whether the presentation format of the memory tasks affected recall performance; and (4) whether binaural beat exposure and the presentation format of the memory tasks had an interaction effect that impacted participant performance.

Chapter 2: Literature Review

Theoretical Foundation of Memory Encoding and Retrieval

Tulving and Thomson (1973) proposed that memories are shaped by both environmental factors and cognitive states during encoding. They theorized that retrieval of information from memory hinges on the extent to which a retrieval cue aligns with the environmental factors and cognitive states present during the formation of any given memory. This principle is known as Encoding Specificity (Tulving & Thomson, 1973). From a behavioural standpoint, evidence of this principle can be found in contextual fear and anxiety studies. Research in this field consistently demonstrates that learnt behaviour can be altered through introducing an aversive stimulus, such as a mild electric shock, paired with a specific environment or sets of circumstances such as flashing lights or maze tasks. Reactions to the aversive stimuli become a conditioned response over time, persisting even when the aversive stimuli are removed. This learnt behaviour emphasises the significance of the context associated with a memory in its formation (Brocas & Carillo, 2016; Josselyn & Tonegawa, 2020; LeDoux, 2012; Poldrack et al., 2001; Poldrack & Foerde, 2008).

The work by LeDoux (2012) on fear and anxiety responses provides a biological basis for understanding how LeDoux's (2012) postulated survival circuits contribute to memory processes using the Encoding Specificity principle (Tulving & Thomson, 1973). LeDoux (2012) proposed that survival circuits are crucial in detecting and responding to challenges and opportunities in daily life, stressing the importance of this biological feature. The author suggests that survival circuits play a central role in optimizing behaviours that promote viability and facilitate responses to threats, implying that learning certain behaviours quicker than others (i.e., avoiding exposed electrical points as opposed to calculus) is driven by the biological need to survive (LeDoux, 2012). Survival circuits may also provide a biological basis for understanding how the brain automatically selects the most suitable neural activity patterns to process information, depending on the type of information being processed (i.e., numerical, linguistic, or thematic), to optimize cognitive performance while minimizing unnecessary resource expenditure.

In the context of binaural beats and their effects on memory performance, LeDoux's (2012) work suggests that survival circuits may play a role in optimizing the processing of auditory stimuli, such as binaural beats, to enhance memory encoding and retrieval. This notion is supported by LeDoux's (2012) postulations regarding the brain's ability to detect and respond to challenges from learnt behaviour, suggesting that memory formation and retrieval are dynamic processes that could be manipulated. Therefore, the use of binaural beats as a cognitive enhancement tool may be particularly effective in optimizing memory performance by leveraging the brain's natural survival circuits to process and retain information.

Considering the retention of information, DuBrow and Davachi (2021) proposed a cognitive need for boundaries within memory formation. The authors suggested that contextual shifts when encoding information into memory serve to separate an otherwise continuous experience into contextually related sequences. In turn, encoding related information into bounded sequences facilitates recalling the order of events contained within the experience (DuBrow & Davachi, 2021). Evidence of contextual shifts can also be found in fear and anxiety studies (LeDoux, 2012; Poldrack et al., 2001; Poldrack & Foerde, 2008) since test subjects do not always react to a particular stimulus (i.e., a flashing light) with the same level of fear or anxiety. DuBrow and Davachi's (2021) contextual shifts could then explain why a flashing light would evoke higher levels of fear or anxiety in an environment resembling that where it was followed by an electric shock compared to an average bedroom (encoding specificity) since the environmental factors related to the experience would have encoded into contextually related sequences.

Kuhbandner's 2020 study challenged the conventional beliefs of retaining information after a delay and long-term memory representations. Kuhbandner (2020) suggested that individuals store considerably more detailed information about written text than abstracts or surface details (commonly referred to as the theme or "the gist"), despite their subjective awareness of the memory. The author suggested that processing a central theme during encoding may reduce the need for contextually related boundaries such as proposed by DuBrow and Davachi (2021), and enhance performance (Kuhbandner, 2020). Presumably, processing a central theme may place lower demands on the encoding process by reducing the need for multiple contextually related boundaries separating a sequence of events, promoting pattern formation and subsequent completion of effective memory formation. In terms of encoding specificity and behaviour, Kuhbandner's (2020) work suggests that a memory of a flashing light in a laboratory setting would be enough to elicit a fearful response in the long term. These findings support the idea that the brain's natural mechanisms for processing and retaining information can be leveraged to optimize cognitive performance.

Individuals gain new knowledge, skills, or behaviours through experience, instruction, or practice. Learning something new involves the formation of new connections between neurons in the brain, supported by various neural and cognitive mechanisms that include attention, working memory, and long-term potentiation. Learning thus relies on memory processes such as encoding, consolidation, and retrieval of information. Tulving and Thomson's Encoding Specificity principle (1973) can be applied to the understanding of how readers decode written words and speech sounds and comprehend the meaning thereof when learning visually-based and auditory-based information. According to the Encoding Specificity principle, the retrieval of information from memory is influenced by the alignment between the environmental factors and cognitive states present during the initial encoding of that information (Tulving & Thomson, 1973). In the context of reading and comprehending written text, this principle suggests that the process of decoding words and extracting meaning is facilitated when the environmental and cognitive factors present during reading align with those present during the initial encoding of the written information.

Research from Cain et al. (2004) and Verhoeven et al. (2011) suggests that learning visually-based information and understanding the written word employs the interactive processes of lower-order word recognition alongside higher-order meaning-making. Further research has shown that as readers develop their skills, they become more efficient at decoding individual words and shifting their focus towards identifying the overall meaning within the text (Samuels & Flor, 1997). This process is suggested to rely on phonological awareness, which involves understanding how written words relate to auditory language and how they can be segmented into smaller units and phonemes (Bruck, 1992; Kirby et al., 2003; Wagner et al., 1997).

Similarly, when learning auditory-based information, such as speech sounds, the Encoding Specificity principle would suggest that the comprehension of these auditory signals is enhanced when the neurocognitive patterns involved in the initial encoding of the information are reactivated during retrieval. Studies on second language learning have emphasized the importance of an integrative understanding of stimuli at the neurological level, involving the collaboration of the ventral stream for speech perception and the dorsal stream for sensory-motor mapping in the left hemisphere (Yang & Li, 2019).

Although learning requires fundamental visual perception and auditory activity, further cognitive processes are required to successfully acquire new knowledge, skills, or behaviours (Verhoeven et al., 2011). Attention, for instance, enables top-down control of functions such as information processing and saccadic eye movements during reading (Schuett et al., 2008). Reading further relies on high-level aspects of executive function such as working memory capacity, which has been identified as a robust predictor of comprehension (Cain et al., 2004; Carretti et al., 2009). Baddeley (2003) postulated that working memory facilitates the rehearsal of phonological information essential for decoding and comprehension through the phonological loop component. Working memory is also suggested to facilitate the retention of visual representations of the layout through the visuospatial sketchpad component, allowing the reader to utilise various aspects of information processing as necessary (i.e. switching between processing and storing) through the central executive system that allows for attentional control (Baddeley, 2003).

Recent research demonstrated that early stages in perception also play a crucial role in memory formation. Pérez-Bellido et al. (2023) highlighted the facilitative role auditory stimulation plays in processing incoming stimuli and the significant effect this role has on how visually acquired information is encoded and retained in memory. It is therefore plausible that binaural beats may function as a modulatory tool to enhance these cross-modal interactions between senses, given their capacity to entrain neural oscillations.

Specifically to the neural activity associated with heightened attention, formation and consolidation of memory (Başar et al., 2000), binaural beat exposure could potentially facilitate early perceptual stages in encoding and preservation of visual information in memory, building upon the findings of Pérez-Bellido et al. (2023). Furthermore, it would be plausible that such entrainment may better facilitate early perceptual stages in encoding and retrieving audibly acquired information since the need for cross-modal sensory interaction would be negated, essentially lightening the required cognitive load (Breus, 2018; Garcia-Agribay et al., 2019; Engelbregt et al., 2019; Kennerley,2009).

Based on the Encoding Specificity principle of Tulving and Thomson (1973) providing the theoretical foundation of this inquiry, the postulations of DuBrow & Davachi (2021), Kuhbandner (2020), and Pérez-Bellido et al. (2023) provided guidelines on the specific testing stimuli used in the present study, as outlined in the materials and methodology sections.

The Effects of Auditory and Visual Presentation on Memory Performance

The prevailing body of knowledge suggests that most experiments testing the effect of binaural beats on memory have primarily used visually presented memory tasks, such as digit span and word-based tasks, to assess memory performance. Few studies have comparatively investigated the effects of binaural beats coupled with auditory presentation of memory tasks versus the effects of binaural beats coupled with visually presented memory tasks.

A study by Rogowsky et al. (2016) investigated how recall differs in everyday circumstances depending on the way information is presented. The authors reported no significant differences in comprehension, retention of information, or recall ability when information is acquired through reading, listening, or reading-while-listening (dual-modality). The authors subsequently reported that participants in each testing condition recalled an equal amount of information regardless if the task information was delivered visually, audibly or in a dual-modality (Rogowsky et al., 2016). The authors suggest that reading-while-listening did not cause interference during the encoding process compared to reading or listening, as would be expected considering earlier production-line-type postulations of the encoding process. However, participants in this study were not exposed to any intervention or external stimulation such as binaural beats.

Supporting the findings of Rogowsky et al. (2016), Deniz et al. (2022) compared the semantic brain activity maps of participants presented with visual stimuli (reading) to the maps generated when the same participants were presented with auditory stimuli (listening). The authors found these maps to be nearly identical. Deniz et al. (2022) suggested that the formation of representations within the brain is somewhat universally coded and not dependent on which sense information might be acquired.

Considering traditional learning methods without binaural beat exposure as in the studies by Deniz et al. (2019) and Rogowsky et al. (2016), existing literature also suggests that learning by listening may be more effective than learning by reading (Kelly et al., 2022; Obleser & Kayser, 2019; Wright et al., 2009). The effectiveness of learning through listening is suggested to be dependent on the individual, the context, and the time spent on the material.

The Role of Brainwaves in Cognition

Understanding how the brain communicates internally is essential in understanding the proposed influence of ABS. The primary messenger cells specialized in transmitting information throughout the brain and body (neurons) engage in communication through a combination of electrical and chemical signals. Although this study does not delve into the intricacies of neural and synaptic communication, it is crucial to recognize that the exchange of information between synapses involves the conversion of electrical signals (action potentials) into chemical signals (neurotransmitters). These neurotransmitters, upon binding to postsynaptic receptors are reconverted into an electrical signal and the process repeats onto its destination and results in a physical or cognitive outcome. As information traverses the network of neurons within the brain, the synchronised electrical activity generates rhythmic voltage fluctuations known as oscillations or brainwaves that propagate across different brain regions (Buzsáki, 2006). Binaural beat stimulation is theorized to influence the rate at which neurons fire through entrainment of the rhythmic voltage fluctuations and can therefore modulate brainwave activity and internal communication patterns.

Distinct brainwave activity has been linked to specific cognitive processes ranging from pain management to memory (Basu & Banerjee, 2023; Başar et al., 2000; Buzsáki, 2020; Garcia-Agribay et al., 2019a; Jurvanen, 2020; Shekar et al., 2018), with the possibility of improving these processes through binaural beat stimulation a focal point in ABS research. Brainwave activity is categorized into five distinct frequency ranges that collectively span a continuous spectrum of neural oscillations. Rather than representing discrete, non-overlapping states, these frequency ranges should be understood as bounded segments along a single, uninterrupted continuum of brainwave activity. The five frequency categories, measured in Hertz (Hz) or cycles per second (cps), include Delta (1-4 Hz), Theta (4-8 Hz), Alpha (8-13 Hz), Beta (13-30 Hz), and Gamma (30-70 Hz). Research has demonstrated that it's possible to enhance the quality of these brainwaves and condition cortical activity through auditory stimulation, a phenomenon known as entrainment (da Silva et al., 2015; Garcia-Agribay et al., 2019; Góes, 2018, Shekar et al., 2018).

One such study by Herweg et al. (2020) on Theta oscillations in human memory provides a review of the role Theta oscillations play in memory formation, particularly in the context of episodic memory. The authors suggest that Theta oscillations specifically support associative memory, whereas the spectral tilt reflects a general index of activation rather than being specific to memory processes.

The spectral tilt is a phenomenon observed in the power spectrum of neural activity, characterized by a decrease in low-frequency power accompanied by an increase in high-frequency power. This tilt is distinct from isolated decreases in low-frequency power and reflects a broader change in the background power spectrum rather than just changes in narrow-band oscillations. The spectral tilt is observed across various brain regions, including the frontal, temporal, and medial temporal lobes, during both memory encoding and retrieval. Fellner et al. (2019) and Herweg et al. (2020) suggested that the spectral tilt is observed during successful memory performance, contrasting with unsuccessful memory performance. The authors further suggested that the characteristic change in the power spectrum, with decreased low-frequency and increased high-frequency power, is a key feature of successful memory performance, distinct from changes in neural oscillations alone (Fellner et al., 2019; Herweg et al., 2020).

Although authors such as Buzsáki (2006, 2020) do not explicitly address the interchangeability of neural oscillations, the work of Fellner et al. (2019) and Herweg et al. (2020) emphasises the adaptability of neural oscillations based on the cognitive demands of the task at hand, highlighting the importance of considering both brainwave oscillations and the spectral tilt in understanding human memory processes. This implies that neural oscillations may be interchangeable depending on the specific memory tasks being performed, highlighting the adaptability and versatility of neural activity in cognitive processes. Additionally, this signifies that the entire brain does not operate exclusively within a single dominant frequency band during a task, but rather seamlessly modulates its activity as needed (Başar et al., 2000; Buzsáki, 2020; Fellner et al., 2019; Herweg et al. 2020).

For example, during an alpha-dominated state such as relaxation, Alpha frequencies would dominate cortical activity concurrently with subordinate underlying neural activity. During this state of relaxation, the underlying neural activity would maintain certain specialized cognitive and biological functions such as hormone release, heartbeat and consciousness, and attention.

The Basis of Synchrony and the Entrainment Hypothesis

The perception of auditory beats resulting from two different frequencies, one presented to each ear of an individual, is often associated with the concept of neural synchronization as proposed by Licklider et al. (1950). The authors suggested that neurons vary in response to external stimuli at different frequencies. At lower frequencies, neurons can fire in some level of coordination with the stimulus waveform but they do not fire simultaneously enough to generate significant synaptic summation. In other words, neurons fire somewhat in sync with the stimulus, but not precisely. Similarly, neurons take turns firing at high frequencies and only a limited number of neurons can fire at any given time. This also results in less synchronization and a staggered firing pattern. At intermediate frequencies, neurons are suggested to participate in multiple rounds of firing (volleys) and display a tendency to discharge almost simultaneously. This results in relatively precise synchrony in each afferent pathway and where these pathways converge in a common neural centre, “beats” emerge (Basu & Banerjee, 2023; Licklider et al., 1950).

This synchrony is achieved through the process of entrainment, a concept originating from the field of physics. Entrainment typically refers to the synchronization of one system's motion or oscillation with the frequency of another, due to a transfer of energy. For instance, when a guitar string starts vibrating in response to a "G-tuned" tuning fork vibrating nearby. In biology, entrainment refers to the synchronization of biological rhythms with environmental cues. In psychology, brainwave entrainment specifically relates to the brain's electrical response to rhythmic sensory stimuli. The brain processes stimuli received through auditory and visual senses as electrical charges, known as Cortical Evoked Responses (Başar et al., 2000; Licklider et al., 1950; Zhuang et al., 2009).

The recent increase in research on ABS has predominantly emphasised its psychological effects concerning improvement with investigations encompassing cognitive functions, emotional states, and associated physiological changes. These studies find their theoretical grounding in the Brainwave Entrainment Hypothesis. The hypothesis suggests that exposing the brain to auditory or visual stimuli at specific frequencies induces synchronization of the brain's electrocortical activity with the stimulus frequency or its harmonics (Ingendoh et al., 2023).

Since 1950 methods for examining brainwave entrainment have consistently been refined by incorporating modern brain imaging technologies such as functional Magnetic Resonance Imaging (fMRI), Electroencephalogram (EEG), Positron Emission Tomography (PET) and Magnetoencephalography (MEG). Typically, electrodes adhered to the scalp are used to measure and examine EEG signals while an individual is engaged in a task. One study by Kaneko et al. (2003) on binaural interaction in the human auditory cortex employed a unique approach by combining a frequency-tagging method with whole-scalp magnetoencephalography (MEG) recordings during their investigation.

The findings from Kaneko et al. (2003) indicated that binaural stimulation demonstrated a notable suppression of ipsilateral input (i.e., the input to the same side of the brain as the stimulated ear) compared to contralateral input (the input to the opposite side) within both hemispheres. The use of whole-scalp neuromagnetometers was particularly advantageous in this study as they allowed for the simultaneous recording of signals from both hemispheres. The authors found that this suppression occurred consistently across varying stimulus intensities, leading to a shift in the balance of hemispheric activity toward the contralateral hemisphere while stimulated. This provided a broader perspective on the differences in neural activity in different hemispheres and how they respond to binaural stimulation (Kaneko et al., 2003). Similar findings were presented by Gao et al. (2014) demonstrating that left and right temporal cortical areas respond differently to binaural beats stimulations, as well as different brain regions to different frequencies (Gao et al., 2014).

EEG studies further suggest that ABS can affect electrocortical activity and modulate the frequency of neuronal oscillations without any prior training, with optimal influence during a given task (Basu & Banerjee, 2023; Gao et al., 2014; Garcia-Agribay et al., 2019a; 2019b). Considering these differential effects and possibilities (Gao et al., 2014; Kaneko et al., 2003), the allure of brainwave entrainment lies in its potential to induce specific physiological and psychological states by targeting distinct frequency bands of the human EEG (Ingendoh et al., 2023). Consequently, investigations into the effects of ABS extend to diverse domains, including cognitive processing, emotional states, mood regulation, pain perception, and memory (Ingendoh et al., 2023; Zhuang et al., 2009).

Empirical support for the Brainwave Entrainment Hypothesis primarily stems from research revealing time-locked Auditory Steady-State Responses (ASSRs) during binaural beat stimulation (Ingendoh et al., 2023). The study conducted by Ioannou et al. (2015) examined the effect of short-term binaural stimulation at frequencies ranging from 1 Hz to 48 Hz on brain responses, with a specific focus on the Alpha and Gamma band EEG signals. The study's findings revealed that frequencies within the Alpha band produced the most significant steady-state responses across the participant groups. Contrasting the postulations of Licklider et al. (1950) suggesting imprecise and inconsistent firing at low frequencies, the processing of low-frequency binaural beats in the Alpha band oscillations (8-13 Hz) had a significant effect on the cortical network patterns. Ioannou et al.'s (2015) results provided valuable neurophysiological insights into how the cortex responds to binaural beat stimulation across various frequencies. Notably, the authors suggested a form of neuronal entrainment in relation to the perceived frequencies (Ioannou et al., 2015).

Further empirical support is found in contemporary EEG research suggesting that perceptual entrainment can take two main forms. Firstly, symmetrical (or "bidirectional") entrainment occurs when two systems mutually influence one another, as observed when individuals synchronize motor movements with one another. Alternatively, studies have suggested evidence of "uni-directional" entrainment, where a robust external oscillator influences a system without the system affecting the oscillation. Uni-directional entrainment has been a fundamental concept in brainwave synchronization following rhythmic stimulation, such as acoustic stimuli (Kalyan & Kaushal, 2016; Zhuang et al., 2009). Current neurophysiological research indicates that the effects of ABS can be measured in the cerebral cortex through EEG techniques as a frequency following response originating in the olivary nuclei and the brainstem (Basu & Banerjee, 2023; Garcia-Agribay et al., 2019a; 2019b).

Despite empirical support from studies such as these, a substantial body of basic research presenting results that do not align with the entrainment hypothesis (Gao et al., 2014) challenges the assumption of sound evidence for brainwave entrainment through ABS. In some cases, the entrainment effect has been assumed rather than independently or empirically demonstrated, while others only offer partial evidence in favour of successful entrainment (Ingendoh et al., 2023).

Ingendoh et al. (2023) attribute the conflicting findings in this field to a multitude of issues within the research landscape. Firstly, the operationalization of entrainment effects in the human EEG exhibits considerable diversity, encompassing time-locked auditory responses, EEG power measures, and even event-related potentials (ERPs). Recent research has expanded its focus beyond EEG frequency and time domains to include brain connectivity measures. Ingendoh et al. (2023) also suggest that heterogeneity is evident in the study designs, from variations in participant samples to differences in frequency bands employed in ABS research. Divergence in presentation methods and experimental and control conditions further complicates the comparison of results. Consequently, systematic analysis and integration of the existing research in this field is essential, especially considering the potential for widespread application of ABS (Borges et al., 2023; Ingendoh et al., 2023).

Cognitive Modulation Through Auditory Stimulation: The Role of Binaural Beats

H.W. Dove (1839) first described the perceptual response to artificially generated stimuli known today as binaural beats (da Silva et al., 2019; Ingendoh et al., 2023). The illusory phenomenon of binaural beats was largely dismissed until Licklider et al. (1950) reignited scientific curiosity by characterizing the perception of binaural beats depending on presented frequencies. Oster (1973) sparked further scientific interest in the potential of binaural beat stimulation by systematically integrating early empirical studies into a study on how binaural beats can be used in practice, highlighting the relevance thereof. However, the notion of tying binaural beat exposure to cognitive enhancement and the development of intervention approaches would not be explored until Atwater (1997) published a seminal study in the field. Reliable neuroscientific evidence of specific brain activity in response to binaural beat exposure would not be presented until early 2000 due to the widespread advent of technologies such as EEG and MEG (Gao et al., 2014; Ioannou et al, 2015; Kaneko et al., 2003; Kaylan & Kaushal, 206; Ingendoh et al., 2023; Zhuang et al., 2009).

Recent studies have suggested sound-driven entrainment to modulate or enhance various cognitive functions, including attention and memory (Basu & Banerjee, 2023; Gola et al., 2013;

Hanslmayr et al., 2007, 2019; Lafon et al., 2017), through external rhythmic stimulation. When individuals are exposed to two sinusoidal tones with slightly differing frequencies, the fluctuation characterised by the intermittent waxing and waning as the two frequencies synchronize and desynchronize results in the listener perceiving a third beating sound equal to the frequency mismatch between the two tones (Ioannou et al., 2015; Kennerley, 2009; Mujib et al., 2021; Shekar et al., 2018).

For instance, when tones of 400 Hz and 410 Hz are presented separately to the right and left ears, they engender a binaural beat at 10 Hz. Empirical investigations have demonstrated that frequencies around 400 Hz, with a maximum difference of approximately 35 Hz between the two frequencies, induce the most robust behavioural and psychological effects (Garcia-Argibay et al., 2019a; Ioannou et al., 2015, Mujib et al, 2021). This perceived amplitude-modulated standing wave is known as a binaural beat. Importantly, binaural beats are not a physical attribute of the acoustic stimulus itself. Rather, it manifests as a perceptual auditory illusion subjectively experienced by individuals. This perceptual phenomenon consistent with findings of entrainment investigations (Kalyan & Kaushal, 2016; Zhuang et al., 2009) is also believed to originate in the olivary nucleus within the brainstem (Basu & Banerjee, 2023; Mujib et al., 2021) influencing brainwave activity. Exposure to binaural beats is ultimately suggested to affect cognitive functions through uni-directional entrainment as neural activity synchronises with the perceived rhythmic frequency of the beat (Garcia-Agribay, Santed & Reales, 2019; Shekar et al., 2018).

It is theorized that binaural beats exhibit the capacity to entrain cortical activity at both the specific frequency of the beat itself (Draganova et al., 2008; Mujib et al., 2021) and through cross-frequency modulations, where the perceived beats influence interhemispheric synchronization of another frequency. This cortical entrainment encompasses a synergistic pattern that naturally alters consciousness in vivo (da Silva et al., 2015; Góes, 2018; Shekar et al., 2018). In effect, while the brain cannot be entrained to operate outside the continuum of brainwave activity and natural frequency range of 1 – 70 Hz, it can be coaxed into exhibiting any dominant brainwave activity within this range through auditory stimulation (Buzsáki, 2006; 2020; Jazayeri & Afraz, 2017; Obleser & Keyser, 2019).

Apart from studies that employ binaural beats to investigate effects on cognitive functioning in neurologically intact participants, binaural beats have also been used in treatments for conditions like anxiety and chronic pain (Garcia-Agribay et al., 2019; Wiwatwongwana et al., 2016; Yusim & Grigaitis, 2020). Further studies also suggest that binaural beats could heighten relaxation and attention (Hanslmayr et al., 2007; 2019). For the purposes of this study specifically, the following section provides a more focused overview of findings in existing literature on the effect binaural beats have on memory.

The Effects of Binaural Beat Stimulation on Memory

Table 1 presents a brief extract of studies examined by Basu and Banerjee (2023) that have explored the potential effects of auditory beat stimulation (ABS) on memory using binaural beats. These studies differed in their methodological approaches for examining the effect of binaural beats on memory. The studies in Table 1 employed variations in frequency choices, exposure duration, experimental designs, and assessment tools.

Table 1

Previous Research on the Effects of Binaural Beats on Memory

Study	Subgroup	Ne Nc	Hedge's g	Variance
Garcia-Agribay et al., 2019a, b	Memory	16 16	0.90	0.14
Garcia-Agribay et al., 2019a, b	Memory	16 16	-0.82	0.14
Roberts et al., 2018	Memory	25 21	2.19	0.14
Roberts et al., 2018	Memory	20 20	2.50	0.18
Beauchene et al., 2017	Memory	34 34	0.18	0.06
Beauchene et al., 2017	Memory	34 34	0.12	0.06
Beauchene et al., 2017	Memory	34 34	0.08	0.06
Kraus & Porubanová, 2015	Memory	20 20	0.68	0.11
Ortiz et al., 2008	Memory	18 18	-0.32	0.11
Ortiz et al., 2008	Memory	18 18	0.41	0.11
McMurray, 2006	Memory	20 20	0.63	0.11
Kennerly, 1994	Memory	27 23	0.70	0.09
Kennerly, 1994	Memory	27 23	0.49	0.08
Kennerly, 1994	Memory	27 23	0.67	0.09

Note. From " Potential of binaural beats Intervention for Improving Memory and Attention: Insights from Meta-Analysis and Systematic Review", by S. Basu and B. Banerjee, 2023, Psychological Research 87, 951–963 (https://doi.org/10.1007/s00426-022-01706-7).

Research in the field often investigated the effects of Alpha and Beta binaural beats on memory, using exposure to random noise, music, or Theta frequencies as control conditions. However, many aspects remain unclear, including the duration of the observed effects after exposure, the effect timing of exposure on memory performance, the optimal frequency for memory enhancement, and the relevance of carrier tones (Borges et al., 2023).

Basu and Banerjee (2023) conducted a meta-analysis that included studies investigating various memory sub-types, including working memory, episodic memory, long-term memory, and verbal memory. Across these studies, binaural beat frequencies ranged from Alpha and Beta to Theta, with frequencies typically ranging between 5Hz and 20Hz. Research on the effects of Gamma range binaural beats was notably absent.

Despite variations in findings among these studies, it is consistently suggested that Alpha, Beta, and Theta binaural beat frequencies appear to have some influence on various memory domains. However, the specific effects may differ contingent on the memory type examined and the particular binaural beat frequency used. For instance, Herweg et al. (2020) found that Theta range binaural beats had a significant effect on associative memory, while Beauchene et al. (2017) suggested Theta binaural beats to hinder working memory.

The Effects of High-Beta Binaural Beats on Memory

Early investigations into auditory stimulation hypothesised that exposure to frequencies inducing Beta-level functioning could significantly enhance memory (Domjan & Burkhard, 1982). This notion found support in the work of Kennerly (2009) amongst others (see Table 1), that identified a positive correlation between Beta band neural activity and improved memory performance. Studies have consistently shown that Beta-band neural activity is associated with heightened alertness and arousal (Breus, 2018; Jurvanen, 2020). More specifically, frequencies within the higher Beta band (between 18Hz and 30Hz) have been associated with increased alertness and improvement in cognitive functions related to problem-solving, planning, prediction, and certain sub-types of memory (Breus, 2018; Garcia-Agribay, Santed & Reales, 2019).

Research by Beauchene et al. (2017), Kraus & Porubanová (2015), McMurray (2006), Varga et al. (2016), and Westerberg et al. (2015) collectively support the notion that exposure to Beta frequencies enhances working memory. Particularly, Beta band binaural beats are associated with improvements in visuospatial and working memory performance, as well as free recall and digit span tasks (Beauchene et al., 2017). The latter enhancement appears particularly relevant in individuals with attention deficit hyperactivity disorder (ADHD) (Basu & Banerjee, 2023; Gola et al., 2013).

Beauchene et al. (2017) investigated the effects of various acoustic stimulation conditions within the Alpha and Beta frequency bands on cortical network topology and the accuracy of participants' responses during a visuospatial working memory task. The study considered six acoustic stimulation conditions, including no exposure, pure tones, classical music, Alpha (5Hz binaural beats and 10Hz binaural beats, respectively) and lower beta (15Hz) binaural beats. The results indicated a significant decrease in response accuracy from participants exposed to Alpha wave binaural beats, while participants exposed to Beta (15Hz) binaural beats during the visuospatial working memory task exhibited an increase in response accuracy. Over 5 minutes, participants' accuracy improved by 3%, suggesting a positive influence of 15Hz binaural beats exposure on working memory performance (Beauchene et al., 2017).

The work of Beauchene et al. (2017) is just one example highlighting that Beta wave exposure has been at the centre of memory enhancement inquiries since the work of Licklider et al. (1950). In contrast, exposure to Theta frequencies has been suggested to tend to hinder recalling the same memory recall processes. Furthermore, the effects of Beta band binaural beats have been linked to improvements in other cognitive functions, including attention and learning (Breus, 2018; Garcia-Agribay et al., 2019a; 2019b; Jirakittayakorn & Wongsawat, 2018; Kennerly, 2009; Rasch & Born, 2013; Scullin, 2013; Shekar et al., 2018).

The Effects of Gamma Binaural Beats on Memory

An increasing body of contemporary research has shown that memory performance can be improved through exposure to Gamma-frequency stimulation. Recent studies have reported that the cognitive benefits observed during Gamma entrainment surpass those typically associated with Beta wave studies (Garcia-Agribay et al., 2019a, 2019b; Jurvanen, 2020; Sharpe & Mahmud, 2020; Shekar et al., 2018). Gamma wave entrainment has shown promise in treating cognitive impairments and trauma, both physical and psychological (Buzsáki, 2020; Garcia-Agribay et al., 2019a; Hutchinson, 1994; Ochs, 1993; Shekar et al., 2018). Neural activity in the Gamma band has been suggested to dominate cortical activity during alert and aroused states. Research has shown that stimulating this activity during memory and attention tasks has the potential to enhance cognitive performance in memory sub-types, such as working memory and episodic memory (Garcia-Agribay et al., 2019a, Jurvanen, 2020).

Gamma band activity (above 30 Hz) is integral to complex cognitive processes, including information and sensory binding, transferring information, and linking data from various brain regions (Engelbregt et al., 2019; Sharpe & Mahmud, 2020). Gamma band activity has also been linked to integrated thinking, and high-level cognitive processes such as logical reasoning, learning, and sustained attention (Borges et al., 2023; Garcia-Agribay et al., 2019a; Góes, 2018; Shekar et al., 2018). However, it is essential to acknowledge that the relationship between Gamma wave entrainment and memory enhancement is not without controversy.

Jirakittayakorn and Wongsawat (2018) found that administering word recall tasks after exposure to Gamma binaural beats resulted in improved word recall scores, indicating the potential for memory improvement (Borges et al., 2023; Jirakittayakorn & Wongsawat, 2018). Contrasting these findings, Engelbregt et al. (2019) conducted a study comparing working memory performance levels while exposing participants to Gamma band (40Hz) monaural and binaural beats. The authors found no significant results to support working memory enhancement. However, Engelbregt et al. (2019) observed reduced reaction times during attention tasks, suggesting that monaural and binaural beats within the Gamma frequency band had different effects on working memory and attention (Borges et al., 2023; Engelbregt et al., 2019).

Shekar et al. (2018) found a similar decrease in both auditory and visual reaction times after entrainment with Alpha and Gamma binaural beats without results supporting improvements to memory performance. The authors concluded that Gamma band binaural beats improved participants' ability to pay attention to the memory tasks and not necessarily memory itself (Shekar et al., 2018). These findings were further substantiated in an inquiry by Mujib et al. (2021) evaluating short-term memory performance under different binaural beat frequencies that included Gamma. The results of this study showed that Alpha binaural beats conditions increased cognitive scores, while both Alpha and Gamma conditions reduced reaction times. This implies that the faster processing of attended information might be attributed to the influence of Gamma binaural beats, even though these studies did not find significant effects on working memory (Borges et al., 2023; Mujib et al., 2021).

Varied Effects of Auditory Beat Stimulation on Memory

The literature on binaural beats and memory performance has yielded contradictory results. While some studies have reported statistically significant effects for both Beta and Gamma stimulation, these effects are often assumed to be weak and short-lived. The inconsistencies in findings may be attributed to factors such as using a singular type of stimuli or task in the studies (i.e., only digit span or target word-based tasks), methodological differences regarding the duration of exposure, and the lack of detailed discussions on the mechanisms involved in generating these effects (Chaieb et al., 2015). The authors further propose that the timing of exposure is particularly crucial for the direction of memory effects, noting studies showing contrasting outcomes depending on when the stimulation is administered during memory tasks.

For instance, enhanced task performance has been observed when binaural beat stimulation occurs during the encoding phase, whereas detrimental effects were noticed while stimulation preceded the memory task (Chaieb et al., 2015; Derner et al., 2018). Exiting studies have also shown that employing different binaural beat frequencies may lead to changes in immediate verbal memory recall (Wais & Gazzaley, 2011). For example, research has shown that fluctuations as small as 5Hz can disrupt phase synchronization and affect memory processes both positively and negatively (Chaieb et al., 2015; Derner et al., 2018).

Other Factors Influencing Auditory Beat Stimulation and Memory Performance

Time-of-Day Effects on Memory Performance

Apart from the challenges associated with studying the effect of binaural beats on memory performance, a further consideration when studying memory specifically is the time-of-day effect. Ebbinghaus's initial observations in 1885 highlighted the significance of time-of-day in influencing cognitive performance during training and testing, with subsequent research providing varying results. For instance, Baddeley et al. (1970; 1974; 2001; 2012) consistently found that immediate recall is highly dependent on when testing occurs during the day, while delayed recall appears more resilient to time-of-day variations.

Petros et al. (1990) supported these findings, attributing varied cognitive performance levels to individual chronotypes - whether an individual is a "morning" or "evening" type of person. Ryan et al. (2002) expanded on the notion of chronotypes by introducing the concept of synchrony. Synchrony refers to the alignment between an individual's preferences and optimal cognitive performance times. The work of May et al. (2017) and Ryan et al. (2002) also suggests that age plays a role in optimal cognitive performance times, with older adults often performing better in the morning and younger adults in the afternoon.

Barbosa and Albuquerque (2008) investigated the effect of time of day on long-term explicit memory performance, accounting for both synchrony and chronotype. They found that explicit long-term memory recall was not affected by chronotype or the time-of-day testing was conducted, but was significantly influenced by the time training occurred during the day. Specifically, training in the afternoon led to better recall compared to training sessions in the morning (Barbosa & Albuquerque, 2008).

While the influence of time of day on memory retrieval has been widely studied, there is limited research exploring the potential mitigation of these effects through ABS or exposure to binaural beats. A common occurrence in memory studies is that time-of-day effects are mentioned as a possible confounding variable if not accounted for in the design. Given the sample for this study predominantly consisted of younger adults, the time-of-day effects discussed in the existing literature were accounted for by testing participants in the afternoon, in line with the suggestions of Baddeley (1970; 1974; 2001; 2012), May et al. (2017) and Ryan et al. (2002).

The Effect of Masking Techniques on Binaural Beat Effectiveness

What is generally regarded as the best way to expose individuals to binaural beat stimulation in the field of auditory beat stimulation (ABS) research, is an ongoing topic with little consensus. Specifically, there is controversy over whether masking binaural beats with white noise, pink noise, or music enhances their effectiveness compared to exposing participants to pure tones. For instance, some studies suggest that adding background noise can improve the efficacy of binaural beats, while others argue that pure tones are more effective for achieving neural entrainment.

A recent study by Borges et al. (2023) has shown that obscured binaural beats, or pure tones hidden under other noises, do not necessarily yield better results. Unmasked binaural beat stimulation is suggested to have larger effects than binaural beats masked by noise or music. These findings imply that masking binaural beats with noises or music may affect their ability to induce entrainment (Borges et al., 2023). On the contrary, Engelbregt et al. (2019) found that masking binaural beats ultimately did not alter the effects on cognition compared to unmasked binaural beats, nor did it reduce the potential for annoyance caused by unmasked pure tones. Engelbregt et al. (2019) suggest that binaural beats may be an effective cognitive enhancement tool even when masked by noises or music.

These findings emphasise the significance of participant comfort while suggesting that task performance may be linked to the subjective pleasantness of the auditory experience (Engelbregt et al., 2019; Hiwa et al., 2018). Minimizing discomfort and unintentional distress within the High-Beta and Gamma testing conditions in the current study was considered crucial for optimizing the efficacy of the binaural beat intervention (Engelbregt et al., 2019; Jurvanen, 2020; Obleser & Kayser, 2019; Shekar et al., 2018; Sharpe & Mahmud, 2020; Wiwatwongwana et al., 2016).

Gaps Within the Current Literature on Binaural Beats

The Effects of High-Beta vs Gamma Binaural Beats Exposure on Memory Performance

Unfortunately, not all studies examining the effect of binaural beat exposure on memory report on the carrier tones used in their respective experimental designs. Some research suggests that carrier tones in the range of 400 - 500 Hz as considered ideal as they are unlikely to originate from the cortex naturally and less likely to interfere with normal cognitive responses (Coffey et al., 2016; Engelbregt et al., 2019; Licklider et al.,1950; Orozco-Perez et al., 2020; Perrott and Nelson, 1969). Nevertheless, these tones are widely regarded as too high for comfortable listening (Engelbregt et al., 2019). Participant comfort plays a crucial role in studying the effects of binaural beats on memory, as task performance is closely linked to the subjective experience and the pleasantness of the noise participants are exposed to during tasks.

Discomfort may lead to unintentional interference, frustration, or annoyance that could negatively influence mood and ultimately affect performance in any testing task (Engelbregt et al., 2019; Garcia-Agribay et al., 2019; Hiwa et al., 2020). Statistically significant outcomes have consistently been observed in studies with carrier tones falling within the range of 230 Hz to 255 Hz (Beauchene et al., 2017; Engelbregt et al., 2019; Garcia-Agribay et al., 2019 a, 2019b; Kraus & Porubanová, 2015), and is recommended for providing a more comfortable auditory experience (Engelbregt et al., 2019; Jurvanen, 2020; Obleser & Kayser, 2019; Shekar et al., 2018; Sharpe & Mahmud, 2020; Wiwatwongwana et al., 2016). Aiming to exact optimal effectiveness and to control for discomfort, unmasked pure tones with a 230 Hz carrier tone were created and used in the present study.

Based on the meta-analyses from Basu and Banerjee (2023), Huang and Charyton (2008), and Garcia-Agribay et al. (2019a, 2019b), the existing literature on binaural beats demonstrates a notable gap. Limited studies have directly contrasted the effects of High-Beta binaural beat exposure against the effects of Gamma binaural beat exposure, creating some debate on the topic of the true nature of the influence on the memory processes. Furthermore, most binaural beat studies have only examined the effects of binaural beat exposure during the learning/encoding phase, while few have investigated the effect binaural beat exposure has on the retrieval process. As a result, it is not clear how the timing of exposure to binaural frequencies impacts the retrieval of information from memory.

Few studies in the field of binaural beat stimulation have examined if there is an interaction effect between binaural beat exposure and the presentation format of memory tasks. Fewer still have investigated how the timing of exposure to binaural beats (during encoding versus during both encoding and recall processes) interacts with the memory task format, and if this interaction affects memory performance. By explicitly addressing these gaps, I aim to make a unique contribution to the existing knowledge by comparatively investigating these gaps, underscoring the significant nature of the research presented in this thesis.

Considering the extent of reported enhancements in memory performance in studies investigating Beta and Gamma binaural beats in isolation without a direct comparison, the current study is designed to comparatively examine the effects of both High-Beta (above 18 Hz) and Gamma (above 30 Hz) binaural beat exposure on memory performance. The aim is to comparatively investigate whether High-Beta and Gamma stimulation enhances immediate and delayed recall, and how the timing of exposure to these frequencies impacts memory performance. Furthermore, this study incorporates an examination of the influence the format of presenting the memory tasks (auditory vs. visual) has on memory performance. This approach facilitates a systematic exploration of potential synergistic effects between auditory beat stimulation in the High-Beta and Gamma frequency ranges, considering various presentation formats.

Research Questions, Objectives and Hypotheses

In line with previous research (Beauchene et al., 2017; Borges et al., 2023; Breus, 2018; Engelbregt et al., 2019; Garcia-Agribay et al., 2019a; 2019b; Góes, 2018; Kelly et al., 2022; Kennerley, 2009; McMurray, 2006; Mujib et al., 2021; Shekar et al., 2018; Obleser & Kayser, 2019; Rogowsky et al., 2016), the primary objective of this study was to investigate the effects of binaural beats on immediate and delayed recall performance in healthy individuals, examining how the timing and presentation format of the memory tasks influence these effects, and whether exposure to High-Beta and Gamma frequencies enhances memory recall and retrieval. This study tested four hypotheses.

Research shows mixed results regarding how sensory modality affects memory performance, as reviewed in the section on “The Effects of Auditory and Visual Presentation on Memory Performance”. Rogowsky et al. (2016) and Deniz et al. (2022) found no significant differences between visual and auditory recall, suggesting similar cognitive processing across modalities. However, these studies did not involve interventions like binaural beats. In traditional learning contexts without such interventions, auditory learning has been shown to enhance processing depending on the task and individual factors (Kelly et al., 2022; Obleser & Kayser, 2019). This contrast in findings led to my first hypothesis:

(1) Participants not exposed to any binaural beats will perform significantly better in recalling the auditorily presented memory tasks compared to visually presented memory tasks.

Summarised in the "Cognitive Modulation through Auditory Stimulation" and the “The Effects of Binaural Beat Stimulation on Memory” sections, research indicates that binaural beats, especially within the High-Beta and Gamma frequencies, may enhance cognitive functions like memory and attention (Basu & Banerjee, 2023; Garcia-Agribay et al., 2019). Studies on Beta frequencies suggest improved recall accuracy, particularly in working memory and visuospatial tasks (Beauchene et al., 2017), while Gamma frequencies are linked to higher-order cognitive functions, including complex memory and sustained attention (Hanslmayr et al., 2007; 2019). This modulation occurs as binaural beats create an illusory beat frequency that entrains cortical activity, potentially enhancing neural synchrony for tasks requiring real-time cognitive processing, like auditory memory tasks (Ioannou et al., 2015; Mujib et al., 2021).

However, research is limited in comparatively examining how these effects are influenced by the mode of task presentation (visual vs. auditory). Literature suggests that visual tasks may benefit differently from binaural beat stimulation compared to auditory tasks, as visual tasks require spatial processing while auditory tasks demand temporal sequencing. This forms the basis for my second hypothesis:

(2) Participants exposed to High-Beta and Gamma binaural beats will demonstrate significantly enhanced immediate and delayed recall performance on memory tasks compared to those not exposed to any binaural beats, particularly for auditorily presented memory tasks.

My third hypothesis is informed by findings that timing of exposure critically influences memory effects, with dual exposure potentially maximizing recall performance (Chaieb et al., 2015; Derner et al., 2018).The literature suggests that binaural beats during encoding can enhance memory consolidation (Basu & Banerjee, 2023; Beauchene et al., 2017; Engelbregt et al., 2019; Garcia-Agribay et al., 2019). However, exposure to binaural beats during both encoding and recall processes may lead to either cognitive enhancement or overload, with outcomes depending on frequency and duration (Chaieb et al., 2015; Derner et al., 2018).

(3) Participants exposed to High-Beta and Gamma binaural beats during both encoding and recall will show significantly improved immediate and delayed recall performance on memory tasks compared to those only exposed during encoding and those not exposed to any binaural beats, irrespective of the presentation format of the memory tasks.

The literature indicates that High-Beta frequencies enhance immediate recall and visuospatial tasks, while Gamma frequencies support long-term memory and complex cognitive functions (Basu & Banerjee, 2023; Beauchene et al., 2017; Garcia-Agribay et al., 2019). Studies also suggest that Gamma's effects may be stronger in tasks requiring integration across brain regions, such as auditory memory tasks (Engelbregt et al., 2019; Shekar et al., 2018). My fourth hypothesis is based on the distinct roles these frequencies play in neural processes underlying memory recall, particularly in different sensory modalities.

(4) Relative to participants not exposed to any binaural beats, the improvement in recall performance is expected to be more pronounced for those exposed to Gamma binaural beats compared to those exposed to High-Beta binaural beats. Additionally, the advantage of Gamma binaural beats over High-Beta binaural beats is expected to be more pronounced for auditory memory tasks compared to visual memory tasks.

Chapter 3: Research Methodology

Experimental Research Design

I employed a between-groups experimental design. As illustrated in Table 2 below, a 3 (frequency condition) x 2 (task presentation format) x 2 (timing of exposure) experimental design was used in the experiment. The frequency variable consisted of three conditions: 1.) Exposure to High-Beta binaural beats, 2.) Exposure to Gamma binaural beats, and 3.) No exposure to any binaural beats. The presentation mode variable had 2 levels, i.e., visual and auditory presentation of the digit span and story-based memory tasks. Both the visual and auditory memory tasks were presented to each participant. The final independent variable was the timing of exposure, also pegged at two levels. The timing of exposure refers to when participants were exposed to binaural beats during the memory tasks: 1.) Participants were either exposed to binaural beats during the encoding process only (single exposure), or 2.) during both encoding and recall (dual exposure) processes while engaged in the memory tasks.

Table 2

Experimental Conditions and Sample Sizes

Independent Variables	Conditions	Experimental group (n)	Notes
Frequency	High Beta	30	
	Gamma	30	
	No exposure	15	
Timing of Exposure	Encoding (single exposure)	15	Number of participants in single and dual exposure groups, respectively.
	Encoding and Recall (dual exposure)	15	
Presentation Mode	Audio		Each participant completed 6 memory tasks in total over two testing rounds, with the first round presented visually and the second presented audibly.
	Visual	75	

Note. The table above outlines 3 frequency conditions, 2 presentation formats and 2 distinct times of exposure to binaural beats. Time of exposure refers to participants being exposed to binaural beats during the encoding phase only, or exposed during encoding and recall of the information presented.

From the total sample size of 75 participants, equal groups of 15 were randomly assigned to each of the 5 experimental conditions outlined in Table 3. The first two experimental groups were exposed to High-Beta binaural beats: the first group during encoding alone (HBG-E, single exposure) and the second during both encoding and recall (HBG-ER, dual exposure). Similarly, the next two experimental groups were exposed to Gamma binaural beats in single and dual exposure conditions. The fifth experimental group served as a control with participants not exposed to binaural beats during the memory tasks (No exposure).

Table 3

Sample Distribution Across Experimental Conditions

Experimental groups	Total Sample (n)	Time of Exposure	Group Reference
High-Beta Group (single exposure)	15	Encoding	HBG-E
High-Beta Group (dual exposure)	15	Encoding and Recall	HBG-ER
Gamma Group (single exposure)	15	Encoding	GG-E
Gamma Group (dual exposure)	15	Encoding and Recall	GG-ER
No exposure	15	None	CNTR

Note. From the total of 30 participants initially assigned to each binaural beats exposure group, 15 were exposed to binaural beats during encoding only (single exposure) and 15 were exposed to binaural beats during encoding and recall (dual exposure). No exposure group (CNTR) – The 15 participants in this group were not exposed to any binaural beats, noise, or music during the experiment.

Sampling Method

A Bayesian Factor Design Analysis (BFDA) of 10 (Stefan et al., 2019), with a default prior ($H_1 = 6,75$; $H_0 = 0,21$) was utilised to determine an appropriate sample size. The calculations indicated that a minimum testing sample of 58 participants would be necessary to obtain a Bayes factor larger than 10, with a probability threshold of $p = 0.5$. A medium effect size (0,5) was chosen to measure the associations between memory performance and binaural beats effects and differences between group means (High-Beta vs. Gamma) for Cohen's d, enhancing the study's power and the strength of evidence for potential findings.

A fixed-N design was chosen with predefined desiderata for Bayes Factors (BF10 > 10, or BF10 < 0.1 and > 10) to evaluate the strength of the evidence (see Appendix C for detailed evidentiary strength classes). This approach allowed for the assessment of the experimental group mean scores against Bayesian factor parameters, indicating either strong evidence supporting the hypotheses (H_1) or strong evidence not supporting the hypotheses (H_0) (Stefan et al., 2018).

Participants

A total of 75 participants aged between 18 and 45 years (mean age = 22.46; SD = 4.46) were recruited for this study. Participants were screened for eligibility using an online questionnaire. The screening criteria included normal or corrected-to-normal vision, the absence of cognitive impairments, reading proficiency, normal hearing, the absence of language-related disorders (e.g., aphasia or dyslexia), and no history or diagnosis of epilepsy. The final screening questionnaire and informed consent form (See Appendix B) were reviewed and accepted by the Ethics Committee appointed by the Department of Psychology at The University of Cape Town. Participants were sourced through the University of Cape Town's Student Research Participation Program (SRPP), which offers course credits for student participation.

From 199 initial applicants, 98 were excluded on the grounds of not meeting the eligibility criteria. Of the exclusions, 25 participants reported taking chronic medication and 2 applicants reported a diagnosis of epilepsy. 8 applicants reported language, reading and hearing-related difficulties. A total of 68 applicants were not available during the scheduled testing times due to exam schedules and 36 applicants did not respond to the invitation. A total of 60 Participants who met the eligibility criteria and self-reported to have average or above-average reading proficiency and normal hearing were recruited to take part in this study. An additional 15 participants who met the inclusion criteria were recruited from outside the UCT SRPP pool. To ensure randomization, participants were randomly assigned to one of five testing conditions: No Exposure, exposure to High-Beta during encoding only (HBG-E), exposure to High-Beta during both encoding and recall (HBG-ER), exposure to Gamma during encoding only (GG-E), or exposure to Gamma during both encoding and recall (GG-ER). This was achieved through a programmed sequence that cycled through the exposure conditions (1-5) each time a new participant logged on to the online testing application, ensuring an equal chance of being presented with any of the five conditions.

Materials

Immediate and Delayed Recall Memory Tasks

Immediate Recall with Sequential Digit Span. Immediate recall performance was assessed using a digitized version of the WISC III digit span test (Stone, 2015; Wechsler, 1991). The digitized version of the classic sequential digit span task used in the experiment was based on the digital version available on GitHub: "cog-tasks: Working Memory Test Battery" by J. Stone. The WISC III digit span memory task requires that the participant repeats back a list of digits presented in sequence. Since I examined both written and auditory formats, the auditory version of the task consisted of a span of digits that are presented via a recording of spoken numbers where the presentation of each number was followed by one second of silence. In other words, a number was presented followed by one second of silence, then the next number followed by another second of silence. This sequence was repeated for each presentation of the presented numbers (WISC-III Manual, Wechsler, 1991). Acknowledging that a sequential digit span task can also be used as an attentional task, attention was not measured in the experiment as participants were not required to selectively attend to the digit span while ignoring potential distractions.

Miller's (1956) "The Magical Number Seven, Plus or Minus Two" introduced the concept that the average person can hold about seven (plus or minus two) items in their short-term memory. This idea, known as "Miller's Law," describes the limited capacity of working memory and its implications for information processing and memory retention. The serial position effect, which explains how the human brain understands only the information present at the beginning and end of a sequence, is another key concept related to Miller's Law. Despite some criticisms and limitations, Miller's Law remains a widely recognized and influential concept in cognitive psychology. However, some critics argue that this law oversimplifies the complexities of working memory capacity. Despite these criticisms, a total of 7 digits were presented in both the auditory and visually presented digit span tasks, in line with Miller’s Law (1956). Participants were instructed to recall as many digits as possible in sequence, starting from the first one presented.

Sequential Digit Span Test Scoring. Scoring for the Sequential Digit Span Test involved assigning points based on the accuracy of digit recall in the correct order. Each digit correctly recalled in the right sequence received one point. For instance, if a participant correctly recalled three out of seven digits displayed in the correct order, a score of 3 was allocated. This scoring method was employed to evaluate working memory performance by recording a participant's ability to recall and sequence numerical information accurately. Scores are calculated by tallying the number of correctly recalled digits and are typically recorded for further analysis. Non-related material, guesses, and responses with deduced patterns are usually excluded from the scoring process to maintain the accuracy and validity of the test results.

Delayed Recall of Target Words. Trifilio et al. (2020) tested the validity and reliability of the Newcomer Story Series as a viable story-driven alternative to widely regarded Logical Memory stories from the Wechsler Memory Scale (Wechsler, 1949, 1991). These tests are traditionally performed where examinees are read stories and asked to recall immediately, and then recall again 20-30 minutes later. The authors made three important findings. Firstly, the Newcomer stories demonstrated strong convergent validity by showing a high correlation with the Wechsler Memory Scale (WMS) III Logical Memory stories, indicating their suitability as a memory assessment tool. Secondly, the Newcomer stories exhibited divergent validity as they were less strongly correlated with tests of visuospatial ability and speeded word reading compared to verbal memory tests, highlighting their specificity as a measure of verbal memory. Lastly, the external validity of the Newcomer stories was supported by findings that delayed memory recall scores were more closely associated with left hemisphere medial temporal lobe structures, essential for verbal memory processes, and less correlated with other non-memory regions within the left hemisphere. These results suggest that the Newcomer stories offer a valid and distinct alternative to traditional memory assessment tools, providing a story-driven approach that aligns well with verbal memory processes in older adults (Trifilio et al., 2020).

For purposes of this study, the "Lucy Carson" and "Adam Jones" stories from the Newcomer Story set (see Appendix D) were used as the memory tasks. It's important to note that these stories were adapted to standard South African English to ensure familiarity and recognition among South African participants and mitigate any potential uncertainty surrounding colloquial language use and practices. For instance, in the original version of the "Adam Jones" story one of the sentences reads: " … from Tuesday through the end of the week". Using the expression "..through the end of the week.." is not commonly used in South African English and may have caused bias or confusion being unfamiliar in general speaking. Thus, the sentence was adapted to plain South African English to read: "… from Tuesday until the end of the week" instead, in keeping with the manner of speech in South Africa.

Comparable in complexity and grade to the traditional Wechsler Memory Scale stories (Trifilio et al., 2020), the Lucy Carson story comprises 4 sentences with a total of 61 words, averaging 1.44 syllables per word. The Flesch-Kincaid grade level for this paragraph is 7.4, providing a total of 44 scorable 'bits.' Similarly, the Adam Jones story consists of 62 words across 4 sentences, with an average of 1.35 syllables per word and a Flesch-Kincaid grade level of 6.4, also providing 44 scorable 'bits' (Trifilio et al., 2020). Data collected during the experiment were scored using two methods: Verbatim Scoring and Thematic Scoring, as per guidelines developed by Newcomer (1994) and Trifilio et al. (2020), respectively.

Verbatim Scoring of Target Words – Delayed Recall. One full point (1.0) was awarded for each “perfect verbatim response” of the identified target words (see Appendix D). Non-content words (i.e., “and”, “the”, and “a”) were not scored. A partial credit of 0.5 points was awarded for the recall of a word with the same lexical root and phoneme (i.e., “grab” for “grabbing”). Points were only awarded if the information recalled by the participants coincides grammatically with the original information, such as the correct use of tenses (i.e., past, present, and future), nouns and pronouns (i.e., “him” for “Adam”), and accurate names or numbers. Correctly recalling the sequence of events as described in each of the Newcomer stories did not factor into the scoring as this was treated as a free recall test. For instance, 1 point was awarded when a participant successfully recalled the target word “sale” anywhere in the response (Trifilio et al., 2020).

It should be noted that partial credit was awarded for instances where the target word was implied, yet misspelled. It should further be noted that this concession only applied when the intention was clear within the grammatical context of the story. Errors in spelling were limited to one erroneous letter contained in a target word that did not alter the lexical root or meaning. For example: when a participant wrote: “pcket” instead of “pocket” partial credit was awarded. Partial credit was not awarded in instances where “Carlson” was submitted by participants instead of “Carson”. Given that local South African currency (South African Rand, or ZAR) is commonly abbreviated using “R”, full credit was awarded where participants submitted “R / 300” or “300 / Rand”. Similarly, 2 points were also awarded when participants submitted “75 / %” or “75 / per cent”.

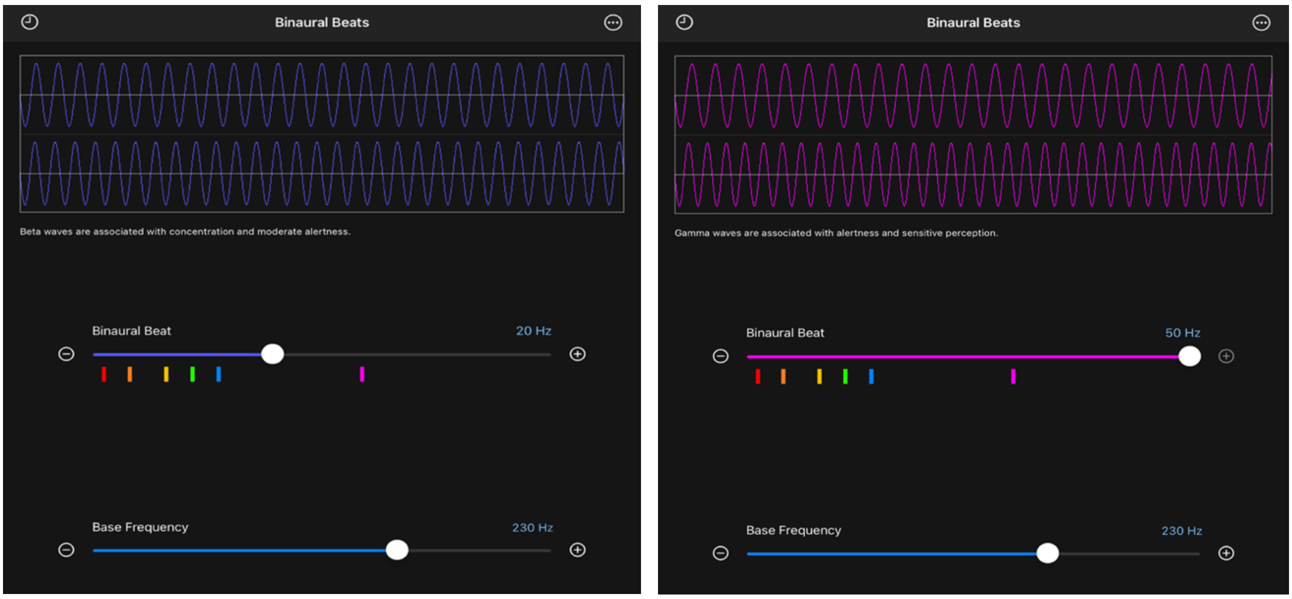
Thematic Scoring of the Newcomer Story Themes – Delayed Recall. As developed and introduced by Trifilio et al. (2020), the thematic type scoring focuses on correctly recalling the gist of the information provided rather than recalling exact or identical words. For example, the phrase “… gave each employee a bottle of champagne for their hard work…” indicates that the employee was rewarded or gratitude was shown towards the individual, as would “…all his employees got champagne as a reward”. Partial credit (0.5 points) was awarded to each thematically correct sentence included in the response recalled and recorded by a participant (Trifilio et al., 2020). This inclusion aims to investigate the significance of context or the schematic gist of information and its effect on recall. Non-related material, guesses and deductive responses will be excluded from all scoring. Scores were totalled and recorded on a master and separate spreadsheets for analysis.

Binaural Beat Interventions in this Study

The binaural beats utilised in this experiment were generated using the BB Generator+ application, developed by TMSOFT, LLC, © 2017-2022 (For additional information, please visit: https://www.tmsoft.com/blog/using-binaural-beats-app/). To ensure participant comfort and minimize unintended distress during the testing phase, unmasked pure tones with a 230Hz carrier frequency were chosen (Engelbregt et al., 2019; Jurvanen, 2020; Obleser & Kayser, 2019; Shekar et al., 2018; Sharpe & Mahmud, 2020; Wiwatwongwana et al., 2016). The binaural beats shown in Figure 1 were integrated into the online testing application of the experiment as a soundtrack and delivered to participants through wired headphones, featuring separate channels for the left and right ears. The volume of the binaural beats was pre-set within the range of -13.6 dB to -17.8 dB (30% to 40%), a level known not to typically cause hearing loss or damage as per the guidelines of the Centre for Disease (CDC).

Figure 1

High-Beta and Gamma Binaural Beats in this Study



Note. On the left, the anatomy of the 20Hz binaural beat within the High-Beta frequency range and on the right, the anatomy of the 50 Hz binaural beat within the Gamma frequency range used in the experiment.

As depicted in the left frame of Figure 1, participants in the High-Beta experimental groups were exposed to an unmasked pure tone of 230Hz in the left ear and a 250Hz pure tone in the right ear. This combination resulted in a perceivable binaural beat frequency of 20Hz, falling within the High-Beta range, as supported by previous research (da Silva et al., 2015; Garcia-Agribay et al., 2019a; Góes, 2018; Shekar et al., 2018). Similarly, participants in the Gamma groups (GG) seen in Figure 1 (right), were presented with an unmasked pure tone of 230Hz in the left ear and a 280 Hz pure tone in the right ear. This arrangement generated a perceivable binaural beat frequency of 50Hz, falling within the Gamma range and consistent with previous experimental designs (da Silva et al., 2015; Engelbregt et al., 2019; Garcia-Agribay et al., 2019a; Góes, 2018; Jurvanen, 2020; Sharpe & Mahmud, 2020; Shekar et al., 2018).

Experimental Design and Software

The experiment used a custom-designed digital application. The application was designed using Umbraco, which is an open-source content management system (www.umbraco.com). The custom app was named "Modulation through Auditory Beat Stimulation" (MABS) and hosted on a secure online server (accessible at mabs.interon.co.za). The MABS application was pilot (beta) tested and debugged over 56 tests conducted by a group of 5 individuals outside of the participant sample to ensure that the application ran as intended and accurately measured participant responses. The MABS application presented participants with a starting screen that recorded initial demographic information that required participants to only provide their initials and ages. No further personal data was collected. This was followed by a sound test and volume check. Participants were then provided with the instructions to each segment of the testing sequence and presented with the memory tasks. Beta testing rounds Appendix G presents screenshots of the actual online application, depicting the entire experiment in a step-by-step manner, ranging from steps 1-20 (see Figure G1 to Figure G21).

Procedure

Participants were assigned specific testing days over 4 weeks to control for time-of-day effects, ensuring uniform testing circumstances. These testing sessions were scheduled between 15H00 and 18H00, in alignment with established research indicating optimal cognitive performance in younger adults during the afternoon hours (May et al., 2017; Ryan et al., 2002). Participants were instructed to abstain from caffeine and tobacco products for at least 2 hours before and during testing, given the documented influence of caffeine and nicotine on memory and recall in young adults (Engelbregt et al., 2019; Sherman et al., 2016). The specific duration of exposure during each test step is outlined in Table 4.

Table 4

Experimental Design and Exposure Times

Trial Event	Single exposure	Dual Exposure	Notes
Initial exposure to binaural beats	60 seconds	60 seconds	*Entrainment Priming
Exposure during presentation of the Newcomer story	180 seconds	180 seconds	Exposure during Encoding
Exposure during instructions before the Digit Span test	20 seconds	20 seconds	
Exposure during the presentation of the Digit Span	15 seconds	15 seconds	Working Memory Encoding
Exposure during the recalling of the Digit Span		30 seconds	Immediate Recall
Exposure during the recalling of the story		120 seconds	Delayed Recall
Total exposure time during each presentation round	275 seconds	425 seconds	*Visual and Audio
Total exposure time	550 seconds	850 seconds	

Note. A step-by-step breakdown of each participant's exposure time to binaural beats during each event of the experiment. *Entrainment Priming refers to the 60 seconds participants were exposed to the respective binaural beats before commencing the experiment. Participants not exposed to any binaural beats had 60 seconds of silence before commencing the test. *Visual and Audio: The exposure time was exactly equal in both visual and auditory presentation rounds. In the table, HBG-E: Exposure to High-Beta binaural beats during encoding, HBG-ER: Exposure to High-Beta binaural beats during encoding and recall, GG-E: Exposure to Gamma binaural beats during encoding, GG-ER: Exposure to binaural beats during encoding and recall.

Upon arriving at the Acsent Computer Lab within the UCT Psychology department, participants were seated individually at partitioned desks to minimize environmental distractions and unforeseen or uncontrolled variables. The seating arrangement aimed to maintain a controlled testing environment. Across studies, protocols for binaural beat exposure vary in duration from as little as 3-5 minutes (Reedjik et al., 2013) to as long as 60 minutes (Basu & Banerjee, 2023; Wiwatwongwana et al., 2016). Consequently, determining the optimal exposure duration to maximise binaural beat effects is difficult (Jurvanen, 2020). However, exposure to binaural beats followed established exposure durations based on related research (Engelbregt et al., 2019; Gao et al., 2014; Reedijk et al., 2013; Sharpe & Mahmud, 2020; Shekar et al., 2018; Garcia-Agribay et al., 2020).

Participants exposed during encoding only were exposed to High-Beta (HBG-E) or Gamma (GG-E) binaural beats for 550 seconds (9 minutes and 10 seconds), while participants in the encoding and recall experimental groups were exposed to High-Beta (HBG-ER) or Gamma (GG-ER) binaural beats for a total of 850 seconds (14 minutes and 10 seconds). This timeframe was adjusted based on studies by Engelbregt et al. (2019), Gao et al. (2014), and Reedijk et al. (2013). Furthermore, the selected exposure times were consistent with findings from Sharpe and Mahmud (2020), Shekar et al. (2018), and the findings from Garcia-Agribay et al. (2019a).

Contrary to experiments in the field, the 15 participants not exposed to any binaural beats (No exposure conditions) were not presented with any form of white noise, music without binaural beats, overlapping sounds, or classical music (Basu & Banerjee, 2023; Huang & Charyton, 2008; Garcia-Agribay et al., 2019a, 2019b). I deliberately chose not to present any form of noise or music to this group of participants as this may have introduced additional variables that could have influenced the results. For instance, some participants might not have enjoyed the genre of music, while others in the group may have. This could have caused distraction from the tasks or unintentional annoyance for some participants, affecting their performance. By not presenting participants with any form of noise or music without binaural beats, I aimed to ensure that the results were solely due to the binaural beats and not influenced by other potentially confounding factors.

Participants in the group not exposed to binaural beats were however instructed to put their headphones on and take them off in an identical fashion to the participants that were exposed to the binaural beat intervention. This ensured that the only difference between the testing groups was the presence or absence of binaural beats, making it easier to isolate the effect of binaural beat exposure on memory performance. Not presenting participants with any form of noise or music without binaural beats and having all participants follow the same procedural instructions allowed me to isolate the effects of binaural beats on memory performance and ensure that the results were due to the binaural beats and not influenced by other factors.

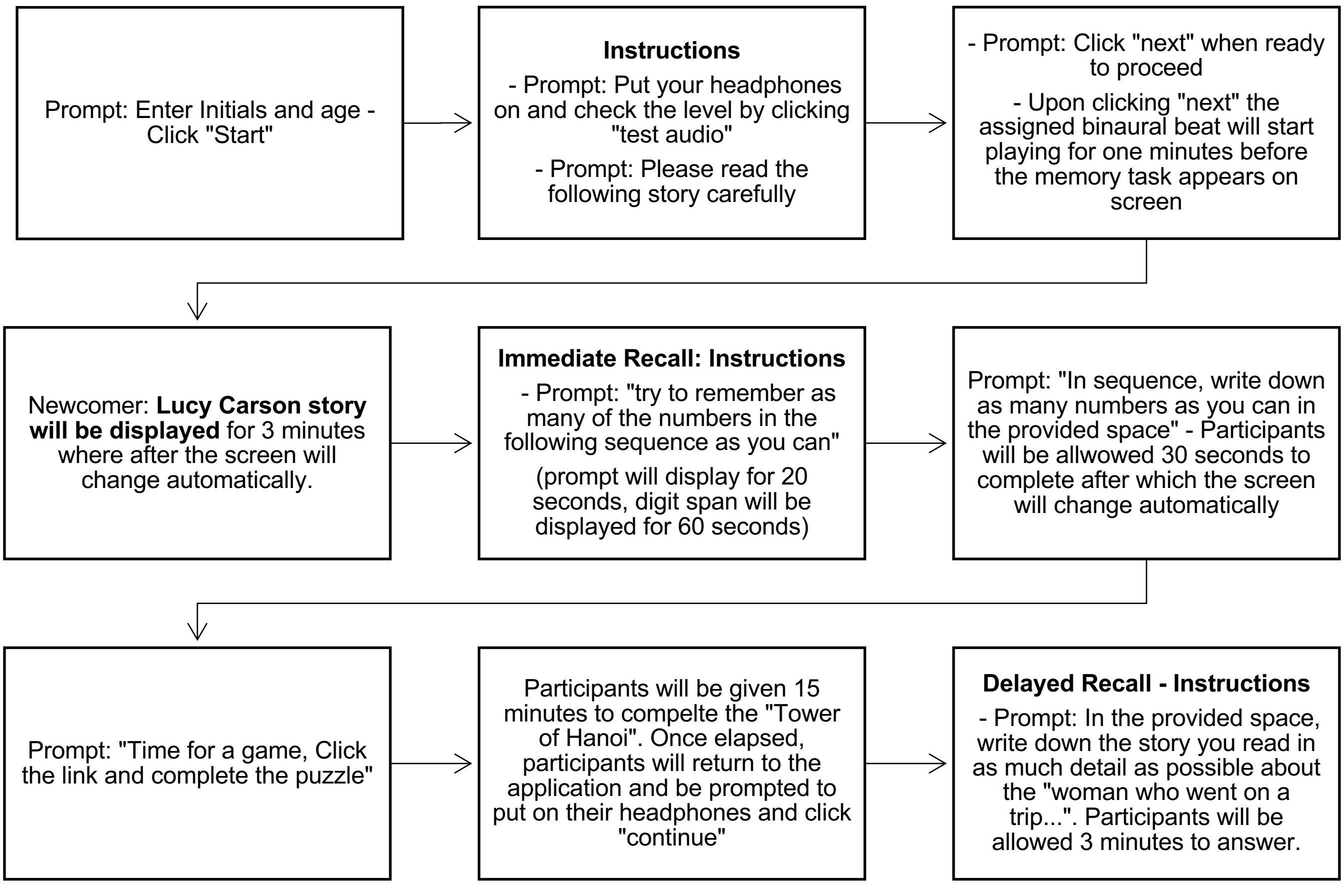
The procedure itself followed a sequence inspired by Forsberg et al. (2021) to incorporate immediate and delayed recall memory tasks. This structured sequence allowed for testing both immediate and delayed recall within a single testing session. Participants in the Forsberg (2021) study were first presented with the stimuli after which they performed a Working Memory probe-recognition task on the presented stimuli, followed by a brief mathematical distraction task, and finally, a second probe-recognition memory test that assessed delayed recall for items from the immediate recall task (Forsberg et al., 2021).

Forsberg's (2021) procedural sequence was adopted and altered for the present study, where the memory task intended for delayed recall (Newcomer Story) was presented before the digit span in each testing condition. Participants were then tasked with performing an immediate recall test where the Digit Span sequence was presented without distractions and participant responses were recorded to measure working memory performance. This was then followed by encouraging participants to test their ability to solve the Tower of Hanoi puzzle for 15 minutes, by increasing the difficulty level by adding more pieces after solving a level as a distraction task. As in the Forsberg study (2021), participants were not informed in advance that their performance on the Tower of Hanoi task was purely a distraction and would not be scored or their performance measured, nor of the delayed recall test that followed to prevent focused attention or rehearsal. Lastly, participants were required to recall the Newcomer Story presented in the first step of each testing round in as much detail as possible. The essential deviation from the Forsberg (2021) method was that participants in this study were tested on two separate sets of stimuli in the form of the Newcomer Story (Delayed recall) and the Digit Span (immediate recall). Forsberg (2021) tested immediate recall and delayed recall on a single set of stimuli.

The total duration of the experiment was 45 minutes per participant, with 5 participants tested simultaneously per session. The stimulus material was presented to participants in two formats: a written format for the reading test and an auditory (recorded) version with the digit sequence and Newcomer story layered over pure tones for the listening test throughout the experiment. See Appendix D for a detailed record of the stimulus material used in both presentation formats. Following the presentation of the Lucy Carson Newcomer Story, the instructions for the digit span, containing 7 digits (Miller, 1956) test were displayed for 15 seconds after which the presentation of the digit span sequence commenced immediately, with no interruption in exposure to the binaural beats in the experimental groups. In the first round of testing where tasks were displayed visually, participants were presented with a series of flashing digits for 15 seconds. Each digit was displayed for 1 second, followed by a 1-second blank screen. Participants were tasked with recalling the digits in sequence within 30 seconds. Figure 2 provides the exact sequence of events participants were guided through during the round where the memory tasks were presented visually.

Figure 2

Sequence of Events During Visual Presentation of the Memory Tasks

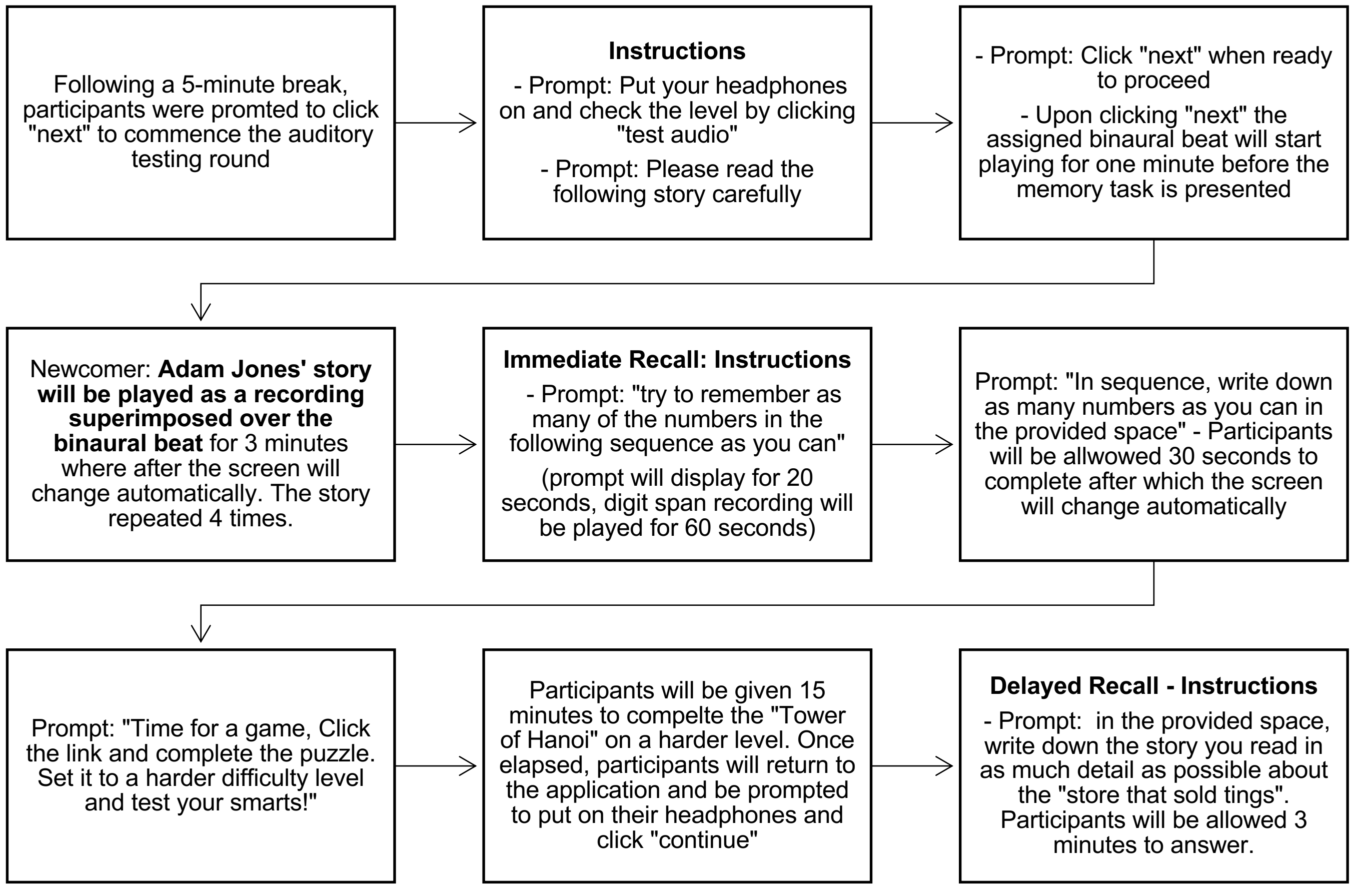


Note. The schematic outline of the testing round where memory tasks were presented visually.

Following immediate recall, a digitised version of the "Tower of Hanoi" puzzle served as a distraction task to minimise further rehearsal of the material. After the distraction task, participants removed their headphones and engaged in a brief interview to provide feedback, assess any adverse effects, and address any questions. This interaction aimed to resolve uncertainties, evaluate participant well-being, and gather initial insights into their subjective experience of the experiment. Figure 3 illustrates the exact sequence of events step-by-step that participants followed during the auditory presentation of the memory tasks. These flowcharts correspond with the screenshots of the MABS application included in Appendix G.

Figure 3

Sequence of Events During the Auditory Presentation of the Memory Tasks



Note. The schematic outline of the testing round where memory tasks were presented audibly.

A five-minute break followed. Participants were prompted to start the second round of testing. For the experimental groups, exposure to the respective binaural beats started directly after the instructions were presented (see Figure 3). After 60 seconds of initial exposure, participants listened to the “Adam Jones” Newcomer Story. The pre-recorded audio version of the Adam Jones story was repeated 4 times, read at a conversational pace of 180 words per minute. This pace was considered appropriate given the simplicity of the Adam Jones story from the Newcomer series. This was followed by instructions for the digit span test for 20 seconds and a different series of digits were presented audibly. The pre-recorded sequential digit span tracks, one without any binaural beats and those overlaying both High-Beta and Gamma binaural beats, respectively, read out digits at a rate of one digit per second and one second apart, as outlined in the WISC-III manual (Wechsler, 1991). Participants were again required to recall and input the "digits-forward," matching the sequence as read or heard, and were allowed 30 seconds to do so. This was followed by the Tower of Hanoi task for 15 minutes. Finally, participants returned to the MABS application and were asked to recall the story of Adam Jones.

The digit span test served a dual purpose: first, to provide data on the effectiveness of binaural beats exposure on immediate recall, and second to introduce a distraction from the Newcomer story, minimising further rehearsal of the material. The digit span used in the present study was not used to measure attention. After completing this round, participants underwent debriefing, which involved gathering feedback on the testing experience and assessing potential confounding variables. (Engelbregt et al., 2019). A more detailed debriefing letter was subsequently sent to each participant individually (see Appendix F).

Data Management and Confidentiality

To uphold the confidentiality of data, experiment data were safeguarded by storing them on two separate portable external storage devices, thereby mitigating the potential risk of loss or breach. Answer sheets were manually saved exclusively on these portable storage devices and were not retained on any central mainframe or server, except during the uploading process to UCT's ZivaHub Cloud Storage Facility. By recording only age and initials in the results, an additional level of confidentiality and anonymity was introduced for all participants. Furthermore, to enhance data security measures, the information was duplicated on two (2) supplementary thumb drives.

Data Processing and Statistical Analyses

The measured variables included the participant scores in the digit span (immediate recall), and Newcomer story (delayed recall - target words and themes, respectively) tasks. One further variable was engineered resulting in an "overall recall" score, representing the aggregated performance of each participant across both immediate and delayed recall tests. The independent variables were;

(1) Binaural Beats at three levels: (i) No exposure, (ii) High-Beta, and (iii) Gamma binaural beats),

(2) Timing of exposure to binaural beats at two levels: (i) single exposure during encoding, (ii) dual exposure during both encoding and recall processes, and

(3) Testing stimuli were presented at two levels: visual and auditory.

Pre-processing the data included standardising the participant scores for all three dependent variables, that is digit span, target word recall and thematic recall scores. When data are standardised, the mean is centred around zero (0) and the standard deviation becomes one (1). This normalisation process was necessary as the analysis required comparisons of variables with differing scales or the total amount of points that could be awarded for each task.

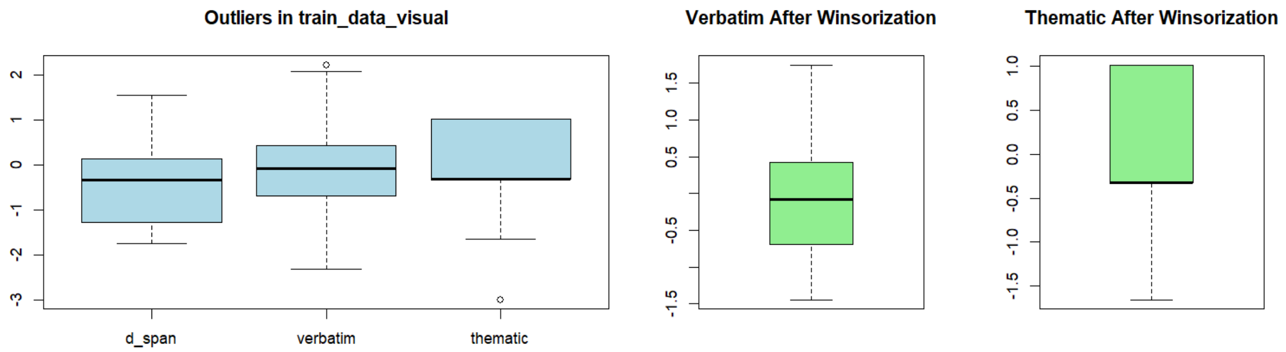
For instance, successfully recalling all 7 digits in the sequential digit span would be awarded a maximum score of 7, successfully recalling the central theme of the Newcomer story would be awarded 2 points out of a maximum of 2 (0.5 per section), and each target word was awarded 1 point accumulating into a participant score out of 44 and 45 in the respective presentation formats. Since the mean is centred around zero after standardization, it is common to observe negative values indicating that the original score is below the mean and positive values indicating original scores above the mean. The final step in pre-processing was to create a binary interaction term in the data set, based on whether exposure to binaural beats was present in a given task using the "one-hot-encoding" method.

Splitting the dataset into conventional training and testing subsets customary to Bayesian methods was inappropriate in the context of this study. Partitioning the data, commonly used in predictive modelling or machine learning tasks (Korjus et al., 2016, Liu & Cocea, 2017), involves dividing the dataset into two disjoint sets for model training and evaluation. However, given the comparative nature of the analysis focusing on predicted probabilities and mean differences across exposure groups, such a division could introduce limitations and biases. By utilizing the entire dataset, the analysis maintains statistical power, minimises bias, and facilitates a more thorough exploration of the research questions.

I used Winsorization to address outliers in my datasets seen in Figure 4 and Figure 5. Outliers such as these could have a significant impact on statistical analyses by potentially introducing bias or weight to the distribution. Winsorization offers a balanced approach to handling outliers as it caps extreme values at a specified percentile (95% in this case) without removing data points entirely. The Winsorization method ensures that the influence of outliers is moderated, making it especially beneficial in studies with limited sample sizes such as the present. Winsorization is less sensitive to assumptions about the data distribution, providing a solution when dealing with non-normally distributed data (Bartlett et al., 2020; Leeb & Pötscher, 2005; Sharma & Chatterjee, 2021). I performed additional checks to identify any direct correlations between the measured variables that could influence the analysis, safeguarding against bias or skewed results. The resulting processed datasets form the basis for the subsequent analyses.

Figure 4

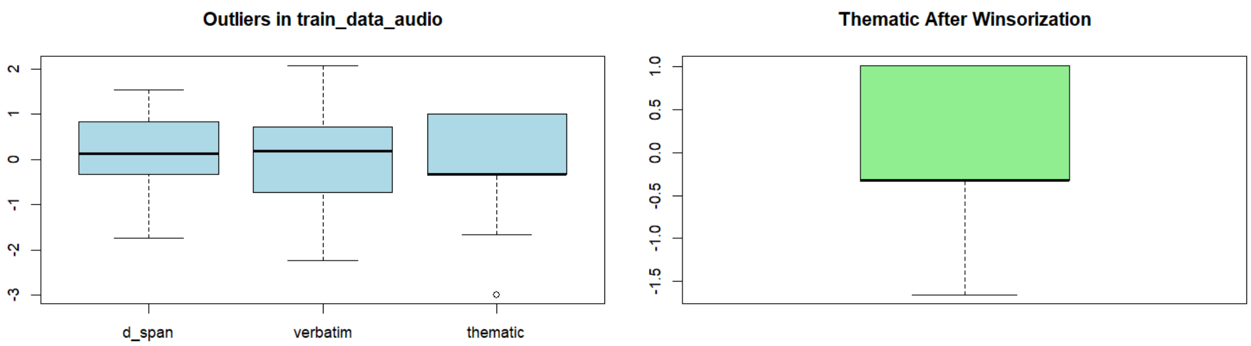
Pre-Processing Raw Data in the Visual Presentation Data Set with Windsorization of Outliers



Note. (Left) Identified outliers within the data contained in the "Verbatim" and "Thematic" columns spanned both extreme positive and negative values. (Right) The identified outliers after Winsorization could be included in the analysis. "Verbatim" refers to the recorded responses during the target word memory task, "thematic" refers to responses containing the story themes.

Figure 5

Pre-Processing Raw Data in the Audio Presentation Data Set with Windsorization of Outliers



Note. (Left) Outlier data within the raw audio data set was identified within the "Thematic" data. (Right) The outlier was handled by capping in within the 95% percentile through Winsorization, and included in the data analysis.

Assumptions of Normality in Data Distribution Using Parametric and Non-Parametric Methods

To ensure that the data met the conditions for the use of parametric tests and evaluate for distributional normality and variance heterogeneity, Shapiro-Wilk Tests for Normality and Quantile-to-Quantile (Q-Q) plot analyses were conducted for each measured variable: “d_span” (digit span), “verbatim” (target words), and “thematic_winsorized” (themes). Although the results for delayed recall (target word) of normal distribution, the results showed that immediate recall (d_span) and delayed recall (thematic) scores (see Table 5 and Appendix A) did not meet the conditions for use of parametric tests. Nuanced central tendencies, a distributional spread similar to normal expectations in the interquartile range, and a higher concentration of extreme values in the upper percentiles were observed. A detailed quantile-to-quantile examination of distributional characteristics including skewness, kurtosis, and the presence of outliers, is provided in Appendix A.

Table 5

Shapiro-Wilk Test of Normality for Memory Performance Variables

Measured Variable	Test Statistic (w)	p-value
Digit Span (Immediate recall)	**0.94**	**< 0.05**
Target Words (Delayed recall)	0.99	0.41
Thematic (Delayed recall)	**0.79**	**< 0.05**

Note. The test statistic (w) and corresponding p-values are reported for each variable. A significance level of 0.05 is used to assess normality, and p-values less than this threshold indicate departures from normality. Immediate recall (digit span) and delayed recall of themes (thematic) show significant departures from normality, while delayed recall of the target words (verbatim) does not.

Given the non-normal distribution of the digit span and thematic recall scores, I employed the non-parametric Kruskal-Wallis rank sum test to analyse each measured variable (digit span, target word recall, and thematic recall) separately across the binaural beats testing conditions. The results presented in Table 6 indicate no statistically significant differences in digit span, target words, or thematic recall performance across the various binaural beats test conditions ($p = 0.66$, 0.15, and 0.40, respectively, all exceeding the typical significance level of 0.05). These findings suggest the binaural beats test conditions did not have a significant effect on participants' performance in immediate or delayed recall tasks.

The results from the Kruskal-Wallis test for normality performed on the raw data implied that the data exhibited homogeneity of variances and normality. This is particularly relevant when considering potential deviations from parametric assumptions observed in the Shapiro-Wilk test for normality. The absence of significant differences in the measured variables across the High-Beta and Gamma binaural beats testing conditions strengthens the credibility of the Bayesian regression results, indicating that any observed effects are less likely to be influenced by variations in the distribution of participant scores in the memory tasks associated with the testing conditions. This suggests the patterns or effects observed in the sample may be more generalisable to a broader population, given the lack of significant differences between participants across the High-Beta and Gamma binaural beats conditions.

Table 6

Kruskal-Wallis Test of Normality for Memory Performance Variables

Measured Variable	Kruskal-Wallis Chi-Squared	Degrees of freedom (df)	p-value
Immediate recall (digit span)	2.40	4	0.66
Delayed recall (target word)	6.81	4	0.15
Delayed recall (themes)	4.06	4	0.40

Note. The Kruskal-Wallis chi-squared statistic, degrees of freedom (df), and corresponding p-values are reported for each variable. A significance level of 0.05 is used to assess differences among groups, and p-values less than this threshold indicate significant differences. For immediate recall (d-span), delayed recall (target words), and delayed recall (themes), the tests did not reveal statistically significant differences across the different levels of the binaural beats testing conditions.

Statistical Analysis Using Bayesian Inference

Rationale. Bayesian Inference was selected as the analytical framework for this study due to its adaptability in assimilating prior knowledge and its capacity to offer a formalized mechanism for updating data-driven beliefs about expected outcomes in line with existing literature (Basu & Banjeree, 2023; Borges et al., 2023; da Silva et al., 2015; Draganova et al., 2008; Garcia-Argibay et al., 2019a; Góes, 2018; Hanslmayr et al., 2019; Ioannou et al., 2015; Kennerley, 2009; Kraus &

Porubanová, 2015; Lafon et al., 2017; Mujib et al., 2021; Shekar et al., 2018). Bayesian regression facilitates the construction of posterior distributions that seamlessly integrate prior knowledge with current data, proving particularly advantageous in scenarios with limited sample sizes and intricate model structures (Anderson, 1998; Moerbeek, 2021; Stefan et al., 2019).

Bayesian regression accommodates uncertainty by providing a distribution of parameter values. The uncertainty associated with each model is captured within these parameters offering a nuanced perspective when interpreting the results, as opposed to a simple confirming or disproving answer. In Bayesian statistics, the emphasis is placed on assessing the probability distribution of parameters given observed data, allowing for a more nuanced understanding of uncertainty. Model comparison within Bayesian analyses is facilitated through methods such as posterior predictive checks and Bayes factors, which evaluate the adequacy of models in predicting new data and quantify the evidence favouring one model over another based on posterior probabilities (Anderson, 1998; Moerbeek, 2021; Stefan et al., 2019).

Bayesian Models in this Study. Weakly informative priors were deliberately selected to balance prior information with observed data, ensuring minimal influence on final results (Anderson, 1998; Kruschke, 2021; Stefan et al., 2019). Updating initial priors with new information from null model analysis refined parameter estimates and enhanced predictive accuracy, capturing inherent uncertainty in fields like Cognitive Psychology (Anderson, 1998; Kruschke, 2021). This methodological approach aligns with Bayesian analysis principles, where prior beliefs guide inference, and data progressively refines these beliefs. The integration of weakly informative priors and Regularization techniques formed a framework that combined prior knowledge and empirical evidence with a data-driven narrative (Anderson, 1998; Kruschke, 2021; Moerbeek, 2021; Stefan et al., 2019).

I employed Bayesian generalized linear models (GLM) with an interaction term between binaural beats conditions and presentation format to investigate potential synergistic effects on memory recall. Posterior distributions of model parameters were based on 15,000 iterations (6,000 warmups and 8,000 simulations), allowing for a systematic assessment of each measured variable (digit span, target word recall, and thematic recall). By adopting a Bayesian approach to statistical inference, this study moved away from the conventional use of p-values, enabling a more nuanced understanding of the effect of binaural beats exposure and presentation format on memory. This Bayesian framework emphasises the assessment of uncertainty and model comparison, providing perspective on the findings and their implications (Anderson, 1998; Moerbeek, 2021; Stefan et al., 2019).

I initiated each Bayesian GLM analysis with weakly informative priors (location = 0, scale = 100) and a Bayesian factor > 10. This criterion necessitated moderate-to-strong evidence to reject the null hypothesis of no significant effect or difference between experimental groups in the null model. Subsequently, the priors were adjusted to capture the variations in estimated mean coefficients and standard deviations among the experimental groups, facilitating a focused investigation in each analysis. This data-driven approach ensured that the findings were driven by observed data rather than predetermined assumptions, while deliberately excluding variables related to inherent individual differences to maintain a specific focus on the effects of binaural beat exposure and presentation formats (visual and auditory task material).

Hypothesis Testing Methodology Using Bayesian Analysis

Hypothesis 1: Effect of Auditory versus Visual Presentation of the Task Material on Overall Recall. To investigate whether the format in which the memory tasks were presented (auditory vs visual) had effects on overall recall performance for those not exposed to any binaural beats, I employed a Bayesian modelling approach. Overall recall consisted of the aggregated scores participants obtained from the digit span, target word, and story theme recall tasks.

First, I examined the estimated marginal means (emmeans) to assess differences in overall recall performance across the auditory and visual presentation conditions. The emmeans provided model-based estimates that accounted for the effects of other variables in the statistical model, offering an adjusted representation of the group differences. Presenting the emmeans first allowed me to establish the baseline performance and set the context for the subsequent comparisons.

Next, I analysed the mean differences in overall recall performance in the posterior samples across the auditory and visual testing rounds. These mean differences, derived from the Bayesian analysis, provided a direct representation of the performance differences between presentation formats. While the mean differences were important to report, they were presented after the emmeans, as the emmeans offered a more statistically rigorous comparison. This sequence allowed me to build upon the foundational understanding of the performance differences established through the emmeans.

Following the comparisons of the means, I examined the predicted probabilities, proportions, and likelihoods of overall recall performance across the auditory and visual presentation conditions. These additional metrics provided insights into the likelihood and magnitude of improved recall with visual and auditory stimuli, allowing me to assess if the mode of presentation affected recall performance. Presenting these metrics after the emmeans and mean differences enabled a further interpretation of the results from a corroborative point of view.

I concluded this investigation by examining the posterior predicted samples of the group not exposed to any binaural beats across both testing rounds. I aimed to determine whether a significant proportion of participants in the group recalled more of the audibly presented memory tasks compared to the visually presented memory tasks. This proportional comparison provided further insight into the relative performance between overall recall performance levels across the testing rounds.

By following this sequence, I was able to establish the baseline performance through the emmeans, build upon it with the mean differences, provide additional insights through the predicted probabilities and likelihoods, and gain an understanding of group performances using proportional comparisons.

Hypothesis 2: Effect of Binaural Beats on Immediate and Delayed Recall. To investigate whether the performance of participants exposed to High-Beta and Gamma binaural beats differed significantly from those not exposed to any binaural beats in immediate and delayed recall tasks with audibly presented testing stimuli, I employed a Bayesian modelling approach.

I first examined the estimated marginal means (emmeans) across testing conditions to assess differences in immediate recall performance between the binaural beats exposure groups and those not exposed to any binaural beats. This allowed me to examine differences between the testing groups while controlling for the effects of covariates, such as cognitive abilities or sensory processing. Presenting the emmeans first allowed me to establish the baseline performance and set the context for the subsequent comparisons.

Next, I comparatively examined the mean differences in immediate recall performance between posterior samples from both testing rounds. These mean differences, derived from the Bayesian analysis, provided a direct representation of the group differences in immediate recall performance when combining binaural beat exposure with auditory presentation of the digit span tasks, relative to No exposure conditions. While the mean differences were important to report, they were presented after the emmeans, as the emmeans offered a more statistically rigorous comparison. This sequence allowed me to build upon the foundational understanding of the group performance established through the emmeans.

To evaluate the likelihood of improved immediate recall with binaural beats exposure, I analysed predicted probabilities, proportions, and likelihoods for each condition. This allowed me to determine if exposure to High-Beta or Gamma binaural beats affected immediate recall performance. Presenting these metrics after the emmeans and mean differences enabled further interpretation of the results.

Finally, I examined the proportions in posterior predicted samples associated with each testing group. I first investigated if any group had a significant proportion of the predicted posterior samples with higher immediate recall scores compared to the other groups. I further investigated if there was a significant proportional difference in recall scores during the round where the memory tasks were presented audibly compared to when the memory tasks were presented visually. I included this analysis to account for any individual differences, and to determine if exposure to binaural beats only improved the performance of some participants without the whole group necessarily having to outperform the group not exposed to binaural beats in the mean amount of information recalled.

This sequence of analyses, from emmeans to mean differences, predicted probabilities and likelihoods, and proportional comparisons, was followed for each of the variables (digit span recall, target word recall, and theme recall) to ensure a systematic examination of the effect of binaural beats exposure on immediate and delayed memory performance.

Hypothesis 3: Effect of Binaural Beat Exposure Timing on Memory. To investigate this I used a Bayesian modelling approach to analyse the effect of dual exposure to High-Beta and Gamma binaural beats on immediate and delayed recall performance. This analysis focused on three distinct dependent variables: digit span recall, target word recall, and theme recall.

Initially, I investigated the estimated marginal means (emmeans) for each recall measure across the various binaural beats exposure conditions and the group not exposed to any binaural beats. Examining the emmeans isolated the true effect binaural beat exposure conditions had on memory performance during the tasks by removing the influence of potentially confounding variables such as discomfort, fatigue, or cognitive ability. By presenting the emmeans first, I established a baseline performance and contextualized subsequent comparisons.

I followed this by examining the mean differences derived from the posterior samples obtained through Bayesian analysis. These mean differences, offering a direct representation of group differences, were presented after the emmeans to ensure further statistical comparison. This sequential approach allowed me to build upon the foundational understanding established by the emmeans.

Following the emmeans and mean differences, I explored the predicted probabilities, proportions, and likelihoods associated with the recall measures. These additional metrics provided insights into the likelihood and magnitude of performance differences between those exposed to binaural beats during both encoding and recall compared to those exposed only during encoding and those not exposed to any binaural beats.

Lastly, I conducted a proportional comparison of performance across the exposure groups, offering a complementary perspective on the relative performance levels. This allowed me to estimate the probability that the groups exposed to High-Beta and Gamma binaural beats during both encoding and recall would show improved performance compared to the single and no-exposure groups during the respective testing rounds, beyond the mean differences between the groups.

This sequence of analyses, from emmeans to mean differences, predicted probabilities and likelihoods, and proportional comparisons, was followed for each of the variables (digit span recall, target word recall, and theme recall) to ensure a systematic examination of the effect of binaural beats exposure on immediate and delayed memory performance.

Hypothesis 4: The Effect of High-Beta Binaural Beats vs. the Effect of Gamma Binaural Beats on Declarative Memory. To investigate if participants exposed to High-Beta binaural beats recalled significantly less declarative information from both the digit span and story-based tasks overall, regardless of the format of the presentation of the memory tasks, I utilised the aggregated "overall recall" scores from the digit span and story-based memory tasks as in the first hypothesis.

I first examined the estimated marginal means (emmeans) across testing conditions to assess differences in overall recall performance between the participants exposed to High-Beta binaural beats compared to those exposed to Gamma binaural beats. The emmeans provided adjusted estimates that accounted for covariates in the statistical model. Examining the emmeans allowed for more accurate comparisons between the groups without being confounded by covariates, and to establish the baseline performance and set the context for the subsequent comparisons. I followed with a pairwise comparison between the High-Beta and Gamma exposure group and presentation types in overall recall performance to assess the differences in the estimated marginal means.

I followed this up by comparatively examining the mean differences in overall recall performance between posterior samples taken from the High-Beta and Gamma exposure groups. These mean differences in the posterior samples, derived from the Bayesian analysis, provided a direct representation of the group differences in overall recall performance between the High-Beta and Gamma exposure groups. This sequence allowed me to establish a foundational understanding of the group performance established through the emmeans.

To evaluate the likelihood of improved overall recall with High-Beta binaural beats exposure compared to Gamma binaural beat exposure, I analysed predicted probabilities, proportions, and likelihoods for each condition. This assessment allowed me to determine if there were any significant differences in the overall effect of exposure to High-Beta binaural beats compared to exposure to Gamma binaural beats.

Finally, I compared proportions in posterior predicted samples where overall recall was higher under High-Beta binaural beats exposure conditions compared to Gamma binaural beat exposure conditions. Since the mean differences between the groups were not statistically significant, examining the proportions of predicted posterior samples could suggest that if one group was found to outperform another, the effects of binaural beat stimulation may be true by quantifying the uncertainty associated with the results. A higher proportion of samples showing that the Gamma group outperformed the group exposed to High-Beta binaural beats would indicate more certainty about the true effect, whereas a lower proportion would suggest more uncertainty in any observed difference.

Chapter 4: Results

Hypothesis 1: Effect of Auditory versus Visual Presentation of Task Material on Overall Recall

In my first hypothesis, I expected participants not exposed to binaural beats to perform significantly better at overall recall of auditory memory tasks compared to visual memory tasks. To test for this, I performed Bayesian linear regression analyses to examine the relationship between the presentation format of the memory tasks and overall recall, then comparatively examined the estimated marginal mean differences, mean differences in the predicted posterior samples, probabilities, proportions, and proportional comparisons of overall recall performance across the testing rounds. The results showed no significant difference in participant ability to recall auditory memory tasks compared to visual memory tasks.

The Effect of Presentation Format on Memory Recall

Mean Coefficient Estimates. The estimated mean difference in overall recall performance between the audio and visual presentation formats was 0.0, (SD = 0.3). The 90% credible interval ranged from -0.3 to 0.4. The intercept representing auditory presentation (β_0) was estimated to be 0.2, with a standard deviation of 0.2.

Fit Diagnostics. The mean posterior predictive distribution (mean ppd) was estimated to be 0.3, with a standard deviation of 0.3. The convergence diagnostics (Rhat) indicated good mixing and convergence of the MCMC chains, with values close to 1 for all parameters. The effective sample sizes (n_eff) ranged from 4754 to 6222, suggesting sufficient samples for reliable inference.

LOO-CV Assessment. The expected log predictive density (elpd_loo) estimate was 1.2 (SE = 0.9), indicating good predictive accuracy. The effective number of parameters (p_loo) was 0.1 (SE = 0.1), suggesting a relatively simple model structure. The leave-one-out information criterion (LOOIC) value was -2.4 (SE = 1.8), indicating a good overall fit to the data.

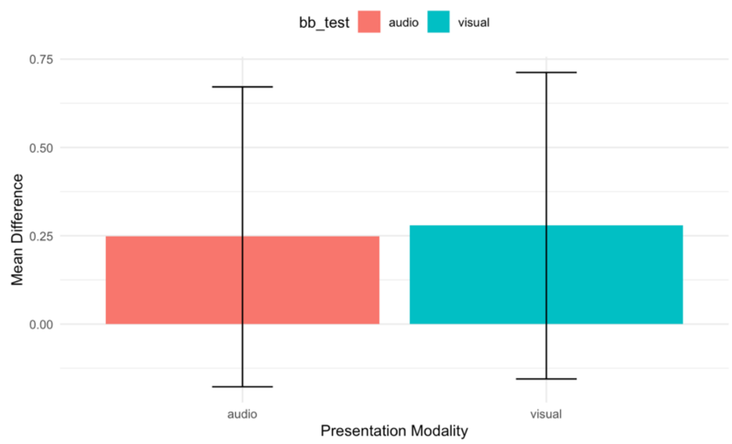
Model Evaluation. The Bayesian model provided a framework for analysing the effects of binaural beat exposure on memory recall performance across different presentation formats of the memory tasks. The good convergence diagnostics, sufficient effective sample sizes, and LOO-CV metrics indicate that the model had a good fit for the data and reliable parameter estimates.

Estimated Marginal Mean Differences in Overall Recall: Auditory vs. Visual. An analysis of the emmeans for the presentation conditions, auditory and visual, supported a negligible difference in the mean overall recall performance of participants for those not exposed to any binaural beats. For the auditory presentation of the memory tasks participants showed an emmean of 0.25 (SD = 0.41; 95% HPD [-0.18, 0.67]) compared to the emmean of 0.28 (SD = 0.43; 95% HPD [-0.16, 0.70]) shown during the visual presentation of the memory tasks. Based on the 95% highest posterior density (HPD) intervals for both conditions including zero, the observed difference in overall recall between the visually and audibly presented memory tasks is not statistically significant.

Mean Differences in Overall Recall: Auditory vs. Visual. The mean difference in overall recall performance between visually and audibly presented memory tasks for participants not exposed to any binaural beats was 0.03 in the posterior samples (Figure 6). The standard deviation of this difference was 0.03 (95% CI [-0.18, 0.67]) under auditory presentation conditions with slightly less variation seen under visual presentation conditions (SD = 0.02; 95% CI [-0.16, 0.71]). These findings indicate that participants did not exhibit a significant difference in overall recall performance between auditory and visual presentation of the memory tasks. The wide 95% credible intervals include zero and suggest notable uncertainty surrounding this comparison.

Figure 6

Mean Differences in Overall Recall Across Presentation Formats



Note. Mean difference in the posterior samples for the overall recall performance of participants not exposed to binaural beats across presentation formats. Error bars representing the 95% credible intervals (CI) for the mean differences.

Predicted Probability of Improved Overall Recall In No Exposure Conditions: Auditory vs. Visual. The predicted probability of higher levels of overall recall performance for participants during the audible presentation was 0.25, with a proportion of 0.47 and a likelihood of 0.94. Under visual presentation conditions, those not exposed to any binaural beats had a predicted probability of 0.28, a proportion of 0.53, and a likelihood of 1.06. These findings suggest a slightly higher predicted probability of recall associated with auditory presentation compared to visual presentation.

Proportional Comparison of Overall Recall: Auditory vs. Visual. For the comparison of overall recall performance between auditory and visually presented memory tasks, the proportion of samples where those not exposed to any binaural beats performed better in the auditory deliver testing round was 0.45 ($p = 0.90$). These results suggest that the difference was not statistically significant at the conventional $p < 0.05$ level.

Overall Summary of Results. The results of the study do not support the hypothesis that participants not exposed to binaural beats would perform significantly better at overall recall of auditory memory tasks compared to visual memory tasks. The estimated marginal mean differences, mean differences in the predicted posterior samples, probabilities, proportions, and proportional comparisons of overall recall performance across the testing rounds all indicate a negligible difference in participant ability to recall auditory memory tasks compared to visual memory tasks. The 95% highest posterior density (HPD) intervals for both conditions include zero, suggesting that the observed difference in overall recall between the visually and audibly presented memory tasks is not statistically significant.

Hypothesis 2: Effect of Binaural Beats on Immediate and Delayed Recall

In my second hypothesis, I expected participants exposed to High-Beta and Gamma binaural beats to perform significantly better in immediate and delayed recall tasks compared to participants not exposed to binaural beats, particularly with auditory memory tasks compared to visual memory tasks. To test this hypothesis, I conducted a series of Bayesian linear regression analyses to examine the relationship between binaural beat exposure, presentation format of the memory tasks, and memory performance (immediate recall and delayed recall, respectively) using participants not exposed to any binaural beats with visual presentation of the memory tasks as a baseline. I compared the estimated marginal mean differences and mean differences in the predicted posterior samples of immediate and delayed recall performance between the experimental groups across the auditory and visual presentation testing rounds. This was followed by an examination of the predicted probabilities, proportions, and likelihoods associated with each testing condition for improved memory performance. I concluded with a proportional comparison of each experimental group against those not exposed to any binaural beats with a visual presentation of the memory tasks to establish if any of the groups outperformed the baseline proportionately.

Given that the presentation format of the memory tasks showed no significant effect on overall recall performance in participants not exposed to binaural beats, as expected in hypothesis 1, I included the combination of exposure status of each experimental group (exposure to High-Beta or Gamma binaural beats and participants not exposed to binaural beats) and the mode in which the memory tasks were presented (auditory or visual) as the contrasting categorical predictors in each analysis.

The Effect of Binaural Beats and Presentation on Immediate Recall

Mean Coefficient Estimates. For the auditory presentation of the memory tasks mode, the mean recall performance difference was 0.2 (SD = 0.2) for both the groups exposed to High-Beta binaural beats during encoding and during both encoding and recall (HBG-E and HBG-ER, respectively), 0.2 (SD = 0.2) for the group exposed to Gamma binaural beats during encoding alone (GG-E), and 0.3 (SD = 0.2) for the group exposed to Gamma binaural beats during both encoding and recall (GG-ER). The intercept representing immediate recall of the digit span for those not exposed to any binaural beats was estimated at -0.1 (SD = 0.1).

For the visual presentation mode, the mean recall performance difference for those not exposed to any binaural beats was estimated at -0.3 (SD = 0.1). The HBG-E, HBG-ER, GG-E, and GG-ER groups all exhibited a mean difference of 0.1 (SD = 0.2).

Fit Diagnostics. The mean posterior predictive distribution had a mean of 0.0 and a standard deviation of 0.1. Convergence diagnostics indicated satisfactory mixing and convergence, with effective sample sizes ranging from 7917 to 9027.

LOO-CV Assessment. The estimated effective log pointwise predictive density (elpd_loo) was 1.8 (SE = 1.0), and the probability of the LOO-CV outperforming the null model (p_loo) was 0.2 (SE = 0.0). The leave-one-out information criterion (LOOIC) value was -3.6 (SE = 2.1), suggesting the model had good predictive accuracy, a relatively simple structure, and a strong fit to the data.

Model Evaluation. The Bayesian model provided a framework for analysing the effects of binaural beat exposure on digit span recall performance immediately after presentation in both visual and auditory presentation formats and experimental conditions. The satisfactory convergence diagnostics, effective sample sizes, and LOO-CV metrics indicate that the model had a good fit for the data with good predictive accuracy and reliable parameter estimates.

Estimated Marginal Mean Differences in Immediate Recall between Experimental Groups. For those not exposed to any binaural beats, the estimated mean (emmean) immediate recall performance was lower for the visual presentation (m = -0.36; 95% HPD [-0.62, -0.10]) compared to the auditory presentation (m = -0.06; 95% HPD [-0.30, 0.20]).

In the binaural beats exposure groups, the estimated mean immediate recall performance was generally higher for the auditory presentation compared to the visual presentation. For the HBG-E condition, the emmean was 0.09 (95% HPD [-0.21, 0.42]) for auditory and -0.12 (95% HPD [-0.51, 0.26]) for visual presentation. The HBG-ER condition showed an emmean of 0.14 (95% HPD [-0.18, 0.46]) for auditory and -0.07 (95% HPD [-0.43, 0.31]) for visual presentation. The GG-E condition had an emmean of 0.13 (95% HPD [-0.19, 0.45]) for auditory and -0.06 (95% HPD [-0.43, 0.32]) for visual presentation. The GG-ER condition had an emmean of 0.19 (95% HPD [-0.13, 0.51]) for auditory and 0.11 (95% HPD [-0.27, 0.47]) for visual presentation.

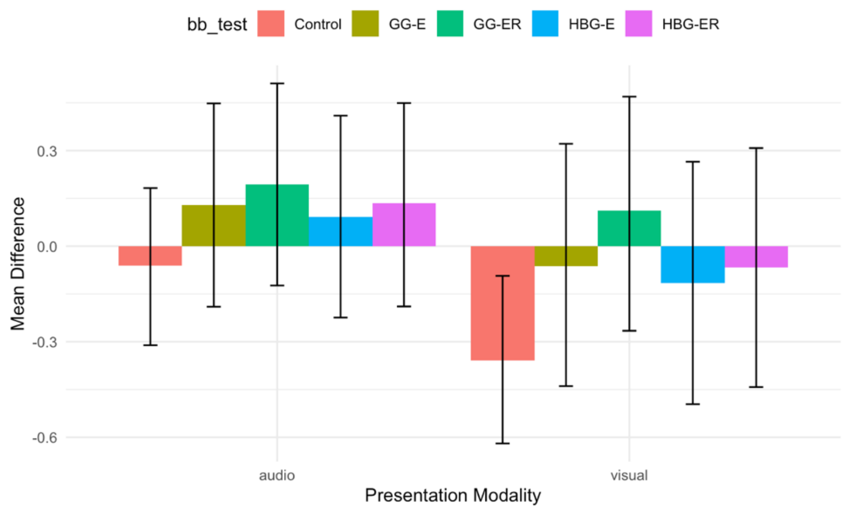
These results do not support the hypothesis. The participants exposed to High-Beta and Gamma binaural beats did not consistently outperform the group not exposed to any binaural beats on the auditory memory tasks. Based on the 95% credible Highest Posterior Density (95% HPD) intervals the differences were not statistically significant.

Mean Differences in Immediate Recall Across Experimental Groups. For the auditory presentation of the digit span, the mean difference between the HBG-E group and those not exposed to any binaural beats was 0.09 (SD = 0.16; 95% CI [-0.22, 0.41]). The mean difference between the HBG-ER group and those not exposed to any binaural beats was 0.14 (SD = 0.16; 95% CI [-0.19, 0.45]). The mean difference between the GG-E group and those not exposed to any binaural beats was 0.13 (SD = 0.16; 95% CI [-0.10, 0.45]). The mean difference between the GG-ER group and those not exposed to any binaural beats was 0.20 (SD = 0.16; 95% CI [-0.12, 0.51]).

For the visual presentation, the mean difference between the HBG-E group and those not exposed to any binaural beats was -0.12 (SD = 0.19; 95% CI [-0.50, 0.27]. The mean difference between the HBG-ER group and those not exposed to any binaural beats was -0.07 (SD = 0.19; 95% CI [-0.44, 0.31]). The mean difference between the GG-E group and those not exposed to any binaural beats was -0.06 (SD = 0.19; 95% CI [-0.44, 0.32]). The mean difference between the GG-ER group and those not exposed to any binaural beats was 0.11 (SD = 0.19; 95% CI [-0.27, 0.47]).

Figure 7

Mean Differences in Posterior Samples Across Exposure Conditions by Presentation



Note. The group not exposed to any binaural beats are represented by the "Control" column.

The results from the mean differences in performance between the posterior samples of the experimental groups seen in Figure 7 do not support the hypothesis. The overlapping 95% credible intervals include zero, suggesting that any observed differences might have been due to change and that the true difference in immediate recall of the digit span between the groups exposed to binaural beats and those not exposed to any may be zero.

Predicted Probability of Improved Immediate Recall Across Testing Conditions. The results of the analysis are presented in Table 7. For auditory presentation, those not exposed to any binaural beats had the highest predicted probability of immediate recall at 0.69, compared to lower probabilities in the HBG-E (0.28), HBG-ER (0.20), GG-E (0.22), and GG-ER (0.11) conditions. The group not exposed to any binaural beats also had the highest proportion of correct responses (0.13) and likelihood (-2.84) for auditory presentation, while the binaural beats exposure groups showed lower performance. For visual presentation, the same pattern emerged, with those not exposed to any binaural beats exhibiting the highest predicted probability (0.99), proportion (0.13), and likelihood (0.08) of immediate recall, outperforming the binaural beats exposure groups.

Table 7

Immediate Recall Performance Across Presentation Formats and Binaural Beats Conditions

Presentation	Exposure Conditions	Predicted Probability	Proportion	Likelihood
Audio	No exposure	0.69	0.13	2.84
	High-Beta exposure during encoding (HBG-E)	0.28	0.16	2.10
	High-Beta exposure during encoding and recall (HBG-ER)	0.20	0.16	1.74
	Gamma exposure during encoding (GG-E)	0.21	0.16	1.79
	Gamma exposure during encoding and recall (GG-ER)	0.11	0.16	1.19
Visual	No exposure	0.99	0.13	0.08
	High-Beta exposure during encoding (HBG-E)	0.73	0.19	1.72
	High-Beta exposure during encoding and recall (HBG-ER)	0.64	0.19	1.97
	Gamma exposure during encoding (GG-E)	0.63	0.19	1.96
	Gamma exposure during encoding and recall (GG-ER)	0.27	0.19	1.78

Note. Overall the predicted probabilities and proportions of successfully recalling the digit span show a generally lower likelihood of improved recall in the binaural beat exposure groups relative to those not exposed to any binaural beats.

These results do not support the hypothesis. The group not exposed to any binaural beats demonstrated the highest immediate recall performance for both auditory and visual presentation formats, contrary to the expected advantage of the High-Beta and Gamma binaural beats exposure groups on auditory recall tasks.

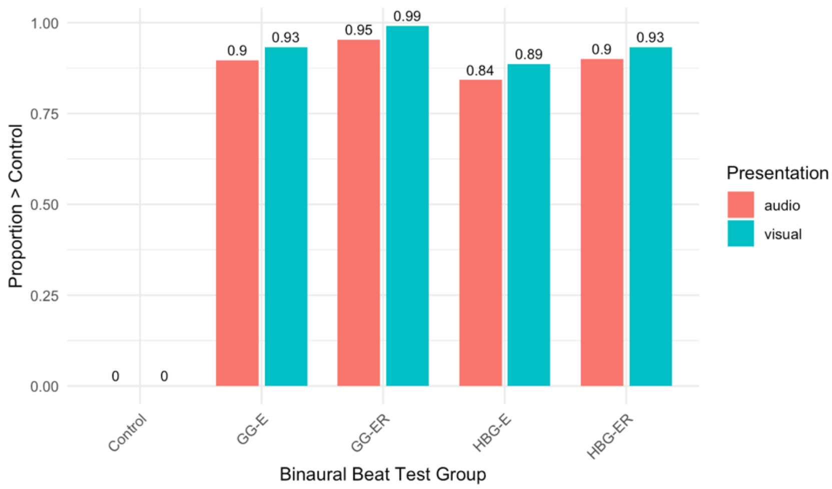
Proportional Comparison of Immediate Recall Across Exposure Conditions by Presentation. For the auditory presentation, the proportion of samples illustrated in Figure 8 where the single exposure High-Beta (HBG-E) group outperformed the group not exposed to binaural beats was 0.84, with a p-value of 0.32. The High-Beta group exposed during encoding and recall (HBG-

ER) had a proportion of 0.90 (p = 0.20) compared to those not exposed to any binaural beats. The single exposure Gamma (GG-E) group had a proportion of 0.90 (p = 0.21), while the Gamma group exposed during encoding and recall (GG-ER) group had a proportion of 0.95 (p = 0.09).

For the visual presentation, the proportion of samples where the HBG-E group outperformed the group not exposed to any binaural beats was 0.89 (p = 0.23). The HBG-ER group had a proportion of 0.93 (p = 0.14), the GG-E group had a proportion of 0.93 (p = 0.14), and the GG-ER group had a proportion of 0.99 (p = 0.02).

Figure 8

Proportional Comparison for Immediate Recall Probabilities by Exposure Group



Note. Proportions represent the proportion of samples where the binaural beats exposure group exhibited higher immediate recall performance compared to the group not exposed to any binaural beats. Dual Gamma exposure coupled with visual presentation is the exception with a significant proportion outperforming the group not exposed to any binaural beats.

These results do not support the hypothesis that the binaural beats exposure groups would perform significantly better than the group not exposed to any binaural beats on immediately recalling the presented digit span, especially for the auditory presentation. Except for the GG-ER group (p = 0.02) outperforming the group not exposed to binaural beats in recalling the visually presented digit span, the differences were not statistically significant at the conventional $p < 0.05$ level.

Overall Summary of Results. The immediate recall analysis did not support the hypothesis that participants exposed to High-Beta and Gamma binaural beats would perform significantly better in immediate recall tasks compared to participants not exposed to binaural beats, particularly with auditory memory tasks compared to visual memory tasks. However, the proportional comparison analysis revealed that participants exposed to Gamma binaural beats during both encoding and recall (GG-ER group) outperformed the group not exposed to any binaural beats in recalling the visually presented digit span task, with a statistically significant difference ($p = 0.02$). This suggests that exposure to Gamma binaural beats during both encoding and recall led to significantly improved immediate recall of visually presented digit span information compared to no binaural beat exposure.

The Effect of Binaural Beats and Presentation on Recalling Target Words After a Delay

Mean Coefficient Estimates. For the auditory presentation of the Newcomer story, the intercept (β_0) representing the No exposure condition was estimated at 0.2 (SD = 0.1). Participants in the HBG-E group exhibited a mean recall performance decrease of -0.2 (SD = 0.2), while the HBG-ER group showed a difference of -0.1 (SD = 0.2). The GG-E group had a difference of 0.0 (SD = 0.2), and the GG-ER group had a difference of -0.2 (SD = 0.2).

For the visual presentation of the Newcomer story, participants in the group not exposed to any binaural beats showed a difference estimated at -0.1 (SD = 0.1). The HBG-E group was estimated at -0.1 (SD = 0.2), the HBG-ER group at -0.2 (SD = 0.2), the GG-E group at -0.1 (SD = 0.2), and the GG-ER group at -0.2 (SD = 0.2).

Fit Diagnostics. The mean posterior predictive distribution (mean ppd) indicated a well-fitted model, with an estimated value of 0.0 (SD = 0.1). Convergence diagnostics showed satisfactory mixing and convergence, with effective sample sizes ranging from 7685 to 8791.

LOO-CV Assessment. The expected log predictive density (elpd_loo) estimate was -0.1 (SE = 1.2), suggesting reasonable predictive accuracy. The effective number of parameters (p_loo) was estimated at 0.3 (SE = 0.0), indicating a relatively simple model structure. The leave-one-out information criterion (LOOIC) value was 0.3 (SE = 2.4), suggesting the model had a good overall fit to the data.

Model Evaluation. The Bayesian model provided a framework for analysing the effects of binaural beat exposure on target word recall performance after a delay across visual and auditory presentation formats of the story tasks and experimental conditions. The satisfactory convergence diagnostics, large effective sample sizes, and LOO-CV metrics indicate that the model had a good fit for the data and reliable parameter estimates.

Estimated Marginal Mean Differences between Experimental Groups in Recalling Target Words After a Delay. For the auditory presentation of the Adam Jones story, the group not exposed to any binaural beats demonstrated an estimated mean (emmean) recall of the target words of 0.23 (95% HPD [-0.03, 0.48]). For the visual presentation of the Lucy Carson story, participants in the group not exposed to any binaural beats had an emmean of 0.10 (95% HPD [-0.18, 0.37]).

Participants in the High-Beta binaural beats exposure groups showed lower emmean recall compared to those not exposed to any binaural beats. For the group exposed only during encoding (HBG-E), the emmean was 0.07 (95% HPD [-0.23, 0.40]) for the auditory Adam Jones story and -0.21 (95% HPD [-0.60, 0.17]) for the visual Lucy Carson story. The group exposed during both encoding and recall (HBG-ER) had an emmean of 0.08 (95% HPD [-0.25, 0.41]) for the auditory story and -0.25 (95% HPD [-0.63, 0.12]) for the visual story.

In the Gamma groups, the group exposed only during encoding (GG-E) exhibited an emmean of 0.19 (95% HPD [-0.13, 0.53]) for the auditory Adam Jones story and -0.08 (95% HPD [-0.48, 0.31]) for the visual Lucy Carson story. The group exposed during both encoding and recall (GG-ER) had an emmean of 0.08 (95% HPD [-0.23, 0.41]) for the auditory story and -0.22 (95% HPD [-0.61, 0.16]) for the visual story.

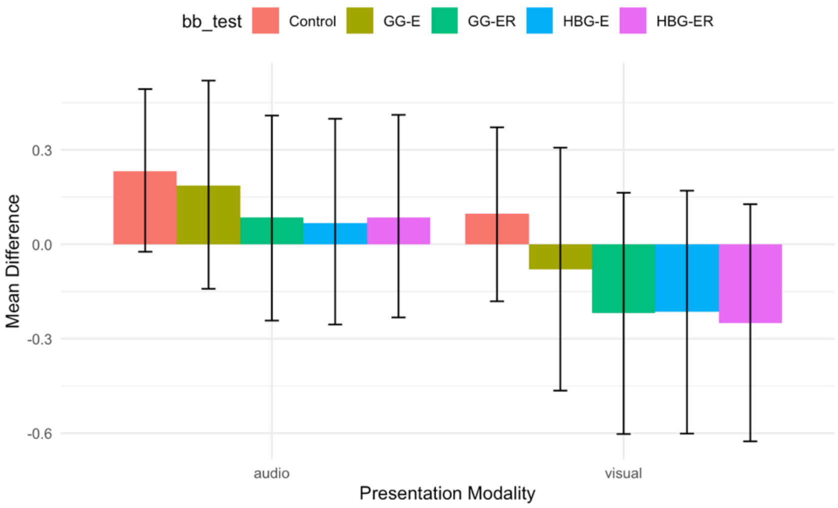
These results do not support the hypothesis. The groups exposed to High-Beta and Gamma binaural beats did not exhibit significantly higher delayed recall of the target words for the auditory presentation compared to participants not exposed to binaural beats.

Mean Differences between Experimental Groups in Recalling Target Words After a Delay. For the auditory presentation, the mean differences in delayed recall performance for target words between the High-Beta and Gamma binaural beats exposure groups and the group not exposed to any binaural beats were 0.07 (SD = 0.17) with a 95% CI of [-0.26, 0.40] for the HBG-E group, 0.09 (SD = 0.17) with a 95% CI of [-0.23, 0.41] for the HBG-ER group, 0.19 (SD = 0.17) with a 95% CI of [-0.14, 0.52] for the GG-E group, and 0.09 (SD = 0.17) with a 95% CI of [-0.24, 0.41] for the GG-ER group (see Figure 9).

For the visual presentation, the mean differences were -0.21 (SD = 0.20) with a 95% CI of [-0.60, 0.17] for the HBG-E group, -0.25 (SD = 0.19) with a 95% CI of [-0.63, 0.13] for the HBG-ER group, -0.08 (SD = 0.20) with a 95% CI of [-0.47, 0.31] for the GG-E group, and -0.22 (SD = 0.20) with a 95% CI of [-0.60, 0.16] for the GG-ER group (Figure 9).

Figure 9

Mean Differences in Target Word Recall Across Exposure Conditions by Presentation Format



Note. Mean differences in the predicted performance of the posterior samples a indicate positive outcomes when the stories were presented audibly. With the exception of the group not exposed to binaural beats, High-Beta and Gamma binaural beats are shown to have had a negative impact.

These results do not support the hypothesis that the binaural beats exposure groups would exhibit significantly better recall performance for target words after a delay compared to those not exposed to any binaural beats, especially when the Newcomer story was presented audibly. The 95% confidence intervals for the mean differences all included zero, indicating the differences were not statistically significant.

Predicted Probability of Improved Target Word Recall After a Delay between Experimental Groups. The results of the predicted probability analysis for the immediate recall task are presented in Table 8. For the auditory presentation, participants not exposed to any binaural beats exhibited the lowest predicted probability of 0.04, with a proportion of 0.13 and a likelihood of 0.64. In contrast, the binaural beats exposure groups showed higher predicted probabilities for the auditory presentation, ranging from 0.13 (GG-E) to 0.34 (HBG-E).

For the visual presentation, the group not exposed to any binaural beats had a higher predicted probability of 0.25, with a proportion of 0.14 and a likelihood of 2.24, compared to the auditory presentation. The binaural beats exposure groups also showed higher predicted probabilities for the visual presentation, ranging from 0.66 (GG-E) to 0.90 (HBG-ER).

Table 8

Predicted Probabilities, Proportions and Likelihoods of Recalling the Target Words

Presentation	Exposure Conditions	Predicted Probability	Proportion	Likelihood
Audio	No exposure	0.04	0.13	0.64
	High-Beta exposure during encoding (HBG-E)	0.34	0.17	2.22
	High-Beta exposure during encoding and recall (HBG-ER)	0.30	0.16	2.12
	Gamma exposure during encoding (GG-E)	0.13	0.17	1.28
	Gamma exposure during encoding and recall (GG-ER)	0.30	0.17	2.11
Visual	No exposure	0.25	0.14	2.24
	High-Beta exposure during encoding (HBG-E)	0.86	0.20	1.12
	High-Beta exposure during encoding and recall (HBG-ER)	0.90	0.19	0.89
	Gamma exposure during encoding (GG-E)	0.66	0.20	1.87
	Gamma exposure during encoding and recall (GG-ER)	0.86	0.20	1.09

Note. Overall the predicted probabilities and proportions of successfully recalling the target words favours the visually presented story of Lucy Carson, with a generally lower likelihood of this occurring.

These results suggest that the binaural beats exposure groups, particularly those exposed only during encoding, exhibited higher predicted probabilities of immediate recall performance compared to the group not exposed to any binaural beats, especially when the Newcomer story was visually presented. However, the findings do not support a significant difference in performance between the groups exposed to binaural beats and the group not exposed to any binaural beats, particularly when the tasks were presented audibly.

Proportional Comparison of Recalling Target Words After a Delay between Experimental Groups. For the auditory presentation of the Adam Jones story, the proportion of samples where the High-Beta binaural beats exposure groups outperformed the group not exposed to any binaural beats was 0.14 ($p = 0.28$) for the HBG-E group and 0.17 ($p = 0.34$) for the HBG-ER group. The Gamma groups had a proportion of 0.39 ($p = 0.78$) for GG-E and 0.17 ($p = 0.34$) for GG-ER. For the visual presentation of the Lucy Carson story, the proportion of samples where the HBG-E group outperformed the group not exposed to any binaural beats was 0.07 ($p = 0.13$), while the HBG-ER group had a proportion of 0.04 ($p = 0.08$). In the Gamma exposure groups, the group with exposure during encoding alone (GG-E) had a proportion of 0.20 ($p = 0.40$), while the group exposed during encoding and recall (GG-ER group) had a proportion of 0.06 ($p = 0.12$).

These results do not suggest that the groups exposed to High-Beta and Gamma binaural beats would perform significantly better than the group not exposed to any binaural beats on the target word recall tasks, especially when the story was presented audibly. While some of the binaural beats groups showed higher proportions of outperforming the group not exposed to any binaural beats, the differences were not statistically significant at the conventional $p < 0.05$ level.

Overall Summary of Results. The results of the delayed recall of target words analysis do not support the hypothesis that participants exposed to High-Beta and Gamma binaural beats would perform significantly better in delayed recall tasks compared to participants not exposed to binaural beats, particularly with auditory memory tasks compared to visual memory tasks. The estimated marginal mean differences, mean differences in the predicted posterior samples, probabilities, proportions, and proportional comparisons of delayed recall performance across the testing rounds all indicate that the group not exposed to any binaural beats performed better than the binaural beats exposure groups, both for auditory and visual presentation formats. The 95% highest posterior density (HPD) intervals for both conditions include zero, suggesting that the observed differences in delayed recall between the visually and audibly presented memory tasks are not statistically significant.

The Effect of Binaural Beats and Presentation Format on Recalling Themes After a Delay

Mean Coefficient Estimates. The intercept (β_0: mean = 0.0; SD = 0.1) represented the expected recall performance under No exposure conditions for the audibly presented story. For the auditory presentation of the Adam Jones story, participants in the HBG-E group had a mean recall difference of 0.1 (SD = 0.2) compared to No exposure. The HBG-ER group showed a similar difference of 0.1 (SD = 0.2). In the Gamma groups, GG-E participants exhibited an increase of 0.1 (SD = 0.2), while GG-ER participants showed no effect (mean = 0.0; SD = 0.2).

For the visual presentation of the Lucy Carson story, participants in the group not exposed to any binaural beats had a decrease in theme recall (mean = -0.1; SD = 0.1) compared to auditory presentation. The HBG-E group showed an increase of 0.2 (SD = 0.2), HBG-ER had no effect (mean = 0.0; SD = 0.2), GG-E showed no effect (mean = 0.0; SD = 0.2), and GG-ER participants had a decrease (mean = -0.1; SD = 0.2) compared to No exposure.

Fit Diagnostics. The mean posterior predictive distribution (mean ppd) was estimated at 0.1 (SD = 0.1), indicating a well-fitted model. Convergence diagnostics showed satisfactory mixing and convergence, with effective sample sizes ranging from 8136 to 9567.

LOO-CV Assessment. The Bayesian model evaluation indicated good predictive performance for the delayed recall of themes task. The expected log predictive density (elpd_loo) estimate was 1.0 (SE = 1.0), suggesting strong predictive accuracy. The effective number of parameters (p_loo) was 0.2 (SE = 0.0), indicating a relatively simple model structure. The leave-one-out information criterion (LOOIC) value was -2.0 (SE = 2.1), indicating an excellent fit to the data.

Model Evaluation. These results suggest that the Bayesian model effectively captured the key factors influencing delayed recall of themes, with strong predictive accuracy and a well-fitted model. The satisfactory convergence diagnostics, large effective sample sizes, and LOO-CV metrics indicate that the model had a good fit for the data and reliable parameter estimates.

Estimated Marginal Mean Differences in Recalling the Story Themes between Experimental Groups After a Delay. For the auditory presentation of the Newcomer story, the estimated mean (emmean) recall performance for those not exposed to any binaural beats was 0.00, with a 95% HPD interval ranging from -0.25 to 0.25.

In the binaural beats exposure groups, the emmean recall performance varied across conditions. Participants exposed to High-Beta binaural beats during encoding alone (HBG-E) had an emmean of 0.08 for auditory and 0.138 for visual presentation. Participants with dual exposure to High-Beta (HBG-ER) showed emmeans of -0.07 for auditory and -0.19 for visual presentation. The Gamma group with single exposure during encoding alone (GG-E) had emmeans of 0.14 for auditory and 0.07 for visual presentation. Participants exposed to Gamma binaural beats during encoding and recall (GG-ER) exhibited emmeans of 0.05 for auditory and -0.15 for visual presentation.

These results do not support the hypothesis that participants in the High-Beta and Gamma exposure groups would perform significantly better in the recall of thematic information after a delay compared to those not exposed to binaural beats, especially when the Newcomer story was presented audibly. The 95% HPD intervals for the mean estimates suggest overlapping ranges, indicating no clear difference in thematic recall between the groups exposed to binaural beats compared to the group that was not exposed to any binaural beats.

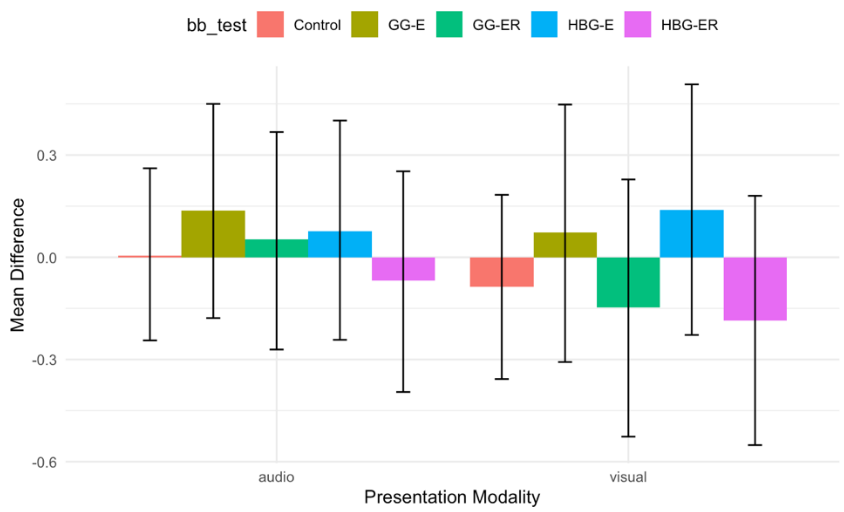
Mean Differences in Recalling the Story Themes between Experimental Groups After a Delay. For recalling the themes of the auditory presentation of the Newcomer story, the mean differences between the binaural beats exposure groups and the group not exposed to any binaural beats were as follows: participants exposed to High-Beta binaural beats during encoding only (HBG-E) had a mean difference of 0.08 (SD = 0.16), with a 95% confidence interval ranging from -0.24 to 0.40; those exposed to High-Beta binaural beats during both encoding and recall (HBG-ER) showed a mean difference of -0.07 (SD = 0.17), with a 95% CI of -0.40 to 0.25; participants exposed to Gamma binaural beats during encoding only (GG-E) had a mean difference of 0.14 (SD = 0.16), with a 95% CI of -0.18 to 0.45; and those exposed to Gamma binaural beats during both encoding and recall (GG-ER) exhibited a mean difference of 0.05 (SD = 0.16), with a 95% CI of -0.27 to 0.37.

Recalling the themes of the visually presented Newcomer story, the mean differences between the binaural beats exposure groups and the group not exposed to any binaural beats were as follows: participants exposed to High-Beta binaural beats during encoding only (HBG-E) had a mean difference of 0.14 (SD = 0.19), with a 95% confidence interval ranging from -0.23 to 0.51; those exposed to High-Beta binaural beats during both encoding and recall (HBG-ER) showed a mean difference of -0.19 (SD = 0.19), with a 95% CI of -0.55 to 0.18; participants exposed to Gamma binaural beats during encoding only (GG-E) had a mean difference of 0.07 (SD = 0.19), with a 95% CI of -0.31 to 0.45; and those exposed to Gamma binaural beats during both encoding and recall (GG-ER) exhibited a mean difference of -0.15 (SD = 0.19), with a 95% CI of -0.53 to 0.23.

The results indicate no significant differences in story theme recall between the binaural beats exposure groups and the group not exposed to any binaural beats, regardless of presentation format, to support the hypothesis. The 95% confidence intervals for all exposure conditions overlap with the group not exposed to any binaural beats, suggesting the true difference in story theme recall may be zero (see Figure 10).

Figure 10

Mean Differences in Recalling the Themes After a Delayby Presentation Format



Note. The mean differences in the posterior samples suggests that the interaction between the format of presentation and the timing of exposure to binaural beats of binaural beats have differential outcomes on recalling thematic content after a delay.

Predicted Probability of Recalling the Story Themes between Experimental Groups After a Delay. For the auditory presentation, the group not exposed to any binaural beats exhibited a predicted probability of 0.49, a proportion of 0.13, and a likelihood of 3.13. In the binaural beats exposure groups, the predicted probabilities and proportions varied: HBG-E had a predicted probability of 0.32 and a proportion of 0.16, HBG-ER had a predicted probability of 0.66 and a proportion of 0.16, GG-E had a predicted probability of 0.20 and a proportion of 0.16, and GG-ER had a predicted probability of 0.37 and a proportion of 0.16.

For the visual presentation, the group not exposed to any binaural beats had a higher predicted probability of 0.73, a proportion of 0.14, and a likelihood of 2.38. The binaural beats exposure groups also showed varying predicted probabilities: HBG-E had a predicted probability of 0.23, HBG-ER had a predicted probability of 0.84, GG-E had a predicted probability of 0.35, and GG-ER had a predicted probability of 0.78.

The results of the analysis on the predicted probability, proportions, and likelihood of recalling thematic information after a delay are presented in Table 9. These results showed that the groups exposed to binaural beats did not exhibit significantly higher predicted probabilities, proportions, and likelihoods of recalling thematic information after a delay compared to the group not exposed to any binaural beats, especially when the Newcomer story was presented audibly. While some of the binaural beats groups showed higher values, the differences were not consistently large or statistically significant.

Table 9

Predicted Probabilities, Proportions, and Likelihoods for Delayed Recall of Thematic Information

Presentation	Exposure Conditions	Predicted Probability	Proportion	Likelihood
Audio	No exposure	0.49	0.13	3.13
	High-Beta exposure during encoding (HBG-E)	0.32	0.16	2.20
	High-Beta exposure during encoding and recall (HBG-ER)	**0.66**	**0.16**	**2.22**
	Gamma exposure during encoding (GG-E)	0.20	0.16	1.73
	Gamma exposure during encoding and recall (GG-ER)	0.37	0.16	2.33
Visual	No exposure	0.73	0.14	2.38
	High-Beta exposure during encoding (HBG-E)	0.23	0.19	1.61
	High-Beta exposure during encoding and recall (HBG-ER)	**0.84**	**0.19**	**1.30**
	Gamma exposure during encoding (GG-E)	0.35	0.19	1.95
	Gamma exposure during encoding and recall (GG-ER)	0.78	0.19	1.55

Note. Overall the predicted probabilities, probabilities and likelihoods from the analysis suggest a higher likelihood of exposure to High-Beta binaural beat exposure having a significant effect on recalling story themes after a delay.

Proportional Comparison of Recalling the Story Themes between Experimental Groups After a Delay. For the auditory presentation of the Newcomer story, the proportion of samples where the binaural beats exposure groups outperformed the group not exposed to any binaural beats was 0.79 (p = 0.42) for the HBG-E group, 0.53 (p = 0.94) for the HBG-ER group, 0.87 (p = 0.27) for the GG-E group and 0.75 (p = 0.49) for the GG-ER group. For the visual presentation, the proportion of samples where the binaural beats exposure groups outperformed the group not exposed to any binaural beats was 0.87 (p = 0.26) for the HBG-E group, 0.31 (p = 0.62) for the HBG-ER group, 0.79 (p = 0.42) for the GG-E group and 0.38 (p = 0.76) for the GG-ER group.

The results from the proportional comparison of the delayed recall of story themes analysis do not support the hypothesis that participants exposed to High-Beta and Gamma binaural beats would perform significantly better in recalling story themes after a delay compared to participants not exposed to binaural beats, particularly with auditory memory tasks compared to visual memory tasks.

Overall Summary of Results. The results do not support the hypothesis that participants exposed to High-Beta and Gamma binaural beats would perform significantly better in immediate and delayed recall tasks compared to participants not exposed to binaural beats, particularly with auditory memory tasks compared to visual memory tasks. The estimated marginal mean differences, mean differences in the predicted posterior samples, probabilities, proportions, and proportional comparisons of delayed recall performance across the visual and auditory testing rounds all indicate that the group not exposed to any binaural beats performed better than the binaural beats exposure groups, both for auditory and visual presentation formats. While some of the binaural beats groups showed higher proportions of outperforming the group not exposed to any binaural beats, the differences were not statistically significant at the conventional $p < 0.05$ level.

Hypothesis 3: Effect of Binaural Beat Exposure Timing on Memory

In my third hypothesis, I expected participants with dual exposure (during both encoding and recall) to High-Beta and Gamma binaural beats (HBG-ER and GG-ER) to show improved immediate and delayed recall performance on memory tasks compared to those only exposed during encoding (HBG-E and GG-E) and those not exposed to any binaural beats, irrespective of the presentation format of the memory tasks. To test this hypothesis, I performed Bayesian linear regression analyses to examine the relationship between the timing of binaural beat exposure and memory performance (immediate recall and delayed recall, respectively) using the performance of the group not exposed to any binaural beats as a baseline for comparison. I compared the estimated marginal mean differences, mean differences in the predicted posterior samples, predicted probabilities, and proportions, and examined the proportional comparisons in immediate and delayed recall performance levels between the experimental groups across the auditory and visual presentation rounds. I used the timing of exposure to binaural beats groups (no exposure, HBG-E, GG-E, HBG-ER and GG-ER) as categorical predictors to examine the aggregated level of immediate and delayed recall performance of each group across both presentation formats.

The Effect of Binaural Beat Exposure Timing on Immediate Recall

Mean Coefficient Estimates. Relative to participants not exposed to any binaural beats (β_0: mean = 0.1; SD = 0.3), participants in the single exposure groups (HBG-E and GG-E) had an estimated difference of -0.1 (SD = 0.4). Participants with dual exposure to Gamma (GG-ER) binaural beats had a mean difference of -0.1 (SD = 0.4), while those exposed to High-Beta during encoding and recall (HBG-ER) had a mean difference of -0.3 (SD = 0.4), irrespective of presentation format.

Fit Diagnostics. The mean posterior predictive distribution (mean ppd) was estimated at 0.0 (SD = 0.3), indicating a well-fitted model. Convergence diagnostics showed satisfactory mixing and convergence, with effective sample sizes ranging from 3973 to 4445.

LOO-CV Assessment. The Bayesian model evaluation indicated strong predictive performance for the immediate recall task. The expected log predictive density (elpd_loo) estimate was 0.3 (SE = 1.3), suggesting excellent predictive accuracy. The effective number of parameters (p_loo) was 0.6 (SE = 0.1), indicating a moderately complex model structure. The leave-one-out information criterion (LOOIC) value was -0.6 (SE = 2.6), indicating a good fit for the data.

Model Evaluation. The Bayesian model provided a framework for analysing the effects of binaural beat exposure on target word recall performance after a delay across visual and auditory presentation formats of the story tasks and experimental conditions. The satisfactory convergence diagnostics, effective sample sizes, and LOO-CV metrics indicate that the model was a good fit for the data and reliable parameter estimates.

Estimated Marginal Mean Differences in Recalling the Digit Span between Dual, Single, and No Exposure Groups. For participants not exposed to any binaural beats, the estimated marginal mean (emmean) was -0.09, with a 95% highest posterior density (HPD) interval ranging from -0.97 to 0.85. In the binaural beats exposure groups, the emmean performance varied. Participants in the HBG-E group had an emmean of 0.05, with a 95% HPD interval of -0.83 to 0.93. The HBG-ER group showed an emmean of -0.25, with a 95% HPD interval of -1.14 to 0.66. The

GG-E group had an emmean of 0.07, with a 95% HPD interval of -0.80 to 0.98. The GG-ER group exhibited an emmean of 0.14, with a 95% HPD interval of -0.81 to 1.02.

These results do not support the hypothesis that the binaural beats exposure groups with dual exposure would exhibit significantly higher immediate recall of the digit span tasks compared to participants not exposed to any binaural beats. The 95% HPD intervals for the binaural beats groups overlap with the 95% HPD interval for the group not exposed to any binaural beats. This suggests no clear difference between the binaural beat exposure groups to the group not exposed to any binaural beats.

Mean Differences in Digit Span Recall between Dual, Single and No Exposure Groups. The mean difference for the group not exposed to any binaural beats was -0.09 (SD = 0.46), and a 95% confidence interval ranging from -1.014 to 0.821. In the binaural beats exposure groups, the single exposure High-Beta (HBG-E) group had a mean difference of 0.04, with a standard deviation of 0.45, and a 95% HPD confidence interval from -0.84 to 0.92. The High-Beta group under dual exposure conditions (HBG-ER) showed a mean difference of -0.25 (SD = 0.46) and a 95% confidence interval from -1.14 to 0.67. Participants exposed to Gamma binaural beats during encoding alone (GG-E) had a mean difference of 0.07 (SD = 0.45) and a 95% confidence interval from -0.84 to 0.96. Lastly, the Gamma group under dual exposure conditions (GG-ER) exhibited a mean difference of 0.14 (SD = 0.47) and a 95% confidence interval from -0.78 to 1.06.

These mean differences between the experimental groups in the posterior samples do not support the hypothesis that the binaural beats exposure groups would significantly outperform the group not exposed to any binaural beats in immediate recall performance. The results suggest no clear distinction between the binaural beat groups with dual exposure to those exposed only during encoding and those not exposed to any binaural beats.

Predicted Probability of Recalling the Digit Span in Dual, Single and No Exposure Groups. The results of the analysis examining the predicted probability, proportions, and likelihood of immediate recall performance are presented in Table 10. For participants in the group not exposed to any binaural beats, the predicted probability was 0.58, the proportion was 0.46, and the likelihood was 0.85. In the binaural beats exposure groups, the High-Beta (HBG-E) single exposure condition had a predicted probability of 0.46, a proportion of 0.45, and a likelihood of 0.87.

Participants with dual exposure to High-Beta binaural beats (HBG-ER) condition had a predicted probability of 0.70, a proportion of 0.46, and a likelihood of 0.75. The single exposure to Gamma binaural beats (GG-E) condition had a predicted probability of 0.44, a proportion of 0.45, and a likelihood of 0.88. Dual exposure to Gamma binaural beats during encoding and recall (GG-ER) condition had a predicted probability of 0.38, a proportion of 0.47, and a likelihood of 0.82.

Table 10

Predicted Probabilities, Proportions, and Likelihoods for Immediate Recall Performance

Exposure Conditions	Predicted Probability	Proportion	Likelihood
No exposure	0.58	0.46	0.84
High-Beta exposure during encoding (HBG-E)	0.46	0.45	0.87
High-Beta exposure during encoding and recall (HBG-ER)	0.70	0.46	0.75
Gamma exposure during encoding (GG-E)	0.44	0.45	0.88
Gamma exposure during encoding and recall (GG-ER)	0.38	0.47	0.82

Note. The predicted probabilities and likelihoods for each testing condition, indicate the associated probability and likelihood of achieving significant increased recall.

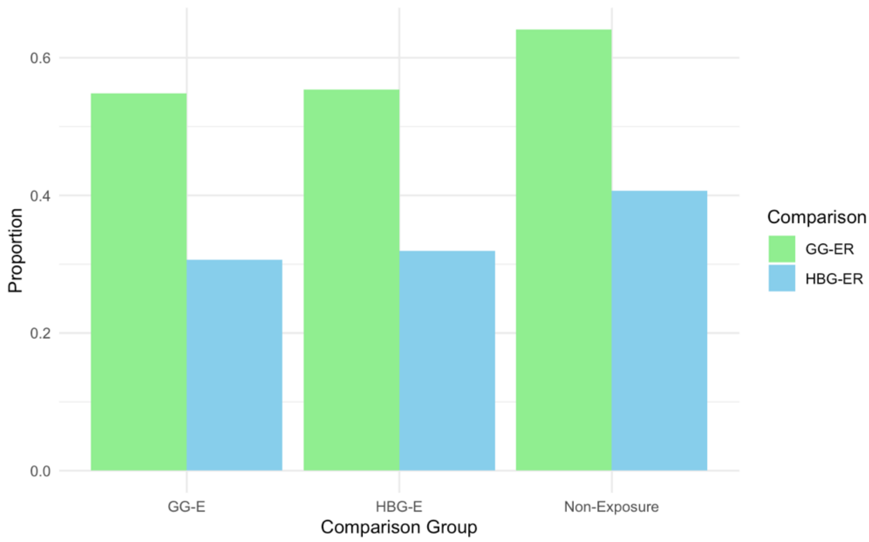
These results do not show that participants in the dual binaural beats exposure groups demonstrated significantly higher predicted probability, proportions, and likelihood of immediate recall performance compared to those exposed only during encoding or those not exposed to any binaural beats.

Proportional Comparison of Immediate Recall between Dual, Single and No Exposure Groups. For the comparison of the dual exposure to High-Beta binaural beats during encoding and recall (HBG-ER) group to the group not exposed to any binaural beats, the proportion of samples where HBG-ER outperformed the group not exposed to any binaural beats was 0.41, with a p-value of 0.81. When comparing the HBG-ER group to the single exposure to High-Beta binaural beats during encoding alone (HBG-E) group, the proportion of samples where HBG-ER outperformed HBG-E was 0.32, with a p-value of 0.64.

For the comparison of the group under dual exposure to Gamma binaural beats (GG-ER) to the group not exposed to any binaural beats, the proportion of samples where GG-ER outperformed the group not exposed to any binaural beats was 0.75, with a p-value of 0.50. When comparing the GG-ER group to participants in the single exposure to Gamma binaural beats during encoding alone (GG-E) group, the proportion of samples where GG-ER outperformed GG-E was 0.31, with a p-value of 0.61.

Figure 11

Comparative Overview of Proportionate Experimental Group Performance



Note. Side-by-side comparison of HBG-ER and GG-ER group proportions of samples for immediate recall vs. testing conditions. Legend: No exposure group, HBG-E – High Beta exposure during encoding, HBG-ER – High Beta exposure during encoding and recall, GG-E – Gamma exposure during encoding, GG-ER – Gamma exposure during encoding and recall.

The results from the proportional comparison shown in Figure 11 do not support the hypothesis that the dual exposure groups (HBG-ER, GG-ER) would significantly outperform the single exposure (HBG-E, GG-E) and No exposure groups. The differences observed were not statistically significant at the conventional $p < 0.05$ level.

In summary, The results did not support the hypothesis that dual exposure to binaural beats would lead to significantly improved immediate recall performance compared to single exposure or no exposure. The analysis of recalling the digit span tasks showed no clear distinction between the binaural beat exposure groups with dual exposure and those exposed only during encoding or not exposed to any binaural beats. The predicted probabilities and proportional comparisons also did not demonstrate a significant advantage for dual exposure groups in immediate recall performance. Overall, the results do not suggest significant differences in immediate recall performance between dual, single, and no-exposure groups.

The Effect of Binaural Beat Exposure Timing on Recalling Target Words After a Delay

Mean Coefficient Estimates. Relative to participants in the group not exposed to any binaural beats (β_0: mean = 0.1; SD = 0.2), participants in the GG-ER group showed a mean difference of -0.5 (SD = 0.3), and the HBG-ER group had a mean difference of -0.3 (SD = 0.3). The single exposure groups (HBG-E and GG-E) recalled slightly fewer target words (mean = -0.1; SD = 0.3, respectively) compared to No exposure, irrespective of presentation mode.

Fit Diagnostics. The mean predictive posterior distribution centred around 0.0 (SD = 0.1), indicating a well-fitted model. Convergence diagnostics showed satisfactory mixing and convergence, with effective sample sizes ranging from 3810 to 4580.

LOO-CV Assessment. The Bayesian model evaluation indicated good predictive performance for the delayed recall of target words task. The expected log predictive density (elpd_loo) estimate was -0.4 (SE = 1.1), suggesting strong predictive accuracy. The effective number of parameters (p_loo) was 0.4 (SE = 0.1), indicating a relatively simple model structure. The leave-one-out information criterion (LOOIC) value was 0.9 (SE = 2.3), indicating an excellent fit to the data.

Model Evaluation. The Bayesian model provided a framework for analysing the effects of binaural beat exposure on target word recall performance after a delay across visual and auditory presentation formats of the story tasks and experimental conditions. The satisfactory convergence diagnostics, large effective sample sizes, and LOO-CV metrics indicate that the model had an excellent fit to the data and was highly effective in capturing the key factors influencing delayed recall of target words, including the anticipated advantage of the binaural beats exposure conditions.

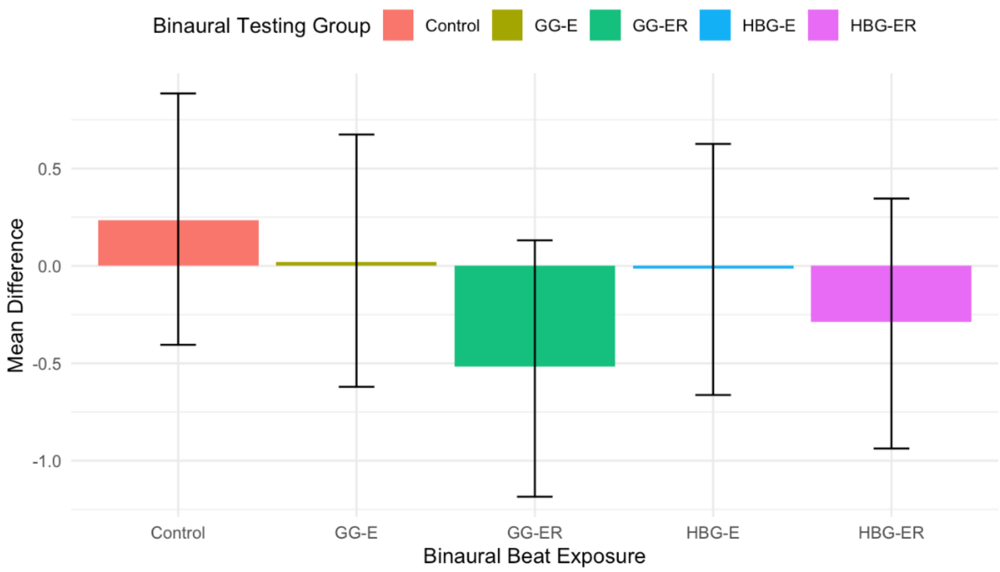
Estimated Marginal Mean Differences for Delayed Recall of Target Words between Dual, Single, and No Exposure Groups. For the group not exposed to any binaural beats, the emmean was 0.23, with a 95% highest posterior density (HPD) interval ranging from -0.39 to 0.89. In the binaural beats exposure groups, the emmean performance varied. The single exposure to High-Beta (HBG-E) group had an emmean of -0.01, with a 95% HPD interval of -0.65 to 0.64. The group with dual exposure to High-Beta binaural beats during encoding and recall (HBG-ER) showed an emmean of -0.28, with a 95% HPD interval of -0.93 to 0.35. The single exposure to Gamma binaural bets during encoding alone (GG-E) group had an emmean of 0.02, with a 95% HPD interval of -0.65 to 0.65. Lastly, the group with dual exposure to Gamma binaural beats during encoding and recall (GG-ER) exhibited an emmean of -0.52, with a 95% HPD interval of -1.16 to 0.15.

These results do not provide sufficient evidence to support the hypothesis that exposure to binaural beats would result in a significant improvement in delayed recall performance for target words compared to the single and no-exposure groups. The 95% HPD intervals for the binaural beats groups all overlapped with the interval for the group not exposed to any binaural beats.

Mean Differences in Target Word Recall between Dual, Single and No Exposure Groups. For the group not exposed to any binaural beats, the mean difference was 0.23, with a standard deviation of 0.33, and a 95% confidence interval ranging from -0.41 to 0.89. In the binaural beats exposure groups seen in Figure 12, participants with single exposure to High-Beta binaural beats (HBG-E) had a mean difference of -0.01(SD = 0.33), and a 95% confidence interval from -0.66 to 0.63.

Figure 12

Mean Differences in Target Word Recall Performance Across Experimental Groups



Note. The mean differences in delayed recall for target words across the respective testing conditions. Legend: Control - No exposure group, HBG-E – High Beta exposure during encoding, HBG-ER – High Beta exposure during encoding and recall, GG-E – Gamma exposure during encoding, GG-ER – Gamma exposure during encoding and recall.

Under dual exposure conditions, the High-Beta (HBG-ER) group showed a mean difference of -0.29 (SD = 0.33), and a 95% confidence interval from -0.94 to 0.35. Participants exposed to Gamma binaural beats during encoding alone (GG-E) had a mean difference of 0.02 (SD = 0.33), and a 95% confidence interval from -0.62 to 0.67. Under dual exposure conditions, Gamma (GG-ER) group exhibited a mean difference of -0.52 (SD = 0.33), and a 95% confidence interval from -1.19 to 0.13.

These results do not support the hypothesis that binaural beat exposure groups would show a significant improvement in delayed recall performance for target words compared to the group not exposed to any binaural beats. The 95% confidence intervals for the mean differences all included zero, indicating the differences were not statistically significant.

Predicted Probability of Recalling Target Words After a Delay between Dual, Single and No Exposure Groups. For the group not exposed to any binaural beats, the predicted probability was 0.24, the proportion was 0.33, and the likelihood was 0.95.

In the binaural beats exposure groups, the HBG-E condition had a predicted probability of 0.52, a proportion of 0.33, and a likelihood of 1.22. The HBG-ER condition had a predicted probability of 0.81, a proportion of 0.33, and a likelihood of 0.83. The GG-E condition had a predicted probability of 0.47, a proportion of 0.33, and a likelihood of 1.22. The GG-ER condition had a predicted probability of 0.94, a proportion of 0.33, and a likelihood of 0.36.

Table 11

Predicted Probabilities, Proportions, and Likelihoods for Delayed Recall of Target Words

Exposure Conditions	Predicted Probability	Proportion	Likelihood
No exposure	0.24	0.33	0.95
High-Beta exposure during encoding (HBG-E)	0.51	0.33	1.22
High-Beta exposure during encoding and recall (HBG-ER)	0.81	0.33	0.83
Gamma exposure during encoding (GG-E)	0.47	0.33	1.22
Gamma exposure during encoding and recall (GG-ER)	0.94	0.33	0.36

Note. The predicted probabilities and likelihoods for each testing condition, indicate the associated probability and likelihood of achieving significant increased recall.

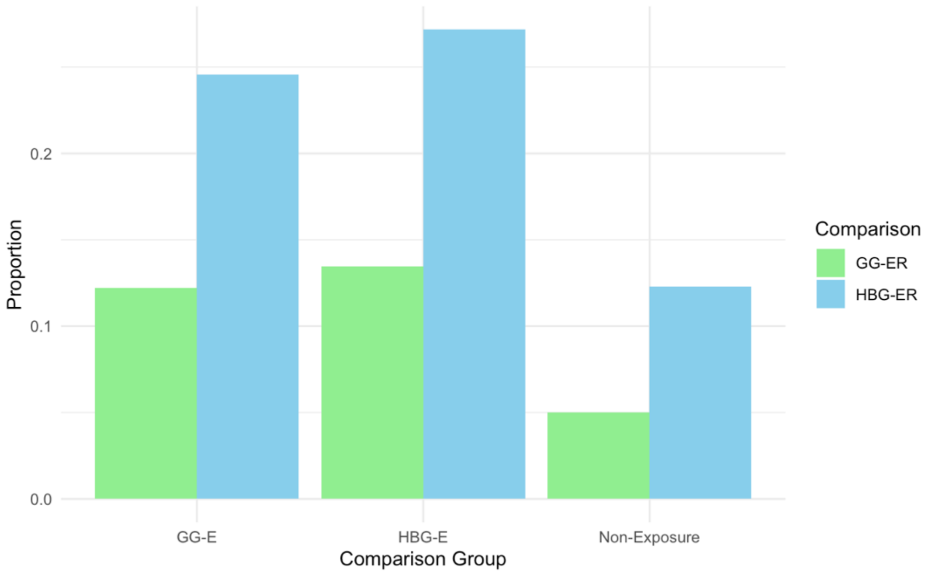
The results of the analysis examining the predicted probability, proportions, and likelihood of delayed recall performance for target words presented in Table 11 do not provide strong evidence to support the hypothesis that dual exposure to binaural beats would exhibit significantly higher predicted probability, proportions, and likelihood of delayed recall performance for target words compared to the single and No exposure groups.

Proportional Comparison of Recalling Target Words After a Delay between Dual, Single and No Exposure Groups. For the comparison of the dual exposure to High-Beta binaural beats (HBG-ER) group to the group not exposed to any binaural beats, the proportion of samples where HBG-ER outperformed the group not exposed to any binaural beats was 0.12 ($p = 0.25$). When comparing the HBG-ER group to the single exposure High-Beta (HBG-E) group, the proportion of samples where HBG-ER outperformed HBG-E was 0.27 ($p = 0.54$).

For the comparison of the dual exposure to Gamma binaural beats (GG-ER) group to the group not exposed to any binaural beats, the proportion of samples where GG-ER outperformed those not exposed to any binaural beats was 0.05 ($p = 0.10$). When comparing the GG-ER group to the single exposure Gamma (GG-E) group, the proportion of samples where GG-ER outperformed GG-E was 0.12, with a p-value of 0.24.

Figure 13

Proportions of Dual Exposure Groups Outperforming the Single and No Exposure Groups



Note. Side-by-side comparison of the proportions of HBG-ER and GG-ER groups showing participants under dual exposure conditions outperforming single and no exposure groups when recalling target words after a delay.

Figure 13 shows the proportion of samples where participants from the dual exposure groups (HBG-ER and GG-ER) accurately recalled more target words from the Lucy Carson and Adam Jones Newcomer stories compared to the single and no exposure groups. The results do not provide strong evidence to support the hypothesis that the dual exposure groups (HBG-ER, GG-ER) would significantly outperform the single exposure (HBG-E, GG-E) and No exposure groups. The differences observed were not statistically significant at the conventional $p < 0.05$ level.

Overall Summary of the Results. Collectively, the results for the delayed recall of target words did not provide strong evidence to support the hypothesis that dual exposure to binaural beats would lead to a significant improvement in delayed recall performance compared to single exposure or no exposure. The analysis of delayed recall performance for target words showed no clear superiority of the dual exposure conditions over single exposure or no exposure, as indicated by overlapping 95% HPD intervals and confidence intervals. The predicted probabilities, proportions, and likelihoods for delayed recall performance also did not demonstrate a significant advantage for dual exposure groups. Contrary to the hypothesis, the study did not find significant differences in delayed recall performance for target words between dual, single, and no-exposure groups.

The Effect of Binaural Beat Exposure Timing on Recalling Story Themes After a Delay

Mean Coefficient Estimates. The intercept (β_0) for recalling themes in the group not exposed to any binaural beats was estimated at 0.2 (SD = 0.2). Compared to the group not exposed to any binaural beats, HBG-E and GG-E participants showed a mean difference of -0.1 (SD = 0.3) each. Under dual exposure conditions, GG-ER participants had a mean difference of -0.3 (SD = 0.3), while HBG-ER participants showed a more pronounced difference of -0.7 (SD = 0.3). Dual exposure to High-Beta and Gamma binaural beats (HBG-ER and GG-ER) may impair recalling broader themes more than single and no exposure conditions.

Fit Diagnostics. The mean posterior predictive distribution (mean ppd) was estimated at -0.1, with a standard deviation of 0.2. Convergence diagnostics indicated satisfactory mixing and convergence of MCMC chains, with effective sample sizes ranging from 3374 to 3998.

LOO-CV Assessment. The expected log predictive density (elpd_loo) estimate was -0.5 (SE = 1.3), indicating reasonable predictive accuracy. The effective number of parameters (p_loo) was 0.4 (SE = 0.1), suggesting a moderately complex model structure. The leave-one-out information criterion (LOOIC) value was 0.9 (SE = 2.6), indicating a good overall fit to the data, and supporting the model's effectiveness in capturing factors influencing delayed recall of thematic information.

Model Evaluation. The Bayesian model provided a framework for analysing the effects of binaural beat exposure on recalling story themes after a delay across visual and auditory presentation formats of the story tasks and experimental conditions. The satisfactory convergence diagnostics, large effective sample sizes, and LOO-CV metrics indicate that the model had a good fit for the data and reliable parameter estimates.

Estimated Marginal Mean Differences in Recalling Story Themes After a Delay between Dual, Single, and No Exposure Groups. For the group not exposed to any binaural beats, the emmean was 0.34, with a 95% highest posterior density (HPD) interval ranging from -0.29 to 1.02. In the binaural beats exposure groups, the emmean performance varied. Participants in the single exposure to High-Beta binaural beats during encoding alone (HBG-E) group had an emmean of 0.12, with a 95% HPD interval of -0.53 to 0.77. Under dual exposure to High-Beta conditions (HBG-ER), participants showed an emmean of -0.75, with a 95% HPD interval of -1.40 to -0.10. Participants exposed to Gamma binaural bets during encoding alone (GG-E) had an emmean of 0.11, with a 95% HPD interval of -0.50 to 0.76, with dual exposure to Gamma binaural beats (GG-ER) showed an emmean of -0.10, with a 95% HPD interval of -0.74 to 0.56.

These results show that dual exposure to High-Beta or Gamma binaural beats did not significantly improve participants’ ability to recall thematic information after a delay compared to single or No exposure conditions. With the exception of the group exposed to High-Beta binaural beats during both encoding and recall, the 95% HPD intervals for the binaural beats groups included zero, indicating no clear advantage of the exposure conditions.

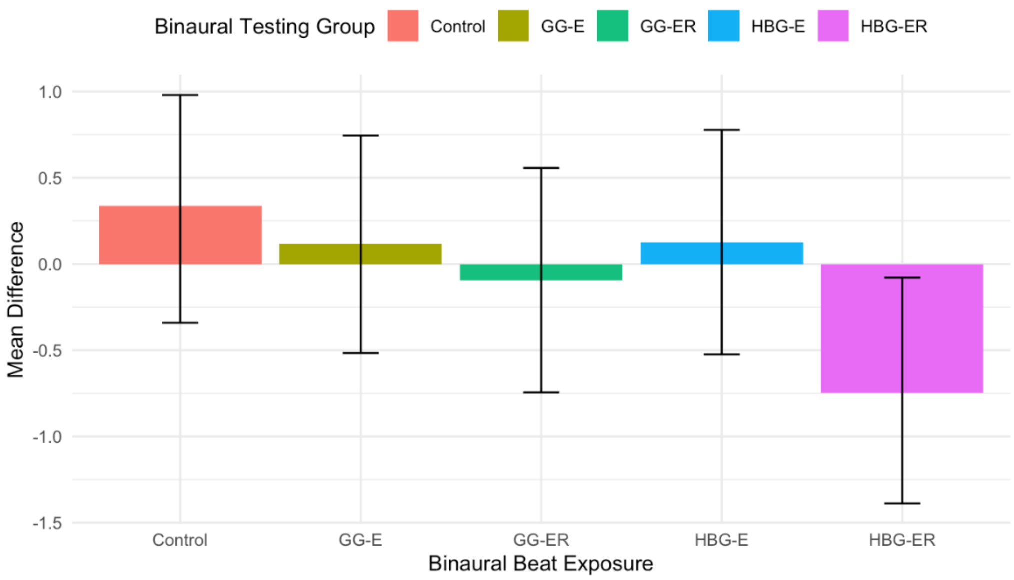
Mean Differences in Recalling Story Themes After a Delay between Dual, Single, and No Exposure Groups. For the group not exposed to any binaural beats, the mean difference was 0.34, with a standard deviation of 0.33, and a 95% confidence interval ranging from -0.34 to 0.98. In the binaural beats exposure groups, the HBG-E group had a mean difference of 0.13 (SD = 0.33) and a 95% confidence interval from -0.52 to 0.78.

The group under dual exposure to High-Beta binaural beats (HBG-ER) showed a mean difference of -0.75 (SD = 0.33), and a 95% confidence interval from -1.39 to -0.08. The Gamma group exposed during encoding alone (GG-E) had a mean difference of 0.12 (SD = 0.32) and a 95%

confidence interval from -0.52 to 0.75. Lastly, the Gamma group under dual exposure conditions (GG-ER) exhibited a mean difference of -0.10 (SD = 0.33) and a 95% confidence interval from -0.75 to 0.56 (see Figure 14).

Figure 14

Mean Differences in Thematic Performance Across Experimental Groups



Note. The mean differences across the respective testing conditions . Legend: Control – No-exposure group, HBG-E – High Beta exposure during encoding, HBG-ER – High Beta exposure during encoding and recall, GG-E – Gamma exposure during encoding, GG-ER – Gamma exposure during encoding and recall.

The results from the mean differences in performance in the posterior samples of the experimental groups suggest that the group exposed to High-Beta binaural beats during both encoding and recall exhibited a significant decrease in memory performance compared to the group not exposed to any binaural beats. The 95% confidence interval excluded zero suggesting that High-Beta binaural beat exposure during both encoding and recall may have a significant negative effect on recalling broader theme-related information after a delay. while the other comparisons between the binaural beats exposure groups and the group not exposed to any binaural beats did not show statistically significant differences.

Predicted Probabilities of Recalling Story Themes After a Delay between Dual, Single, and No Exposure Groups. The results of the analysis examining the predicted probability, proportions, and likelihood of recalling thematic information after a delay are presented in Table 12.

For the group not exposed to any binaural beats, the predicted probability was 0.15, the proportion was 0.33, and the likelihood was 0.72.

Table 12

Predicted Probabilities and Likelihoods of Recalling the Themes Across Experimental Conditions

Exposure Conditions	Predicted Probability	Proportion	Likelihood
No exposure	0.15	0.33	0.72
High-Beta exposure during encoding (HBG-E)	0.35	0.33	1.13
High-Beta exposure during encoding and recall (HBG-ER)	**0.99**	**0.33**	**0.09**
Gamma exposure during encoding (GG-E)	0.36	0.33	1.17
Gamma exposure during encoding and recall (GG-ER)	0.61	0.33	1.16

Note. The predicted probabilities and likelihoods for each testing condition, indicate the associated probability and likelihood of achieving significant increased recall.

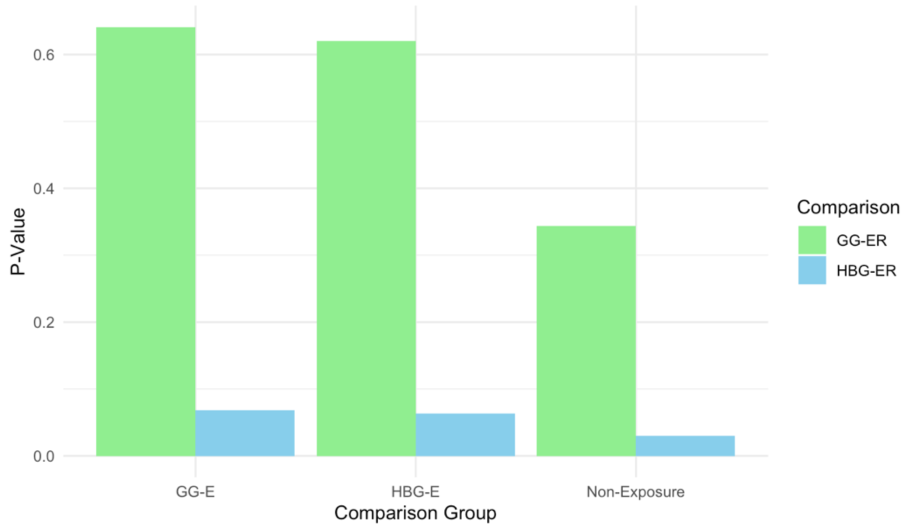
In the binaural beats exposure groups, the single exposure to High-Beta binaural beats during encoding alone (HBG-E) condition had a predicted probability of 0.35, a proportion of 0.33, and a likelihood of 1.13. The dual exposure to High-Beta binaural betas during encoding and recall (HBG-ER) condition had a predicted probability of 0.99, a proportion of 0.33, and a likelihood of 0.09. For the Gamma groups, the single exposure during encoding alone (GG-E) condition had a predicted probability of 0.36, a proportion of 0.32, and a likelihood of 1.17. The dual exposure to Gamma binaural beats during encoding and recall (GG-ER) condition showed a predicted probability of 0.61, a proportion of 0.33, and a likelihood of 1.16.

The results suggest that dual exposure to High-Beta binaural beats during both encoding and recall conditions had a notably high probability of impacting thematic information after a delay in a sizeable proportion compared to the other groups. The likelihood value for HBG-ER indicates the odds of the HBG-ER group achieving significantly improved thematic recall is low, indicating that the observed effect may not be positive.

Proportional Comparison of Recalling Story Themes After a Delay between Dual, Single, and No Exposure Groups. The results of the proportional comparison are shown in Figure 15. For the comparison of the dual exposure to High-Beta (HBG-ER) group to the group not exposed to any binaural beats, the proportion of samples where HBG-ER outperformed the group not exposed was 0.02 (p = 0.03). When comparing the HBG-ER group to the single exposure to High-Beta binaural beats (HBG-E) group, the proportion of samples where HBG-ER outperformed HBG-E was 0.03 (p = 0.06).

Figure 15

Proportion Comparison of Recall Performance between Experimental Groups



Note. Side-by-side comparison of the associated p-values associated with the proportions of sample differences across the experimental groups with HBG-E showing a significant proportion of samples outperforming those not exposed to any binaural beats (Non-Exposure).

For the comparison of the dual exposure to Gamma binaural beats (GG-ER) group to the group not exposed to any binaural beats, the proportion of samples where GG-ER outperformed the group not exposed to any binaural beats was 0.17 (p = 0.34). For the comparison of the GG-ER group to the Gamma group exposed during encoding alone (GG-E), the proportion of samples where GG-ER outperformed GG-E was 0.32 (p = 0.64).

The results for the delayed recall of story themes do not support the hypothesis that dual exposure to High-Beta or Gamma binaural beats during both encoding and recall would significantly improve performance compared to single exposure during encoding or no exposure. However, the results from the proportional comparison show that a small proportion of the group exposed to High-Beta binaural beats during both encoding and recall showed a significantly altered level of performance across the collective memory tasks, compared to the group not exposed to any binaural beats ($p = 0.03$). However, the differences between the other binaural beats exposure groups and the group not exposed to any binaural beats were not statistically significant at the conventional $p < 0.05$ level.

Overall Summary of the Results. In summary, the results do not support the hypothesis that participants with dual exposure (during both encoding and recall) to High-Beta and Gamma binaural beats (HBG-ER and GG-ER) would show improved immediate and delayed recall performance on memory tasks compared to those only exposed during encoding (HBG-E and GG-E) and those not exposed to any binaural beats, irrespective of the presentation format of the memory tasks.

For immediate recall, the analysis of recalling the digit span tasks showed no clear distinction between the binaural beat exposure groups with dual exposure and those exposed only during encoding or not exposed to any binaural beats. The predicted probabilities and proportional comparisons also did not demonstrate a significant advantage for dual exposure groups in immediate recall performance.

The results for delayed recall of target words did not provide strong evidence to support the hypothesis. The analysis showed no clear advantage of the dual exposure conditions over single exposure or no exposure. The predicted probabilities, proportions, and likelihoods for delayed recall performance also did not demonstrate a significant advantage for dual exposure groups.

For delayed recall of story themes, the group exposed to High-Beta binaural beats during both encoding and recall (HBG-ER) had a significantly lower mean recall performance compared to the group not exposed to any binaural beats. However, the other binaural beat exposure groups did not show a clear advantage over the no-exposure group. The mean differences in thematic recall performance supported the finding that the HBG-ER group performed significantly worse than the group not exposed to any binaural beats. The predicted probability analysis highlighted the detrimental effect of dual High-Beta exposure.

Hypothesis 4: The Effect of High-Beta Binaural Beats vs. the Effect of Gamma Binaural Beats on Declarative Memory.

In my fourth hypothesis, I expected that participants exposed to Gamma binaural beats would show a greater improvement in recall performance compared to those not exposed to binaural beats, relative to the improvement seen in the High-Beta binaural beats group compared to the group not exposed to any binaural beats. Furthermore, this difference in improvement between the Gamma and High-Beta groups relative to those not exposed will be more pronounced for auditorily presented memory tasks compared to visually presented memory tasks.

To test this hypothesis, I performed Bayesian linear regression analyses to examine the relationship between binaural beat exposure, presentation format of the memory tasks, and memory performance using the overall recall performance levels of participants not exposed to any binaural beats with visual presentation of the memory tasks as a baseline for the comparison. I compared the estimated marginal mean differences between the exposure groups and conducted a pairwise comparison of the difference in emmeans between audio and visual presentations for each group. Next, I examined the mean differences in overall recall performance between the predicted posterior samples of participants exposed to High-Beta binaural beats to participants exposed to Gamma binaural beats, across the auditory and visual presentation rounds.

I compared the predicted probabilities, proportions and likelihoods of each testing condition relative to the baseline and performed a pairwise comparison to assess the significance of the observed differences. Lastly, I performed a proportionate comparison of the overall recall performance between the High-Beta and Gamma groups to identify if one group significantly outperformed the other. I included presentation format (auditory and visual presentation) as a categorical predictor in combination with the exposure group (High-Beta versus Gamma) and timing of exposure (encoding only versus both encoding and recall) in the initial analysis and used participants not exposed to binaural beats performance as a baseline for comparison.

Overall Recall in High-Beta and Gamma Binaural Beats Experimental groups

Mean Coefficient Estimates. The intercept (β_0) representing the No exposure and auditory presentation conditions was estimated to have a mean of 0.0 and a standard deviation of 0.1. For auditory presentation, the mean difference from the baseline for the High-Beta groups (HBG-E and HBG-ER) was 0.1 (SD = 0.1), and for the Gamma groups (GG-E and GG-ER) it was 0.2 (SD = 0.1). For visual presentation, the mean overall recall difference in the group not exposed to any binaural beats was -0.2(SD = 0.1). The mean difference for the High-Beta groups was 0.1 (SD = 0.1), and for the Gamma groups, the mean difference was 0.0 (SD = 0.1).

Fit Diagnostics. The mean posterior predictive distribution (mean ppd) was estimated at 0.0 (SD = 0.1). Convergence diagnostics indicated satisfactory mixing and convergence, with effective sample sizes ranging from 5913 to 8193.

LOO-CV Assessment. The expected log predictive density (elpd_loo) estimate was 0.8 (SE = 0.8), indicating moderate predictive performance. The effective number of parameters (p_loo) was 0.1 (SE = 0.0), suggesting a relatively simple model structure. The leave-one-out information criterion (LOOIC) value was -1.7 (SE = 1.6), indicating a good overall fit to the data.

Model Evaluation. The Bayesian model provided a framework for analysing the effects of binaural beat exposure on target word recall performance after a delay across visual and auditory presentation formats of the story tasks and experimental conditions. The satisfactory convergence diagnostics, large effective sample sizes, and LOO-CV metrics indicate that the model had reasonable predictive accuracy and a good fit for the observed data.

Estimated Marginal Means Difference in Overall Recall between High-Beta and Gamma Exposure Groups. The estimated mean (emmean) for overall recall performance was calculated for each group (No exposure, High-Beta and Gamma) and presentation format (audio, visual). For the group not exposed to any binaural beats (No exposure), the emmean in overall recall with auditory presentation of the memory tasks was -0.03 (SE = 0.19, 95% HPD [-0.40, 0.34]) and -0.53 (SE = 0.19, 95% HPD [-0.90, -0.16]) when the memory tasks were presented visually.

For participants exposed to High-Beta binaural beats (HBG), the emmean in overall recall with the auditory presentation of the memory tasks was 0.10 (SE = 0.13, 95% HPD [-0.16, 0.36]) and with visual presentation of the memory tasks -0.05 (SE = 0.13, 95% HPD [-0.31, 0.21]). For participants exposed to Gamma binaural beats (GG), the emmean in overall recall with the auditory presentation of the memory tasks was 0.26 (SE = 0.13, 95% HPD [0.01, 0.53]) and 0.00 (SE = 0.13, 95% HPD [-0.26, 0.26]) with visually presented memory tasks.

The results from the estimated marginal means presented in Table 13 suggest that participants exposed to Gamma binaural beats outperformed those exposed to High-Beta binaural beats in both audio and visual presentation formats. This indicates a greater improvement in overall recall performance for the Gamma group compared to the High-Beta group. Additionally, the Gamma group showed a significant improvement in overall recall performance with auditory presentation of the memory tasks compared to participants not exposed to any binaural beats, while the other did not.

Except for the Gamma exposure group with auditory presentation of the memory tasks, the 95% HPD intervals indicate that the differences between the exposure and No exposure conditions were not statistically significant.

Table 13

Estimated Marginal Mean Overall Recall Performance for High-Beta and Gamma Experimental Groups

Binaural Beat Type	Presentation	emmean	Lower HPD	Upper HPD
No exposure	audio	-0.03	-0.40	0.34
Gamma	**audio**	**0.26**	**0.01**	**0.46**
High-Beta	audio	0.10	-0.16	0.36
No exposure	visual	-0.53	-0.19	0.32
Gamma	visual	0.00	-0.26	0.26
High-Beta	visual	-0.05	-0.31	0.21

Note. Estimated Marginal Means are reported with an HPD interval probability of 95%.

Pairwise Comparison between the Posterior Samples of High-Beta and Gamma Exposure Groups. Pairwise comparisons were conducted to assess the difference in emmeans between audio and visual presentations for each group. For the group not exposed to any binaural beats, the difference was 0.50 ($SE = 0.26$, 95% CI [-0.02, 1.01]; $t(144) = 1.90$; $p = 0.060$). For the GG group, the difference was 0.27 ($SE = 0.19$; 95% CI [-0.10, 0.64]; $t(144) = 1.45$; $p = 0.149$). For the HBG group, the difference was 0.15 ($SE = 0.19$; 95% CI [-0.22, 0.52]; $t(144) = 0.81$; $p = 0.418$).

The results from the pairwise comparison do not support the hypothesis that participants exposed to Gamma binaural beats will show a greater improvement in recall performance compared to those not exposed to binaural beats, relative to the improvement seen in the High-Beta binaural beats group compared to the group not exposed to any binaural beats. The results also show that the format in which the memory tasks were presented had no significant effect on recall performance. The results showed no significant differences between the testing groups suggesting that neither exposure to High-Beta nor Gamma binaural beats had a significant effect on recall performance.

Mean Differences in the Predicted Posterior Values between High-Beta and Gamma Exposure Groups. Relative to the group not exposed to any binaural beats, the differences in mean overall recall performance between the High-Beta (HBG) and Gamma (GG) exposure groups are presented in Table 14.

Table 14

Mean Differences in Declarative Memory Performance Across Binaural Beats Exposure Groups and Presentation Formats

Presentation	Exposure Group	Mean Difference	SD Difference	Lower CI	Upper CI
Audio	High-Beta (HBG)	0.10	1.03	-1.92	2.13
	Gamma (GG)	0.21	1.03	-1.82	2.24
Visual	High-Beta (HBG)	0.17	1.04	-1.87	2.21
	Gamma (GG)	0.24	1.04	-1.80	2.27

Note. Mean differences in the posterior samples are reported with a credible interval probability of 95%.

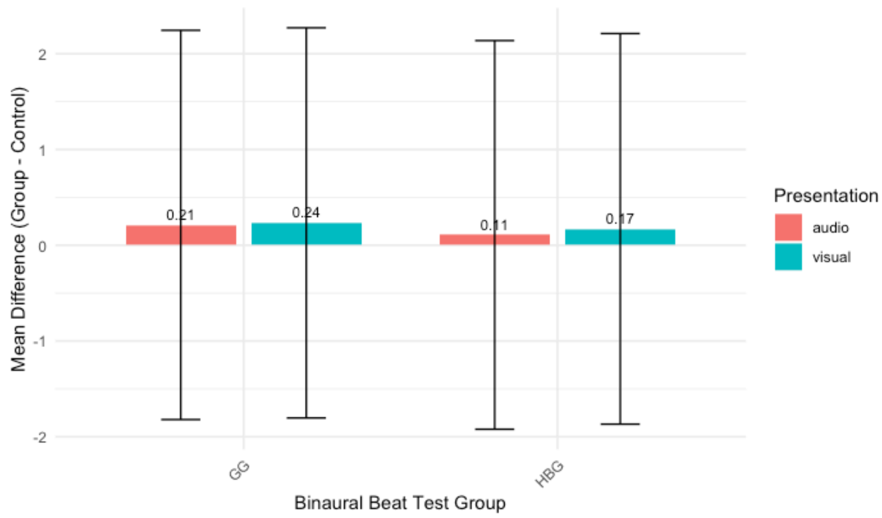
Compared to the group not exposed to any binaural beats with auditory presentation of the memory tasks, the group exposed to High-Beta binaural beats had a mean difference of 0.10 (SD = 1.03; 95% CI [-1.92, 2.13]), and the group exposed to Gamma binaural beats (GG) had a mean difference of 0.21 (SD = 1.03, 95% CI [-1.82, 2.24]).

Compared to participants not exposed to any binaural beats with visual presentation of the memory tasks, participants exposed to High-Beta binaural beats had a mean difference of 0.17 (SD = 1.04, 95% CI [-1.87, 2.21]), with participants exposed to Gamma binaural beats showing a mean difference of 0.24 (SD = 1.04, 95% CI [-1.80, 2.27]).

The mean differences in overall recall performance in the posterior samples between experimental groups shown in Figure 16 show exposure to Gamma binaural beats may have had a better influence on overall recall performance, relative to the improvement seen in the High-Beta binaural beats group. However, the overlapping 95% credible intervals for each binaural beat exposure group include zero suggesting that these differences are not significant.

Figure 16

Mean Differences in Overall Recall Between Experimental Groups



Note. Mean differences in overall recall performance between the groups exposed to High-Beta (HBG) and Gamma (GG) binaural beats, relative to the group not exposed to any binaural beats present in the posterior samples.

Predicted Probabilities, Proportions, and Likelihoods of Improved Declarative Memory Performance in High-Beta and Gamma Exposure Groups. In the audio presentation of the memory tasks round, the predicted probability for the group not exposed to any binaural beats was 0.52, with a proportion of 0.81 and a likelihood of 0.49. The Gamma (GG) group had a predicted probability of 0.35, a proportion of 0.69, and a likelihood of 0.52. The High-Beta (HBG) group had a predicted probability of 0.45, a proportion of 0.77, and a likelihood of 0.51.

For the round where the memory tasks were presented visually, the group not exposed to any binaural beats had a predicted probability of 0.74 with a proportion of 0.84 and a likelihood of 0.39. The Gamma (GG) group had a predicted probability of 0.23, a proportion of 0.44, and a likelihood of 0.87. The High-Beta Gama (HBG) group had a predicted probability of 0.29, a proportion of 0.51, and a likelihood of 1.13 (see Table 15).

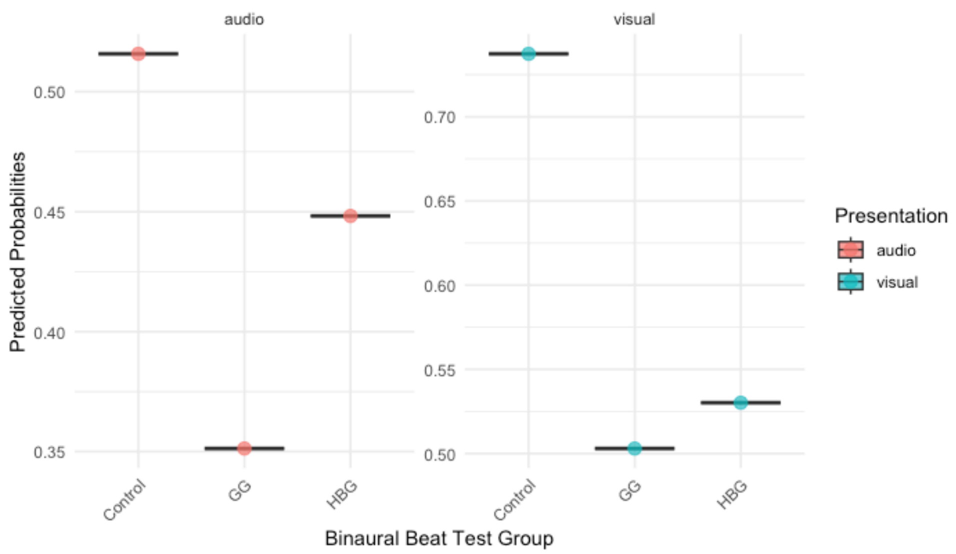
Table 15

Predicted Probabilities, Proportions, and Likelihoods of Memory Performance Across Experimental Groups and Presentation Formats

Group	Presentation	Predicted Probability	Proportion	Likelihood
No exposure	audio	0.52	0.81	0.49
Gamma	audio	0.35	0.69	0.53
High-Beta	audio	0.45	0.77	0.51
No exposure	visual	0.74	0.84	0.39
Gamma	visual	0.50	0.63	0.63
High-Beta	visual	0.53	0.66	0.60

Figure 17

Proportions of Increased Overall Recall Between High-Beta and Gamma Groups



Note. The proportionate distribution of predicted probabilities for the aggregated High-Beta (HBG) and Gamma (GG) groups across presentation formats.

The results examining the predicted probabilities, proportions, and likelihood of declarative memory performance across the binaural beats exposure groups (Gamma and High-Beta) and presentation formats (audio, visual) illustrated in Figure 17 do not provide strong evidence to support the hypothesis that participants exposed to High-Beta binaural beats would recall less declarative information compared to the Gamma group, especially when presented with auditory memory tasks.

The results show that the participants not exposed to any binaural beats had a higher predicted probability for visual presentation compared to audio. The group exposed to High-Beta binaural beats also had a higher predicted probability for visual presentation compared to auditory. Similarly, the participants exposed to Gamma binaural beats exhibited a higher predicted probability for visual presentation compared to audio.

Proportional Comparison of Overall Recall Performance between High-Beta and Gamma Exposure Groups. The results examining the proportion of samples in the posterior where the binaural beats exposure groups outperformed those not exposed to any binaural beats are presented in Table 16. With the auditory presentation of the memory tasks, a proportion of 0.54 (p = 0.91) of the group exposed to High-Beta binaural beats and a proportion of 0.58 (p = 0.83) of the group exposed to Gamma binaural beats outperformed the group not exposed to any binaural beats. With the memory tasks presented visually, a proportion of 0.57 (p = 0.87) of the group exposed to the High-Beta binaural beats and a proportion of 0.59 (p = 0.82) of the group exposed to Gamma binaural beats outperformed the group not exposed to any binaural beats.

Table 16

Proportion of Samples of Binaural Beats Exposure Groups Outperforming No Exposure Conditions

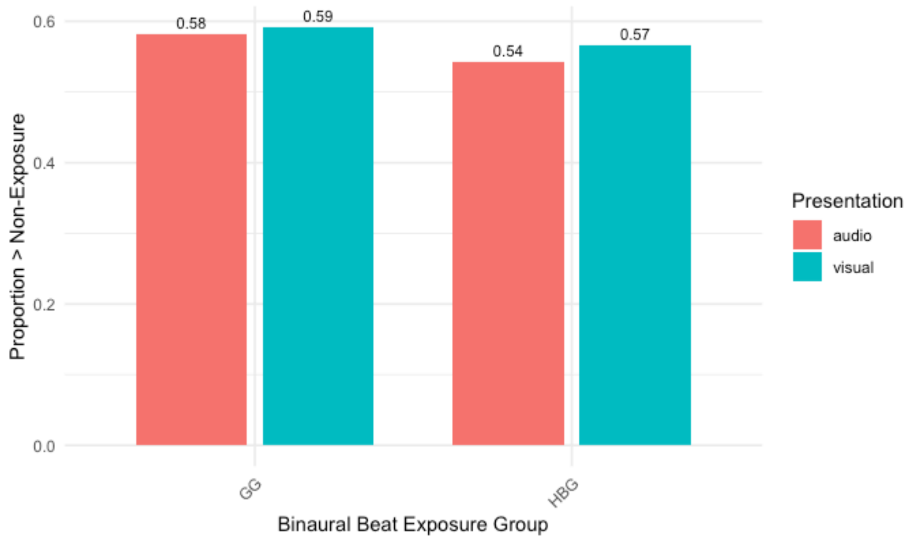
Presentation	Exposure Conditions	Sample (n)	Proportion	P-Value
Audio	High-Beta	30	0.54	0.91
	Gamma	30	0.58	0.83
Visual	High-Beta	30	0.57	0.87
	Gamma	30	0.59	0.82

Note. Proportions are presented with sample size and corresponding P-values to note no significant findings.

Proportionately, the findings do not indicate that the groups exposed to either High-Beta or Gamma binaural beats significantly outperformed the group not exposed to binaural beats. These results do not support the hypothesis that the Gamma group will significantly outperform the group not exposed to binaural beats by a larger margin compared to how much the High-Beta group outperforms the group not exposed to any binaural beats. While both exposure groups showed similar proportions in outperforming the group not exposed to any binaural beats the differences were not large enough to be considered statistically significant. Furthermore, the results do not indicate that the mode of presentation (auditory vs. visual) had a proportionately significant effect on the relative performance of the binaural beats exposure groups (Figure 18).

Figure 18

Proportions of Overall Recall Performance: High-Beta vs. Gamma Exposure Relative to No Exposure



Note. Comparative view of the proportions of High-Beta and Gamma groups outperforming the group not exposed to any binaural beats by presentation. Legend: GG – Participants exposed to Gamma binaural beats, HBG – participants exposed to High-Beta binaural beats.

Overall Summary of the Results. The results partially support the hypothesis. Although the findings indicate that participants exposed to both High-Beta and Gamma binaural beats proportionately outperformed those not exposed to any binaural beats in both testing rounds, the improvement in overall recall is more pronounced for the Gamma group compared to the High-Beta group, relative to the no-exposure group. Although the pairwise comparison did not show a significant difference between the two groups in terms of emmeans for audio and visual presentations, the Gamma group did show a significant improvement in overall recall performance with auditory presentation compared to participants not exposed to any binaural beats. However, the differences between the exposure and no exposure conditions were not statistically significant.

Chapter 5: Discussion

In this study, I examined whether exposing participants to High-Beta or Gamma binaural beats influenced immediate and delayed recall. I tested whether exposure to binaural beats would result in better memory performance overall, and whether the format of presentation of the memory tasks (visual vs. auditory) would influence performance.

I hypothesised that: 1) Participants not exposed to any binaural beats would perform significantly better in recalling the auditory memory tasks compared to visual memory tasks, 2) Participants exposed to High-Beta and Gamma binaural beats would demonstrate significantly improved immediate and delayed recall performance on the memory tasks compared to those not exposed to any binaural beats. This improvement was expected to be more pronounced for the auditorily presented memory tasks, 3) Participants with dual exposure to High-Beta and Gamma binaural beats during both encoding and recall were expected to show a significant improvement in immediate and delayed recall performance on the memory tasks compared to those only exposed during encoding and those not exposed to any binaural beats, irrespective of the presentation format of the memory tasks, and 4) Relative to participants not exposed to any binaural beats, I expected that exposure to Gamma binaural beats would result in a greater improvement of recall performance compared to those exposed to High-Beta binaural beats. Additionally, I expected that the advantage of Gamma binaural beats over High-Beta binaural beats would be more pronounced for auditorily presented memory tasks compared to visually presented memory tasks.

The results did not support the overall improvement in memory performance as hypothesised. Instead, the results of this study indicated that the effectiveness of binaural beats on memory recall may be contingent on the task type and how it is presented. For Instance, the significant finding partially supporting Hypothesis 2 was that participants exposed to Gamma binaural beats during both encoding and recall (GG-ER) only outperformed participants not exposed to any binaural beats in recalling the visually presented digit span. In contrast, the improvement expected in Hypothesis 3 was not supported as exposure to High-Beta binaural beats during both encoding and recall (HBG-ER) showed a significant negative impact on recalling story themes after a delay. Lastly, Hypothesis 4 was partially supported as the group exposed to Gamma binaural beats only showed greater improvements in overall declarative memory performance compared to the High-Beta binaural beat group for the auditory memory tasks. In the following paragraphs, I will discuss these findings concerning the hypotheses.

Hypothesis 1: Effect of Auditory versus Visual Presentation of Task Material on Overall Recall

Overall, I expected better recall of auditory digit span and story tasks relative to when similar tasks were presented in written form. The results do not support this hypothesis. Looking at results from the group that was not exposed to any binaural beats, there was no significant difference in performance for auditory or written tasks.

The results of the present study are consistent with the findings of Rogowsky et al. (2016) who examined the effect that the presentation format of task material has on recall. Rogowsky et al. (2016) reported similar findings after having participants read, listen, or read while listening to the preface and one chapter of a book on World War II. In their study, 91 college-educated participants completed a comprehension test consisting of 48 multiple-choice questions immediately after being presented with the task to test for comprehension. Participants completed a second multiple choice test two weeks later, where Rogowsky et al. (2016) examined retention and recall of information from the book preface and chapter after a delay. The authors found that participants in each condition recalled similar amounts of information regardless of whether they listened to an audiobook, read an e-text, or read the e-text while listening to the audiobook. Rogowsky et al. (2016) concluded that the format in which information is presented does not lead to substantial variations in comprehension, retention and recall.

Rogowsky et al.'s (2016) findings may be attributable to variations in the level of interest participants had in the topic, where some may have found the preface and chapter of the non-fiction novel on World War II interesting and others did not. Potential bias favouring the outcomes from the reading-only group may have been introduced into the study as the preface and chapter were read at a pace of 149 words per minute in the audio and dual-modality conditions. This pace is generally much slower than the average adult reading speed of around 200 – 300 words per minute. It should also be noted that while participants in the dual-modality condition were listening to the story being read to them at 149 words per minute, the corresponding e-text was automatically highlighted on a digital screen at the same speed from which they read the story. The slow speed may have introduced a level of frustration in some, impeding the ability to pay attention to or follow the story.

Contrasting the present findings, studies by Kelly et al. (2022) and Obleser & Kayser (2019) have shown significant findings to suggest that learning through listening might be more effective than learning through reading. The scoping review of 62 articles by Kelly et al. (2022), in which the authors aimed to examine the efficacy of audio-only podcasts in medical education, found that learning through listening led to improved knowledge retention. The authors suggested that the observed improvement is attributable to the convenience and entertainment value associated with podcasts. It could also be argued that there was an interest in the topic (medical education) since the study used a sample of medical student for their investigation, which may explain the contrasting findings to those of Rogowsky et al. (2016). However, individual interest in the topic of the story may not fully explain the present findings as the Newcomer stories are not factual or as topic-specific as medical education or World War II books.

Rogowsky et al.'s (2016) findings may be attributable to variations in the level of interest participants had in the topic, where some may have found the preface and chapter of the non-fiction novel on World War II interesting and others did not. Potential bias favouring the outcomes from the reading-only group may have been introduced into the study as the preface and chapter were read at a pace of 149 words per minute in the audio and dual-modality conditions. This pace is generally much slower than the average adult reading speed of around 200 – 300 words per minute. It should also be noted that while participants in the dual-modality condition were listening to the story being read to them at 149 words per minute, the corresponding e-text was automatically highlighted on a digital screen at the same speed from which they read the story. The slow speed may have introduced a level of frustration in some, interfering with the ability to pay attention to or follow the story.

Despite having controlled for hearing and reading proficiency as best as possible in the pre-screening, it is plausible that participants in the current study may have experienced similar frustrations or distractions. Considering that participants were allocated 180 seconds to read and memorize the story of Lucy Carson, I anticipated that each participant would be able to read through the story an average of four times, at the average reading pace of 200 – 300 words per minute. Based on this assumption the audio version of the Adam Jones story was also presented at a total of four times over 180 seconds, resulting in a presentation pace of 180 words per minute. Considering that not all participants provided explicit feedback on the pace of the audio story as much as how many times they were able to read through the Lucy Carson story, it is possible that some participants found the pace with which the Adam Jones story was read to them to be too fast compared to the pace of Rogowsky et al. (2016). This may have contributed to participants feeling frustrated or distracted from the task. It might also be possible that some participants managed to read through Lucy Carson's story only twice, while others managed to read through it five times.

Rogowsky et al. (2016) tested recall related to comprehension and retention by comparing recall performance across different presentation formats using 3 184 words relating to World War II. Deniz et al. (2022) examined the recall of semantic information acquired through listening versus reading using 10 – 15 minutes of recorded or transcribed autobiographical content. Both Rogowsky et al. (2016) and Deniz et al. (2022) used longer and more complex stories as the testing material than what was used in the present study, highlighting the potential influence of the testing material itself when investigating the effectiveness of the presentation format. However, since the Newcomer stories used in this study were describing experiences and were not factual or topic-specific, I am of the view that both the Adam Jones and Lucy Carson stories taken from the Newcomer story series were more appropriate as testing material than that used in Deniz et al.'s (2022), Kelly et al. (2022), Obleser & Kayser (2019), and Rogowsky et al.'s (2016) studies.

To effectively control for this type of potential bias or variance, future research may consider designing the experiment based on repetitions, instructing participants only to move on to the next phase of the testing sequence once they had read the story a specified number of times, rather than have the sequence time-locked. Future research might consider using longer versions and slightly more complex story-driven material, yet similar to the Newcomer story series in topic, to investigate the potential effects of presentation format on recall performance.

Although Rogowsky et al. (2016) did not explicitly provide a possible explanation for their findings, the postulations of Deniz et al. (2022) offer a possible explanation for the present findings having found similar results. Deniz et al. (2022) compared brain representations of semantic information when participants listened to 11 autobiographical stories versus reading the same stories. Using fMRI to record brain activity while participants listened to or read the stories, the authors created voxelwise interactive brain maps to visualise how semantic concepts are mapped across the cortical surface for both listening and reading formats. Their findings suggest that the brain processes semantic information similarly, whether acquired through listening or reading. Deniz et al. (2022) concluded that all incoming information is somewhat universally encoded into memory. However, their study only gathered functional data from four participants across four testing conditions (single words, semantic blocks, sentences, and narratives) to base this conclusion. Given the very small sample size, it is questionable whether their findings could reliably be generalized to the broader population. It could be argued that the correlational similarities the authors found may be due to chance, and that further investigation on a larger and wider sample would be required if universal encoding is to explain the non-significant difference in the present findings.

Another possible explanation for the findings is that participants in the sample group not exposed to binaural beats may have been predominantly visual learners. Individual differences in learning style preferences were not controlled for in this study and may have influenced the effectiveness of different presentation formats of the testing material and subsequent recall thereof. Further research into the effectiveness of presentation format may consider including personal learning style preferences in the pre-screening phase when selecting a sample. Prospective participants can self-report how they prefer to learn, which might be considered a confounding or categorical variable in subsequent analyses and interpretations of gathered data.

The current results might also be explained when considering that the tests used in the present study may not be sensitive enough to detect the cognitive effects that the format in which the tasks were presented had on recall performance in the sample. Cognitively, students are high-functioning with robust training in learning through both listening to (i.e., listening to lectures and seminars) and reading information (i.e. studying from textbooks, studies, and existing research), each method playing a central role in tertiary education. Furthermore, the simplicity and length of the presented Newcomer stories in the respective testing rounds may have played a central role in failing to identify any significant difference. Since the stories of Adam Jones and Lucy Carson were short and simple, longer and more complex stories might have revealed an advantage to either presentation format.

The present study may also have lacked sufficient statistical power due to the small sample size of participants not exposed to binaural beats in this study ($n = 15$). Similar to the findings of Deniz et al. (2022), it is my opinion that generalizing no significant difference between what individuals could recall from what they had heard versus what they had read to a broader population requires caution and further enquiry.

Despite the non-significant outcome, it merits comment that the present study showed a trend towards better performance when participants were recalling the numbers and Newcomer story they had heard compared to what they read. Participants may have experienced curiosity around the digit span and Adam Jones' story while waiting to hear what comes next or what happened, leading to more attentive listening and potentially better recall. Within a larger sample size, this small difference may emerge as significant.

From a biological point of view, a plausible explanation for the observed trend in the present findings can also be found in the work of Obleser and Kayser (2019) on neural entrainment and attentional selection in the listening brain. The authors investigated how the brain synchronises neural activity with external stimuli, particularly in speech processing and auditory attention. Their research suggested that listening to and processing speech can entrain the brain of the listener, enhancing attention to the auditory stimuli. Heightened attention allows pertinent information to be identified and encoded effectively, potentially facilitating better retention and recall of the auditory content. It is thus my opinion that while participants were listening to the story of Adam Jones in an everyday situation, the external auditory input engaged the natural oscillations of the listening brain while participants were processing the speech. This engagement coupled with curiosity about the story may have heightened selective attention and facilitated the subsequent recall of details relevant to the story. However, the lack of statistical significance indicates that this effect, if present, is likely small and may require larger sample sizes or more sensitive measures to detect.

Hypothesis 2: Effect of Binaural Beats on Immediate and Delayed Recall

I hypothesized that participants exposed to High-Beta and Gamma binaural beats would demonstrate better recall in both digit span and story-based memory tasks compared to those not exposed to any binaural beats. Additionally, I anticipated that these groups would recall the auditory versions of the memory tasks better than the visual versions. This hypothesis predicted improved performance across all measured variables: digit span, target words, and story themes. For the main hypothesis to be supported, participants exposed to binaural beats needed to significantly excel in each of these tests.

Overall Findings and Main Hypothesis

The results did not support the main hypothesis. The observed differences in memory performance between the groups exposed to High-Beta and Gamma binaural beats and those not exposed to any binaural beats across all three memory tasks were not consistently significant. Contrary to expectations, the only significant finding was that participants exposed to Gamma binaural beats during both encoding and recall (GG-ER) outperformed the group not exposed to any binaural beats in recalling the visually presented digit span. Apart from this, the presentation format of the memory tasks (audio vs. visual) did not significantly influence recall performance across the testing conditions. While previous studies (Beauchene et al., 2017; Borges et al., 2023; Kennerly, 2009; Sharpe & Mahmud, 2018) indicated that binaural beat exposure can enhance certain aspects of memory, the present results are inconsistent with these findings when considering each task individually.

Effect of Binaural Beat Exposure on Recalling the Digit Span

It was anticipated that participants exposed to High-Beta and Gamma binaural beats would outperform those not exposed to binaural beats in recalling numbers from a digit span task, especially when the digit span was presented audibly. The results do not support the hypothesis. However, a significant proportion of participants exposed to Gamma binaural beats during both encoding and recall (GG-ER) remembered more digits from the visually presented digit span task compared to those not exposed to any binaural beats. Despite this, participants exposed to Gamma binaural beats did not recall more digits in sequence on average than the group not exposed to any binaural beats. The 95% Highest Posterior Density intervals for the mean differences between the testing groups included zero, indicating that while more individuals in the GG-ER group showed better recall of the digit span, the group's average performance was not significantly different.

The present results are consistent with the findings of Borges et al. (2023), in their work investigating the influence of Gamma binaural beats on memory performance and associated changes in Electroencephalography (EEG) spectral density, using a within-participant design and 30 participants. During the first round of testing, participants completed a visually presented digit span task without any binaural beat exposure. In the second round of testing, participants were exposed to Gamma binaural beats (40Hz) while completing a second visually presented digit span task. EEG recordings were taken during both testing rounds. Borges et al. (2023) found that participants remembered significantly more digits under Gamma exposure conditions, with the EEG analysis showing increased power in the Gamma frequency band during the digit span task.

Borges et al. (2023) concluded that Gamma binaural beats enhance working memory and modulate neural activity in the Gamma frequency range, which may underlie the observed memory improvements. However, the present results suggesting that Gamma binaural beat exposure had a significant influence on immediate recall when coupled with a visually presented digit span on a proportion of the group are more consistent with the findings of Engelbregt et al. (2019) and Shekar et al. (2018). Findings from these studies may also explain the findings of Borges et al. (2023).

Engelbregt et al. (2019) examined the effects of monaural and binaural beat stimulation on attention and working memory in individuals with different levels of emotionality. Using a within-participant design, 24 participants completed a Flanker attention task and a Klingberg working memory task under three conditions: white noise, 40Hz Gamma binaural beats, and 40Hz Gamma monaural beats. In the Flanker task, participants had to focus on a central target arrow while suppressing surrounding flanker arrows. The Klingberg task consisted of two series: one where participants replicated dot patterns in the same order as presented, and another where they tapped in reverse order. Engelbregt et al. (2019) noted that the speed with which participants completed the Flanker task was faster under Gamma binaural and monaural beat conditions compared to when they were completing the same task while exposed to white noise. This finding indicated that participants showed increased attention to the task while exposed to Gamma binaural beats. However, the authors did not find significant differences in the quality their participants showed on the Flanker or Klingberg tasks across the testing conditions. Engelbregt et al. (2019) concluded that monaural and binaural beats may enhance attention speed, but not working memory performance.

Shekar et al. (2018) found similar results in their work on the effects of Alpha and Gamma binaural beats on reaction times and short-term memory. Using a comparative interventional design, 40 participants completed reaction time and memory tasks in three experimental sessions on alternate days: no exposure, 10Hz Alpha binaural beats, and 40Hz Gamma binaural beats. Auditory and visual reaction times were measured by having participants press a key in response to auditory (1000Hz beep) or visual (picture) cues. Participants reacted significantly faster in both Alpha and Gamma exposure conditions compared to when they were not exposed to binaural beats. To assess memory, participants memorized number lists and identified if probe numbers were present immediately after the presentation.

Shekar et al. (2018) found that exposure to Gamma binaural beats significantly improved reaction times in both auditory and visual presentation formats. While exposure to Gamma binaural beats improved memory scores, the improvements were not significant compared to when participants were not exposed to binaural beats. Shekar et al. (2018) concluded that the significant improvement found in attention during the Gamma binaural beat exposure trial may have accounted for the memory performance differences.

Engelbregt et al. (2019) and Shekar et al. (2018) used different methods and memory tasks in their respective studies on the effect of Gamma frequency binaural beats has on attention and memory. Engelbregt et al. (2019) demonstrated improved attention processing with Gamma exposure, as evidenced by faster performance on the Flanker task. Similarly, Shekar et al. (2018) observed faster reaction times in both auditory and visual reaction tasks under Gamma binaural beat exposure testing conditions. Both Engelbregt et al. (2019) and Shekar et al. (2018) found that Gamma binaural beat exposure did not show any significant effects on working memory quality or improved memory scores. However, the authors from both studies indicated that Gamma exposure had a significant impact on attention which may explain the differences they found in memory scores in their studies.

It is noteworthy that the present results indicate a proportional improvement in working memory with Gamma binaural beats exposure when recalling visually presented numerical information, consistent with the findings of Borges et al. (2023), Engelbregt et al. (2019), and Shekar et al. (2018). All three of these studies had notably larger sample sizes than the present study and the improvement in immediate recall observed among participants in the group exposed to Gamma binaural beats is therefore unlikely to be a chance occurrence.

Taken together, the studies by Borges et al. (2023), Engelbregt et al. (2019), and Shekar et al. (2018) provide a further explanation of why more participants in the GG-ER group in the present study recalled more digits from the visually presented digit span, without the GG-ER group showing a higher average immediate recall score. Borges et al. (2023) suggested that the improved memory performance may be attributed to the enhancing effects of Gamma binaural beats on working memory and the increased neural activity in the Gamma frequency band. The present results suggest that this is unlikely since participants did not show a similar improvement when required to recall the audibly presented digit span task. It seems more plausible that the proportionate difference may be explained by the increased levels of attention observed by Engelbregt et al. (2019) and Shekar et al. (2018), and that increased levels of attention in a proportion of the GG-ER sample resulted in improved memory performance.

Taking the present findings together with the findings of Borges et al. (2023), Gamma-band neural activity might underpin encoding and recalling visually perceived numerical information. However, EEG recordings while performing an audibly presented digit span task would be needed to substantiate such a relationship. Interestingly, further findings from the present study indicate that how a series of digits are presented may not have a substantial effect on how well high-functioning individuals remember these digits when exposed to High-Beta binaural beats or no binaural beats whatsoever. Future research could investigate the relationship between Gamma binaural beats attention and memory, potentially exploring variations of tasks such as the 'reading-while-listening' paradigm used in Rogowsky et al.'s (2016) study.

Another implication of this study is the need to consider the level of cognitive functioning, learning style, and sensory regulation while learning. Since some individuals may prefer learning through listening to the lecture while others may prefer reading the lecture, teachers and lecturers may find that individuals with lower cognitive functioning may have a better recollection of the information when the class or lecture is presented in different formats that include entertaining and participative features. On the contrary, the ability of high-functioning individuals to recall information might not significantly be affected by how the information is presented. This implies that understanding the audience that any given information is intended for is central to building up flexibility and promoting retention of memory. By taking into account the ability of the individual and incorporating fun and interactive tools using multimedia, it is possible to provide conditions that will help a variety of students with different levels of cognitive abilities and learning styles to memorize information effectively.

The Effect of Binaural Beats on Recalling Target Words from the Stories

I also expected that participants exposed to High-Beta and Gamma binaural beats would recall more target words from the stories, particularly from the audibly presented story. This expectation was also a component of the main hypothesis. The results do not support this expectation. There were no significant differences in the mean amount of target words successfully recalled by participants exposed to High-Beta or Gamma binaural beats compared to those not exposed to any binaural beats. Furthermore, no proportion of the predicted posterior samples from the groups exposed to High-Beta or Gamma binaural beats did not outperformed the group not exposed to any binaural beats. The presentation format did not significantly impact target word recall. The 95% HPD intervals for mean differences between the groups in both auditory and visual versions of the memory tasks included zero, suggesting any observed differences were due to chance.

While not statistically significant, participants across the testing conditions tended to remember more target words from the auditory presentation of the Adam Jones story compared to the visual presentation of the Lucy Carson story. Contrasting this tendency, a small group of participants exposed to High-Beta binaural beats during both encoding and recall (HBG-ER) remembered more target words from the visually presented Lucy Carson story compared to the group not exposed to binaural beats. This finding is consistent with the results from Beauchene et al. (2017) in their work on the effect of binaural beats on verbal working memory and cortical activity. The authors found that participants exposed to Beta (15Hz) binaural beats demonstrated improved response accuracy in a target word recognition task over 5 minutes, increasing by 3%. This suggested a positive influence of 15Hz binaural beats on working memory performance (Beauchene et al., 2017).

One possible explanation for the present results could be found in the increase in response accuracy observed by Beauchene et al. (2017). The authors exposed participants to Beta band binaural beats for 5 minutes. The exposure time to High-Beta binaural beats in the present study may have increased the accuracy with which participants in this group were responding to the memory tasks, similar to the findings of Beauchene et al. (2017). This would explain why this difference in recall performance was only observed in the target word task and not in the digit span or story theme tasks. At the time of completing the visually presented digit span task, participants would have been exposed to High-Beta binaural beats for approximately 4 minutes. By the time they completed the target word recall task, they would have been exposed to High-Beta binaural beats for approximately 5 minutes. Despite the break between testing rounds, it might be possible that 5 minutes between the testing rounds was not enough time for the effects of the binaural beats stimulation to wear off. This would suggest that by the time participants had to recall the audibly presented story task, they would have been exposed to High-Beta binaural beats for approximately 12 minutes and mental fatigue of habituation could have affected task performance. This would suggest that the optimal exposure time to High-Beta binaural beats would be in the range of 5 – 12 minutes for it to have a significant effect on memory.

Curiously, the group exposed to High-Beta binaural beats during encoding alone did not exhibit the same tendency. This suggests that High-Beta band neural activity may underpin accurately recalling specific information such as target words encoded from a visual source, but may not necessarily underpin the encoding process. It also suggests that High-Beta band neural activity might not underpin encoding and recalling audible information. Considering this possibility and the tendency to recall audibly acquired information observed in the Gamma exposure and no exposure groups, a possible explanation could also be that all incoming information is not universally encoded as suggested by Deniz et al. (2019). Additionally, this raises questions about memory retrieval, and whether all information is similarly retrieved from memory using similar neural activity patterns.

Another possibility is that this improvement was by chance and that participants in the HBG-ER group were predominantly visual learners. This would imply that High-Beta binaural beat exposure during both encoding and recall may only improve memory performance for specific tasks for certain individuals. Future research could investigate whether exposure to High-Beta binaural beats significantly impacts delayed recall performance among individuals who prefer learning from visual sources such as books, by using variations of word-based tests and varying exposure times.

The Effect of Binaural Beats on Recalling the Story Themes

I anticipated that participants exposed to High-Beta and Gamma binaural beats would better recall the themes of the stories, especially when the story was presented audibly. The results from the analysis of thematic recall performance in this study do not support this hypothesis. There were no significant differences in theme recall between participants exposed to binaural beats and those not exposed. The presentation format did not significantly affect performance on recalling story themes. The 95% HPD intervals included zero, suggesting any observed differences were due to chance.

The present findings are consistent with the work of Kuhbandner (2020) on long-lasting verbatim memory for words of a book without the intention to learn. Considering participant performance in recalling the story themes relative to their performance in recalling target words, the results align with those of Kuhbandner (2020) suggesting that individuals store more detailed information about written text than abstracts or themes. Considering the increase in recalling target words from the story compared to the themes, particularly in the group exposed to High-Beta binaural beats in dual exposure conditions, the results expand on Kuhbandner's (2020) findings by introducing the possibility of a distinction between how much information is stored without the intention to learn when listening versus when reading.

The Effect of the Interaction between Binaural Beats and Presentation Format on Memory

The results show that the interaction between binaural beat exposure and memory task format only influenced participants' ability to recall the story theme, but this influence did not result in a significant improvement. Participants exposed to High-Beta binaural beats during encoding alone (HBG-E) performed better in recalling the story themes from the audibly presented story compared to those not exposed to binaural beats. Interestingly, participants exposed to High-Beta binaural beats during both encoding and recall (HBG-ER) showed a decrease in performance. This result was not significant, yet suggests that High-Beta binaural beats may have a positive influence on encoding abstract concepts such as story themes, but negatively affect the retrieval of thematic information. Considering that the decrease was not observed when recalling the theme from the visually presented story, this implies that exposure to High-Beta binaural beats only has a detrimental effect on recalling themes when a story is heard.

Similarly, exposure to High-Beta or Gamma binaural beats while encoding the visually presented story improved participants' ability to recall the theme after a delay, but dual exposure conditions decreased performance compared to those not exposed to binaural beats. Overall, the interaction effect between binaural beat exposure and memory task presentation format did not significantly impact immediate recall or recalling the target words after a delay. The present results are inconsistent with the findings of Deniz et al. (2019) and their work on semantic representations of information in the brain. Although the authors found that semantic information represented nearly identically on semantic brain maps regardless of how the information was acquired, the current results suggest that encoding and retrieving semantic information may be dependent on different frequency bands of neural activity.

Summary of the Findings on the Effect of High-Beta and Gamma Binaural Beats on Memory

Participant performance in recalling digits, target words, and story themes varied with binaural beat exposure and task presentation format. Except for a proportion of the group exposed to Gamma binaural beats during both encoding and recall (GG-ER) showing an improvement in recalling the visually presented digit span, no other testing condition showed significant memory performance improvements. This suggests that the effects of binaural beats on memory may be specific to frequency, presentation format, and information type. Furthermore, High-Beta and Gamma exposure during both encoding and recall with visual presentation decreased theme recall, indicating potential interference with the retrieval process of semantic information such as story themes. These results were not significant, but further research could investigate whether binaural beat exposure decreases the ability to recall abstract story-based representations, and if this interference stems from a mismatch between external stimuli and internal brain activity during cognitive processes.

The varied results from the digit span and story-based tasks may be further explained by previous research on brain oscillations and their role in the perception and memory processes. Başar et al. (2000) proposed that different cognitive processes involved in perception and memory are supported by distinct patterns of neural oscillations in the brain. The work of Başar et al. (2000) highlighted the significance of neural activity in Alpha, Theta, Delta, and Gamma frequency bands in sensory and cognitive functions. The authors suggested that these oscillatory systems act as resonant communication networks within the brain that directly influence memory and integrative functions. The 'neurons-brain' doctrine proposed by Başar et al. (2000) suggests that brain oscillations are integral to information processing and reflect the dynamic interactions between neurons in the brain.

The adaptability of neural activity based on the cognitive demands of the task at hand is emphasised in the study by Herweg et al. (2020) on Theta oscillations in human memory. This aligns with the 'neurons-brain' doctrine proposed by Başar et al. (2000) suggesting that different cognitive processes involved in perception and memory are supported by distinct patterns of neural activity in the brain. The ability to be adaptable in selecting and using neural activity in various frequency bands may underlie the brain's ability to optimize functioning for different perception and memory processes.

Furthermore, Buzsáki's (2006) work on neural activity in the brain emphasises the dynamic and state-dependent nature of brain function. Buzsáki (2006) proposed that ongoing neural activity shapes both perceptual experiences and the organization of memories in space and time. This implies that the brain does not passively process sensory information, but rather that the brain actively constructs perceptions based on its current state and that this construction is modulated by neural activity at the time. The author concluded that since one individual can experience the same sensory input in different ways, such as reading a text message when one is depressed compared to when one is happy, how the input is initially perceived may be dependent on the predominant neural activity patterns at the time of perception.

The interplay between these theoretical frameworks suggests that the brain dynamically utilises different neural activity patterns for distinct functions, working interchangeably based on task demands. For example, encoding and retrieving numerical information may involve Gamma frequency activity, as shown in the results. In contrast, encoding and storing specific words or central ideas from a storybook could be associated with High-Beta activity, while recalling that information may involve Gamma activity. Adaptability in using various frequencies may underlie the brain's ability to optimize functioning for different perception and memory processes. This suggests that the brain engages distinct neural activity patterns for processing, encoding, storing, and retrieving different types of information, depending on how the information was acquired.

The ability to adapt neural activity to a given task could explain the varied findings in the present study. External stimulation through binaural beats may affect the brain’s ability to adapt and engage the optimal neural activity that facilitates distinct perception and memory processes. Taken together, it is plausible that early-stage perception of the combination of how information is presented to the perceiver (audibly or visually) and what type of input needs to be processed (i.e., numerical, linguistic, or semantic) informs the brain of which range of neural activity is best suited to encode and retain this information. This opinion is based on the Encoding Specificity Principle by

Tulving and Thomson (1973) and combined works by Pérez-Bellido et al. (2023) on the impact of sound in early perception stages and Obleser and Kayser (2019) on neural entrainment in the listening brain.

The Encoding Specificity Principle (Tulving & Thomson, 1973) states that memory retrieval is most effective when the information available at the time of retrieval (the retrieval cue) is identical to or highly similar to the information encoded with the memory trace at the time of storage. Contextual information, both external (e.g. physical environment) and internal (e.g. mental state), is encoded alongside memories and can serve as retrieval cues. Semantically related retrieval cues are not always effective if not present during encoding, even if strongly associated with the target memory. Recalling from memory is enhanced when encoding and retrieval contexts match, such as studying and taking an exam in the same room. This aligns with the postulations of Buzsáki (2006) on how the brain actively constructs perceptions and memories.

Using magnetoencephalography (MEG) recordings of 24 participants, Pérez-Bellido et al. (2023) compared the neural responses to visual stimuli presented alone versus when accompanied by 1000Hz pure tone sounds delivered binaurally. The authors found that sounds modulate visual processing in two distinct ways: (1) by enhancing the decoding of visual targets across the perceptual hierarchy, primarily by improving maintenance over time of post-perceptual representations, and (2) by automatically driving activity patterns in the visual cortex in a bottom-up fashion. Interestingly, the authors also suggested that sound-induced enhancement of visual information maintenance in short-term memory is highly dependent on stimulus relevance and likely mediated via top-down attentional mechanisms. These findings support the Encoding Specificity Principle (Tulving & Thomson, 1973), the postulations by Buzsáki (2006) on how the brain constructs perceptions, and Herweg et al.'s (2020) proposed adaptability of neural oscillations based on the cognitive demands of the task at hand.

If memory is to be considered as fundamentally contextual by nature (Tulving & Thomson, 1973), it is plausible that mediation by similar top-down attentional mechanisms at early-stage perception as suggested by Pérez-Bellido et al. (2023) serves to determine the nature of incoming stimuli (numerical, linguistic, or thematic). Once the nature of the incoming stimuli is determined, a cognitive regulatory system such as the "neurons-brain" doctrine suggested by Başar et al. (2000) initiates the distinct patterns of neural activity in the brain optimized for decoding the incoming stimuli based on the task at hand, as proposed by Herweg et al. (2020). After the information is decoded, the ongoing neural activity is reassessed by the dynamic and state-dependent nature of brain function (Buzsáki, 2006) to shape the perceptual experience and organize the encoding of the incoming information into memory. Lastly, the success of retrieving the encoded memory is then determined by how well the brain state, underlying neural activity, and information available at the time of retrieval match the constructed perception of the information encoded with the memory trace at the time of encoding.

It is my opinion that this sequence of events can be influenced by neural entrainment as suggested by Obleser and Kayser (2019), and that neural entrainment through binaural beats facilitates the process from early stage perception to retention in memory. This suggests that an individual's memory performance may depend on how effectively the incoming information is initially identified, matched with the appropriate neural activity to support its decoding and construction of state-dependent perception, and subsequently encoded into memory processes.

However, similar to the study of Sharpe and Mahmud (2020), the present findings may not generalize effectively to the broader population due to the small sample size. Paradoxically, in studies with small samples that yield significant results, like Sharpe and Mahmud (2020), there is an increased risk of false positives or Type I errors due to the consistent threshold for significance regardless of sample size. As in the study by Sharpe and Mahmud (2020), the findings from the present study could have been a chance occurrence, particularly if learning style preferences and habituation effects were not adequately addressed throughout the study.

The studies from Beauchene et al. (2019) and Kennerly (2009) on the effect of Beta frequency binaural beats used 25 participants in their respective experiments. Engelbregt et al. (2019) used 50 participants, while both Borges et al. (2023) and Shekar et al. (2018) examined the effects of Gamma binaural beats on memory with 40 participants. In contrast, the present study only utilised 15 participants per experimental group. It is plausible that each group was too small to capture the differences between the High-Beta, Gamma, and No exposure groups in the auditory and visually presented memory tasks. A larger number of participants per group (25 – 40) would provide a wider distribution and variance in the data, potentially allowing the small differences presently observed to reach statistical significance.

Another possible reason why the present study did not find any significant differences in recall performance between the testing groups could be the simplicity of the memory tasks. The digit span and story recall tasks may not have been sufficiently challenging for the sample consisting of psychology students who are likely cognitively high-functioning. For instance, the digit span task only involved sequences of seven digits, presented visually in the first round and auditorily in the second round. Performance was measured by the maximum number of digits recalled correctly. The story recall tasks required participants to read the Lucy Carson story and listen to the Adam Jones story, and their performance was assessed by the number of target words used verbatim in their recollection and whether the overall theme was captured.

However, both stories were short with simple narratives about a lost girl and a man having a sale at his store. In contrast, previous studies that found significant effects of binaural beats on memory used tasks that progressively increased in difficulty over multiple rounds of testing. For example, Beauchene et al. (2017) used a digit span task with sequences of varying lengths across five testing rounds. Shekar et al. (2018) also presented participants with progressively longer lists of numbers to memorize. Both studies required that participants complete the memory tasks under no exposure and exposure to two experimental conditions.

Hypothesis 3: Effect of Binaural Beat Exposure Timing on Memory

I hypothesized that participants exposed to High-Beta and Gamma binaural beats during both encoding and recall (dual exposure groups) would show a significant improvement in performance on both immediate and delayed recall tasks compared to those exposed only during encoding (single exposure) and those not exposed to any binaural beats. This hypothesis would be supported if participants in the groups exposed to High-Beta and Gamma binaural beats during both encoding and recall demonstrated significantly better performance across all memory tasks (digit span, target words, and story themes) relative to those exposed only during encoding and those not exposed to any binaural beats, irrespective of the presentation format of the memory tasks. The results do not support this hypothesis.

On the contrary, the results showed that dual exposure to High-Beta binaural beats during both encoding and recall had a significant negative impact on recalling story themes after a delay. Contrary to expectations, the lower mean difference and estimated marginal mean associated with the HBG-ER group suggest that dual exposure to High-Beta binaural beats may have had a detrimental effect on recalling broader thematic information. Furthermore, the HBG-ER group had a very high predicted probability of High-Beta binaural beats exposure influencing their performance in approximately a third of the sample, although their actual performance was quite poor with only 2% outperforming the group not exposed to any binaural beats. This suggests that sustaining exposure to High-Beta binaural beats during recall may have had a detrimental effect on participants' ability to effectively recall thematic information.

The findings did not show any further significant differences in performance on the digit span and target word recall tasks between the group exposed to High-Beta binaural beats during both encoding and recall relative to the group not exposed to any binaural beats. The group exposed to Gamma binaural beats during encoding and recall (GG-ER) did not demonstrate significant improvements in the digit span or story-based memory tasks compared to those exposed to Gamma binaural beats during encoding only and those not exposed to any binaural beats. The 95% Highest Posterior Density (HPD) intervals included zero, suggesting the observed differences were likely due to chance.

The results also show that participants in the group exposed to High-Beta binaural beats during encoding only demonstrated lower emmeans for the digit span, target words, and themes compared to participants not exposed to any binaural beats. However, these differences do not suggest a negative effect on memory performance. The differences were much less pronounced when compared to the differences observed between participants exposed to High-Beta binaural beats during both encoding and recall relative to those not exposed to any binaural beats. This suggests that while exposure to High-Beta binaural beats during encoding only had a minor negative effect on memory performance, the more significant detrimental effect was observed when participants were exposed to High-Beta binaural beats during both encoding and recall. This suggests that the additional exposure during recall, rather than encoding, was the primary factor contributing to the decreased memory performance.

Additionally, the results showed varied outcomes between those exposed to binaural beats compared to those not exposed to any binaural beats, and between those exposed during both encoding and recall compared to those exposed during encoding only. For instance, participants in the group exposed to Gamma binaural beats during both encoding and recall exhibited differences in recall performance compared to the group not exposed to any binaural beats, with higher estimated marginal means (emmeans) for the digit span and lower emmeans for the target words and themes. However, none of these differences were statistically significant. The overlapping 95% highest posterior density (HPD) intervals suggest the group exposed to Gamma binaural beats during encoding and recall did not meaningfully outperform or underperform the group not exposed to any binaural beats on any of the memory tasks.

While binaural beat research has focused on effects on attention and memory, few studies have specifically examined the effect binaural beat exposure has on encoding semantic representations or recalling story themes. However, Gola et al. (2013) investigated the relationship between EEG Beta band activity and attention in elderly adults compared to young adults. They recruited 20 young participants (ages 18-30) and 20 elderly participants (over 60) to complete a visual attention task while their EEG was recorded. The task required detecting a target stimulus that appeared 3-11 seconds after a cue stimulus, while behavioural performance and EEG beta power were analysed throughout the task.

The results from Gola et al.'s (2013) study showed that increases in Beta power over occipital regions preceded correct responses in both young participants and high-performing elderly participants. The authors proposed that Beta activity is linked to attentional processes. However, a subgroup of low-performing elderly participants exhibited decreases in Beta power during the most challenging attentional conditions. The researchers interpreted this Beta power decrease as reflecting difficulties in activating and sustaining attention in the low-performing group. Gola et al. (2013) proposed that the Beta power decrease observed in low-performing elderly participants reflected an inability to effectively engage attentional resources, leading to poorer task performance. The present results are not necessarily consistent with the findings of Gola et al. (2013) but expand on them.

Findings from the present study are also inconsistent with those of Deniz et al. (2022). The authors suggested universal encoding of semantic information independent of the presentation format of the information, based on their finding that the brain represents semantic concepts similarly during listening and reading tasks. Using voxelwise modelling, the researchers determined that brain regions involved in semantic processing were largely consistent across presentation formats. Deniz et al. (2022) suggested that the brain's ability to process semantic information is not limited to a specific sensory modality but can be applied across different presentation formats as a general cognitive capacity. Finding that exposure to High-Beta binaural beats during encoding and recall (HBG-ER) showed a significant decrease in the present study contrasts the proposals of Deniz et al. (2019) since the significant decrease was not observed in the group exposed to High-Beta binaural beats during encoding only. Acknowledging that Deniz et al. (2019) may have been referring to the building blocks of memories rather than the mechanics of memory encoding in their postulation of universal encoding, the present study shows that the underlying mechanisms facilitating memory encoding are not universal.

The present results are more aligned with the findings of Derner et al. (2018) and their work on modulating item and source memory through ABS. Derner et al. (2018) demonstrated that binaural and monaural beat stimulation have differential effects on long-term memory, with binaural beats enhancing and monaural beats impairing memory. Using an associative learning task with presurgical epilepsy patients who had implanted depth electrodes, the researchers found that both monaural and binaural beat stimulation were associated with increased phase locking of 5 Hz oscillations within the rhinal cortex, but with opposite phase shifts. These findings indicate that the behavioural effects of auditory beat stimulation on memory are related to modulations of neural activity, specifically phase-locking patterns, within the medial temporal lobe. Concerning the present study, exposure to High-Beta binaural beats during the process of memory retrieval may have similar opposing phase-locking effects as Derner et al. (2018) observed with monaural stimulation, resulting in decreased memory performance.

The present results are also consistent with the findings of Shekar et al. (2018), in their work on the effects of Alpha and Gamma binaural beats on reaction times and short-term memory. Shekar et al. (2018) found that exposure to Gamma-frequency binaural beats significantly improved reaction times in both auditory and visual tasks, indicating enhanced attention. However, while Gamma binaural beat exposure also improved memory scores, the memory improvements were not statistically significant compared to when participants completed the memory tasks while not exposed to any binaural beats. The authors concluded that the significant attentional benefits observed during Gamma binaural beat exposure may account for the memory performance improvements, even though the memory gains did not reach statistical significance.

In the context of this study, encoding both explicit and abstract information relating to these stories would require attention to story elements and events as the story progresses. Recalling story themes after a delay would require accessing and reconstructing the encoded information about key elements and events. This involves binding the explicit and abstract information into contextually related sequences and integrating it into an overall understanding of the story's underlying message. Considering these requirements, a plausible explanation for the significant decrease in recalling story themes after a delay among participants exposed to High-Beta binaural beats during both encoding and recall can be found in the combined works of Gola et al. (2013) and Shekar et al. (2018).

Acknowledging that Gola et al. (2013) measured Beta band activity during a detection task, the results from the present study showed that increasing Beta band power while recalling thematic information had a significantly negative effect in young adults who are cognitively high-functioning.

This would suggest that overstimulating Beta band activity in young adults has a detrimental effect on memory retrieval that may be attributable to similar difficulties in effectively engaging attentional resources. Although the present study did not investigate the effect that High-Beta or Gamma binaural beats may have on attention, the present results show a significant decrease in recall performance among participants exposed to High-Beta binaural beats during both the encoding and recall of a semantic memory task involving story themes. Two plausible hypotheses grounded in the existing literature on the relationship between Beta-band brain activity, attention, and memory might explain these inconsistencies with previous findings.

First, Shekar et al. (2018) proposed that improved memory performance may be attributable to increased attention resulting from binaural beat entrainment. Beta-frequency binaural beats have been linked to increased attention in existing literature (Beauchene et al., 2017; Borges et al., 2023). In my opinion, it is plausible that over-stimulation of Beta-band neural activity may have a detrimental effect on the ability to either encode and retrieve thematic or semantic information. This is based on the findings of Gola et al. (2013), who demonstrated that decreased beta-band activity leads to attentional challenges in elderly individuals. Therefore, an increase in Beta activity induced by external factors (i.e. binaural beat exposure) may have similar detrimental effects on attention in high-performing individuals, similar to the effects of a natural decrease in Beta-band activity observed in older adults (Gola et al., 2013). Furthermore, this decrease in attention may subsequently impair the memory process, as Shekar et al. (2018) suggested that increased attention leads to improved memory performance.

Second, the decreased performance levels of the group exposed to High-Beta binaural beats during both encoding and recall were also observed in the digit span and target words tasks. Although the results from the digit span and target word tasks were not significant, taken together this suggests an alternative explanation that entraining High-Beta activity specifically during recall may interfere with the process of retrieving information. This notion is supported by the finding that participants exposed to the same High-Beta binaural beat frequency during encoding only did not show any significant difference in recall performance compared to those not exposed to binaural beats in both the digit span and story-based memory tasks. Considering these results alongside the work of Buzsáki (2006), this further supports the implication that the encoding and recall processes may be facilitated by neural activity within different frequency bands. As with the potential relationship between Gamma binaural beats and immediate recall, the potential for High-Beta binaural beats to interfere with recall could further be investigated.

Another plausible explanation for the varied, non-significant findings may lie in the contrasting proposals of Deniz et al. (2022) and Derner et al. (2018). Taken together with the present results showing differential effects of binaural beats on each memory task, it is plausible that different modulations of neural activity and phase-locking patterns within the rhinal cortex and medial temporal lobe (Derner et al., 2018) may underpin the encoding of numerical, linguistic, and thematic information. This suggests that incoming information may not be universally encoded into memory but is likely dependent on various frequency bands of neuronal activity within the brain, determined by the context and type of incoming information. The variations in the present study's non-significant findings across digit span and story-based recall tasks may suggest that these different types of information are processed and encoded differently based on the specific frequency bands stimulated by the binaural beats.

In summary, the present study underscores the importance of additional research examining the relationship between High-Beta binaural beats and memory, and how exposure to these frequencies influences recalling declarative information versus semantic information.

Hypothesis 4: The Effect of High-Beta Binaural Beats vs. the Effect of Gamma Binaural Beats on Declarative Memory

I hypothesised that, relative to those not exposed to any binaural beats, participants exposed to High-Beta binaural beats recall less declarative information from both the digit span and story-based memory tasks overall compared to those exposed to Gamma binaural beats. I also anticipated that this difference would be more pronounced in the overall recall scores obtained from the audibly presented versions of the memory tasks relative to those visually presented. For this hypothesis to be supported, participants exposed to Gamma binaural beats would have had to show a significant improvement in both the auditory and visually presented memory tasks, significantly greater than the improvement shown by participants exposed to High-Beta binaural beats, relative to participants not exposed to any binaural beats. The results partially support this hypothesis.

The significant difference in the estimated marginal means between the testing groups indicates that exposure to Gamma binaural beats resulted in improved overall recall of the audibly presented memory tasks compared to exposure to High-Beta binaural beats. This suggests that Gamma binaural beat exposure improved declarative memory by a greater margin than High-Beta binaural beat exposure did when participants were recalling declarative information from the digit span and story they had listened to. However, the Gamma group did not show a significant improvement in overall recall performance when the digit span and story-based memory tasks were visually presented relative to the group not exposed. In contrast, the High-Beta group did not show a significant difference in emmeans compared to the group not exposed to any binaural beats, nor between auditory and visual presentation formats.

Although this finding partially supports the notion that the benefits of Gamma binaural beats might exceed those of High-Beta binaural beats on declarative memory (Garcia-Agribay et al., 2019a, 2019b; Jurvanen, 2020; Sharpe & Mahmud, 2020; Shekar et al., 2018), it also suggests that Gamma binaural beat exposure would only be more effective when individuals are exposed while listening to information. Despite the results suggesting that the improvement is dependent on the format in which the task is presented, the present results are consistent with the findings of the works of Shekar et al. (2018) on the effects of Gamma binaural beats on attention and short-term memory, Obleser and Kayser (2019) on attentional selection in the listening brain, and Weger et al. (2014) on active listening.

Shekar et al. (2018) investigated the effects of Gamma binaural beats on auditory reaction time, visual reaction time, and short-term memory. Forty participants were assessed in three sessions: without any intervention, with Alpha binaural beats (10 Hz), and with Gamma binaural beats (40 Hz). The authors found that Gamma binaural beats significantly improved attention, as measured by decreased reaction times, but did not have a statistically significant effect on short-term memory performance. Although memory scores improved after exposure to Gamma binaural beats, the results were not statistically significant. Shekar et al. (2018) concluded that entrainment through Gamma band binaural beats can enhance attention and that this increase could explain the observed improvement in memory performance. In the present study, an increase in attention may have been the result of the combination of Gamma frequency entrainment and auditory presentation of the memory tasks, allowing for increased selective attention as proposed by Obleser and Kayser (2019).

The work of Obleser and Kayser (2019) on the neural mechanisms underlying attentional selection in the listening brain concluded that neural entrainment is a crucial mechanism that enables the brain to selectively attend to specific sounds, enhancing the representation of those sounds held in memory. Obleser and Kayser (2019) linked the ability to selectively attend to specific sounds to memory formation and retrieval, emphasising its importance in effective communication and comprehension of auditory input. In line with the findings of Engelbregt et al. (2019) and Shekar et al. (2018), exposure to Gamma binaural beats may have improved the ability to selectively attend to the audibly presented digit span and story, as proposed by Obleser and Kayser (2019), and may have resulted in a form of unintentional active listening, as proposed by Weger et al. (2014).

Weger et al. (2014) investigated the role of active listening in initial social interactions by comparing participants' ability to actively listen while receiving unsolicited advice, listening to another participant then giving advice, and simple acknowledgements in conversation. Weger et al.'s (2014) work did not directly link increased attention to active listening or memory, although the authors discuss the importance of attention in active listening. Weger et al. (2014) concluded that active listening is facilitated by attentive engagement, leading to an individual having a better understanding of the conveyed message during the testing rounds. By implication, this would suggest that participants in Weger et al.'s (2014) experiment would have engaged memory processes, such as working memory, to keep track of the conversation and be able to manipulate this information to form their opinions and give advice. If the quality with which participants were listening to each other was influenced by how much attention was paid to the conversation, this would suggest that the mental representation of this conversation was impacted by the listener's ability to selectively attend to what was being said, which affected how well the conversation was held in memory (Obleser & Kayser, 2019).

Taken together, it is plausible that exposing participants to Gamma beats may have affected participant attention (Shekar et al., 2018), entraining neural activity to an improved level of selective attention (Obleser & Kayser, 2019), which resulted in unintentional active listening (Weger et al., 2014) to the audibly presented memory tasks. This combination of entrainment and active listening may have facilitated the formation and retrieval of the auditory stimuli (digit span and story details), resulting in the observed difference in overall recall performance across both tasks. This suggests that Gamma binaural beats did not necessarily improve the memory process directly, but rather improved the underlying cognitive mechanisms responsible for processing incoming auditory information. This would be consistent with the findings of Shekar et al. (2018) on the effect of Gamma binaural beats on memory.

Having found no significant difference between the recall performance of the group exposed to High-Beta binaural beats compared to those exposed to Gamma binaural beats in recalling the visually presented memory tasks in the study may be attributed to several practical reasons and potential confounding variables. One key factor could be individual differences in cognitive abilities among participants, such as variations in working memory capacity, attention span, and learning styles. These individual differences may have influenced recall performance regardless of binaural beats exposure, potentially masking any significant effects of the intervention.

Considering that the sample of the current study consisted of psychology students, participants may have been familiar with the specific memory tasks used in the study, what was being tested and what to expect from the tasks. Any prior knowledge of or experience with a digit span or story-based task could have affected their motivation in attending to the tasks and influenced their overall performance. These potential differences in motivation levels and engagement with the memory tasks used in this study may have affected their performance, regardless of the binaural beats exposure. Given the consistency of the academic responsibilities associated with being a student such as lectures, assignments, and exams, factors such as fatigue, boredom, or distractions during the study could also have influenced the results.

Lastly, individual differences in sensory processing abilities among the participants may have also contributed to the non-significant findings. Some individuals may have had greater ease in processing and encoding auditory information, while others may have excelled at visual processing - factors that could have influenced their performance on the respective memory tasks regardless of binaural beat exposure. Differences in the ability to process and encode auditory information could have affected performance on the auditory memory tasks, while variations in visual processing abilities may have influenced performance on the visual memory tasks. Factors such as undisclosed hearing or visual impairments, background noise and volume, lighting conditions, or individual differences in sensory processing could have played a role. These practical reasons and confounding variables could have introduced additional sources of variability, reducing the statistical power to detect significant differences between the binaural beats exposure groups and the no exposure condition.

Chapter 6: Conclusion

In this study, I aimed to investigate the effects of High-Beta and Gamma frequency range binaural beats on immediate and delayed recall performance. I aimed to directly compare the effect of High-Beta and Gamma binaural beats on memory to determine if these frequency bands had differential effects on immediate and delayed recall, and if so which was more effective in improving memory performance. I further aimed to examine the effect that timing of exposure (during encoding alone versus during both encoding and recall) had on memory performance and whether the presentation format of the memory tasks (auditory versus visual) influenced participants' ability to recall declarative information. Collectively, this study was aimed at investigating if different combinations of binaural frequency, timing of exposure, and presentation format of the memory tasks impacted memory performance differently.

First, I hypothesised that participants not exposed to binaural beats would perform significantly better on auditory memory tasks compared to visual memory tasks. The investigation into the effect the presentation format of the memory tasks had on memory performance under participants not exposed to any binaural beats showed no significant difference in overall recall performance across presentation formats. Contrary to expectations, the presentation format (audio vs. visual) did not significantly affect participant performance in the digit span and story tasks. The results indicate that the format in which tasks were presented did not have a significant effect on recall performance under participants not exposed to any binaural beats.

Second, I hypothesised that participants exposed to High-Beta and Gamma binaural beats were expected to demonstrate significantly improved immediate and delayed recall performance on the digit span and story-based memory tasks compared to those not exposed to any binaural beats, with more pronounced improvements in auditory memory tasks. The investigation into the effect of High-Beta and Gamma binaural beats on immediate and delayed recall respectively, did not consistently support this expectation. Contrary to expectations, only a significant proportion of the group exposed to Gamma binaural beats during both encoding and recall demonstrated improved recall performance compared to those not exposed to any binaural beats in recalling the visually presented digit span and not in the audibly presented digit span task. However, there were no significant differences in the average memory performance between the groups exposed to High-Beta and Gamma binaural beats and those not exposed to any binaural beats in the story-based target word and theme recall memory tasks.

Third, I hypothesised that timing the exposure to High-Beta and Gamma binaural beats during both encoding and recall would significantly improve immediate and delayed recall performance on memory tasks compared to exposing participants only during encoding and those not exposed to any binaural beats. I expected that this improvement would be significant regardless of the format the memory tasks were presented in. This hypothesised improvement did not find support in the results. However, the investigation found that exposure to High-Beta binaural beats during both encoding and recall significantly decreased participants in this group's ability to recall the story themes after a delay. Since this decrease was not observed in the group exposed to High-Beta binaural beats during encoding alone, this suggests that exposure to High-Beta binaural beats might have had a detrimental effect on recalling semantic information.

Lastly, I hypothesised that the improvement in recall performance relative to those not exposed to any binaural beats would be more pronounced for those exposed to Gamma binaural beats compared to High-Beta binaural beats, and this difference would be greater for auditorily presented memory tasks. The results partially support this hypothesis, indicating that participants exposed to Gamma binaural beats outperformed the High-Beta group in recalling the audibly presented memory tasks. However, the Gamma group did not show a significant improvement in overall recall performance when the digit span and story-based memory tasks were visually presented compared to the High-Beta exposure group.

The findings from this study suggest that numerical, linguistic, and thematic information may not be universally encoded into memory. Rather, processing and encoding different types of information may require neural activity from different frequency bands depending on whether the information is acquired auditorily or visually. It might also be that how well the information is retrieved may be dependent on how well the retrieval cues and external factors match with those while encoding occurred.

To my knowledge, this is one of few studies to investigate how exposure to binaural beats affects the encoding and retrieval processes respectively. While exposure to Gamma binaural beats during both encoding and recall may have a greater effect on declarative memory, exposure to High-Beta binaural beats during both encoding and recall may have detrimental effects on semantic memory. Further findings on how High-Beta and Gamma binaural beats impacted immediate recall and delayed recall as separate processes may have significant implications in developing novel therapeutic interventions for various memory-related conditions since the potential of binaural beats to enhance working memory and interfere with recalling semantic memories could be used in practice in the fields of Behavioural Psychology, Cognitive Psychology, and Cognitive Neuroscience.

For instance, patients with post-traumatic stress disorder (PTSD) often experience intrusive memories, flashbacks, and nightmares related to a traumatic event. Since exposure to High-Beta binaural beats was shown to have the potential to interfere with the ability to recall semantic information, exposure sessions to stimulate neural activity in the High-Beta frequency band could be incorporated into treating PTSD. Further research could investigate if this effect is specific to semantic memory, and if suppression can reliably be replicated in varying circumstances. Should further research provide evidence that targeted exposure to High-Beta binaural beats selectively suppresses recalling the semantic aspects of intrusive memories, this could be used as a portable therapeutic tool to reduce the intensity and vividness of flashbacks as they occur.

Findings from this study also have potential benefits in the research and development of treatment programs for patients with Alzheimer’s Disease. Given that memory impairment is a hallmark symptom of Alzheimer's, using Gamma binaural beats as a potential therapeutic tool to improve working memory could significantly enhance the quality of life for those affected by the disorder and their caregivers. If the results from the present study can be replicated and tested for reliability, further research into the effects of Gamma binaural beats on cognitive function in Alzheimer's disease is warranted. If found effective, this non-pharmacological intervention may help slow down the progression of memory-related impairments associated with the disease. Importantly, binaural beats are readily available and much more affordable than pharmacological products, potentially allowing for widespread application if proven beneficial.

Limitations of this Study

The present study has several limitations that should be considered when interpreting the results. First, the present study sample size was limited and relied on self-reported measures of individual factors such as variations in hearing and reading abilities. The small sample size may have had a considerable effect on the generalizability of the findings, while self-reporting individual abilities may have introduced biases that were not controlled for in the study design. Factors such as undisclosed hearing or visual impairments, background noise and volume, lighting conditions, or individual differences in sensory processing could have directly influenced the results.

A second limitation concerns the simplicity of the tasks, which may not have been engaging enough to capture the full range of cognitive abilities of the sample. The tasks used in the current study were relatively simple and may not have been challenging enough to engage the full range of cognitive abilities of the participants included in the sample. This is particularly relevant given that the sample consisted of students who are likely cognitively high-functioning and able to complete the memory tasks included in this study with ease.

A third limitation involves the testing procedure, where participant performance was measured through one round of testing for the visually presented tasks and one for the audibly presented memory tasks. The use of repeated measures would have been beneficial in assessing any potential differences in individual performance under all three testing conditions; no exposure, High-Beta exposure, and Gamma exposure.

The lack of a direct measure of attention is an important limitation of the present study. Although a sequential digit span task can be used in combination with distractions to assess attention, the digit span task used in this study was designed specifically to assess working memory performance rather than attentional processes. While the digit span task can be operationalized to provide a measure of attention by introducing distractors or requiring sustained focus over a longer duration, the present study did not utilize this approach. An attentional task would typically involve instructing participants to focus on the digit sequence while ignoring irrelevant information, with the primary measure being the accuracy and speed of recall alongside secondary measures of attentional control and cognitive load. The lack of such an attentional measure in the current study design limits the ability to determine if any observed changes in memory performance were mediated by changes in attention. Previous research has shown that Gamma band binaural beats can enhance attention and working memory. If the current study had included an additional digit span task with distractions as a measure of attention, such as a dual attention task or a measure of attentional focus, it could have provided valuable insights into whether improved attention under the High-Beta and Gamma binaural beat exposure conditions were associated with better memory performance.

Lastly, the study lacked measures to track neural activity such as EEG or alternative imaging measures. The ability to record neural activity throughout both testing rounds could have provided valuable insights into the neural activity underlying memory processes. EEG recordings could have offered a more direct assessment of the brain's response to binaural beat stimulation and potentially confirmed if entrainment was achieved in the allocated timeframes of exposure.

Future Research Directions

Future research should explore whether binaural beat exposure during specific memory processes, such as retrieval, leads to interference effects rather than improvements. The encoding specificity principle suggests that the contextual combination of information presentation informs the necessary neural activity for memory retention. Neural entrainment through binaural beats may facilitate this process, indicating that memory performance relies on initial information identification and appropriate neural activity for encoding and retention.

Employing larger sample sizes (25-40 participants per group) and more complex tasks can provide a wider distribution of data, potentially allowing small differences to reach statistical significance. Future studies should incorporate repeated measures, increase task difficulty progressively, and consider using challenging stimuli to investigate binaural beat effects on memory. Employing a within-participant design with repeated measures that include a measure for attention, and considering signal detection measures could enhance methodological rigour.

Longitudinal studies into the effects of binaural beats exposure on memory recall sustainability and persistence is suggested. In terms of experimental design, including larger and more diverse samples, EEG measures, more complex or challenging tasks, repeated measures, and accounting for individual factors, can enhance the current understanding of the impact binaural beats can have on cognitive processes such as memory performance. By addressing the limitations of the present study and expanding on the current research with the proposed future research directions, the positive and negative effects of binaural beat exposure can be identified and with this, bring the practical application of binaural beats as a therapeutic tool into practice and have targeted non-pharmacological interventions included in treatment programs.

Concluding Statement and Significance

In this study I comparatively investigated how binaural beats in the High-Beta and Gamma bands impact immediate and delayed recall performance as separate memory processes, emphasizing that exposure to binaural beats may have different effects on encoding and recall. The efficacy of these effects may be dependent on more than just the frequency band. From the results, I concluded that exposure to Gamma binaural beats may improve an individual’s ability to immediately recall visually presented numerical information, while exposure to High-Beta binaural beats may significantly affect an individual’s ability to recall semantic information such as themes. With targeted application, both Gamma and High-Beta binaural beats can be incorporated into treatment programs for mental challenges that currently require constant supervision. Binaural beats have the potential to go beyond improving cognitive functions and modulating neural activity through entrainment may provide a solution to conditions where overstimulation can be moderated. The varying effects that High-Beta and Gamma binaural beats could have by targeting exposure to specific cognitive processes could have significant implications for the development of optimal protocols for binaural beat stimulation in various fields, including Cognitive Behavioural Psychology, Cognitive Neuroscience, and Education.

Conflict of Interest

I confirm that, to the best of my knowledge, there are no conflicts of interest associated with the research presented in this thesis. I have received no financial support, grants, or any other form of assistance from external sources that could be perceived as influencing the outcome of this study. I have no financial or personal relationships with individuals or organizations that could introduce bias or compromise the integrity of the research. This statement is made to ensure the transparency and credibility of the research findings presented herein.

References

Anderson, B., Vance, A., Kirwan, B., Eargle, D., & Howard, S. (2014). Users aren't (necessarily) lazy: Using neurois to explain habituation to security warnings.

Anderson, J. L. (1998). Embracing uncertainty: the interface of Bayesian statistics and cognitive psychology. *Conservation Ecology*, 2(1).

Atwater, F. H. (1997). Accessing anomalous states of consciousness with a binaural beat technology. *Journal of scientific exploration*, 11(3), 263-274.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, 63: 1-29.

Baddeley, A. D. (2003). Working memory and language: An overview. *Journal of Communication Disorders*, 36, 189–208.

Baddeley, A. D., & Hitch, G. (1974). Working Memory. *Psychology of Learning and Motivation*, 8, 47-89. http://dx.doi.org/10.1016/S0079-7421(08)60452-1

Baddeley, A. D., Hatter, J. E., Scott, D., & Snashall, A. (1970). Memory and Time of Day. *Quarterly Journal of Experimental Psychology*, 22(4), 605–609. https://doi.org/10.1080/14640747008401939

Baddeley, A., Vargha-Khadem, F., & Mishkin, M. (2001). Preserved recognition in a case of developmental amnesia: Implications for the acquisition of semantic memory? *Journal of Cognitive Neuroscience*, 13(3), 357–369.

Barbosa, F.F. and Albuquerque, F.S. (2008). Effect of the time-of-day of training on explicit memory. *Neurosciences and Behavior*, Braz J Med Biol Res 41 (6), June 2008, https://doi.org/10.1590/S0100-879X2008005000023

Bartlett, P. L., Long, P. M., Lugosi, G., & Tsigler, A. (2020). Benign overfitting in linear regression. *Proceedings of the National Academy of Sciences*, 117(48), 30063-30070.

Başar, E., Başar-Eroğlu, C., Karakaş, S., & Schürmann, M. (2000). Brain oscillations in perception and memory. International journal of psychophysiology : *official journal of the International Organization of Psychophysiology*, 35(2-3), 95–124. https://doi.org/10.1016/s0167-8760(99)00047-1

Basu, S. & Banerjee, B. (2023). Potential of binaural beats intervention for improving memory and attention: insights from meta-analysis and systematic review. *Psychological Research*, 87(4), 951-963.

Beauchene, C., Abaid, N., Moran, R., Diana, R. A., & Leonessa, A. (2017). The effect of Binaural Beats on verbal working memory and cortical connectivity. *Journal of Neural Engineering*, 14(2), [026014]. https://doi.org/10.1088/1741-2552/aa5d67

Borges, L. R., Arantes, A. P. B. B., & Naves, E. L. M. (2023, March). Influence of binaural beats stimulation of gamma frequency over memory performance and EEG spectral density. *In Healthcare* (Vol. 11, No. 6, p. 801). MDPI.

Breus, M.J. (2018, October 11). How Can Binaural Beats Help You Sleep Better? Retrieved from https://www.psychologytoday.com/za/blog/sleep-newzzz/201810/how-can-binaural-beats-help-you-sleep-better

Brocas, I., & Carrillo, J.D. (2016). A neuroeconomic theory of memory retrieval. *Journal of Economic Behavior and Organization,* 130, 198-205.

Bruck, M. (1992). Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology*, 28, 874-886.

Buzsáki, G. (2006). *Rhythms of the Brain*. Oxford university press. https://scholar.google.com/scholar_lookup?title=Rhythms+of+the+Brain.&author=G.+Buzsaki&publication_year=2006&

Buzsáki, G. (2020). Neural oscillation. *Encyclopedia Britannica website*. Retrieved 21:14, 15 Apr, 2020 from: https://www.britannica.com/science/brain-wave-physiology

Cain, K., Oakhill, J., & Bryant, P. (2004). Children's reading comprehension ability: Concurrent prediction by working memory, verbal ability, and component skills. *Journal of Educational Psychology*, 96, 31-42.

Carretti, B., Borella, E., Cornoldi, C., & De Beni, R. (2009). Role of working memory in explaining the performance of individuals with specific reading comprehension difficulties: A meta-analysis. *Learning and Individual Differences*, 19, 246-251.

Chaieb, L., Wilpert, E. C., Reber, T. P., & Fell, J. (2015). Auditory beat stimulation and its effects on cognition and mood States. *Frontiers in psychiatry*, 6, 70. https://doi.org/10.3389/fpsyt.2015.00070

Coffey, E., Herholz, S., Chepesiuk, A. et al. Cortical contributions to the auditory frequency-following response revealed by MEG. *Nat Commun* 7, 11070 (2016). https://doi.org/10.1038/ncomms11070

Colzato, L. S., Barone, H., Sellaro, R., & Hommel, B. (2017). More attentional focusing through binaural beats: Evidence from the global–local task. *Psychological Research Psychologische Forschung*, 81(1), 271–277. https://doi.org/10.1007/s00426-015-0727-0

da Silva, V. F., Ribeiro, A. P., Dos Santos, V. A., Nardi, A. E., King, A. L., & Calomeni, M. R. (2015). Stimulation by Light and Sound: Therapeutics Effects in Humans. Systematic Review. *Clinical practice and epidemiology in mental health* : CP & EMH, 11, 150–154. https://doi.org/10.2174/1745017901511010150

da Silva Junior, M., de Freitas, R. C., dos Santos, W. P., da Silva, W. W. A., Rodrigues, M. C. A., & Conde, E. F. Q. (2019). Exploratory study of the effect of binaural beat stimulation on the EEG activity pattern in resting state using artificial neural networks. *Cognitive systems research*, 54, 1-20.

Deniz, F., Nunez-Elizalde, A., Huth, A. and Gallant, J., (2022). The Representation of Semantic Information Across Human Cerebral Cortex During Listening Versus Reading Is Invariant to

Stimulus Modality. *Journal of Neuroscience* 25 September 2019, 39 (39) 7722-7736; DOI: https://doi.org/10.1523/JNEUROSCI.0675-19.2019

Derner, M., Chaieb, L., Surges, R., Staresina, B. P., & Fell, J. (2018). Modulation of Item and Source Memory by Auditory Beat Stimulation: A Pilot Study With Intracranial EEG. *Frontiers in human neuroscience*, 12, 500. https://doi.org/10.3389/fnhum.2018.00500

Domjan, M. & Burkhard, B., (1982). *The Principles of Learning and Behavior*. Brooks/Cole Publishing Company: Monterey, CA.

Draganova, R., Ross, B., Wollbrink, A., & Pantev, C. (2008). Cortical steady-state responses to central and peripheral auditory beats. *Cerebral Cortex*, 18(5), 1193-1200.

DuBrow, S., & Davachi, L. (2013). The influence of context boundaries on memory for the sequential order of events. *Journal of experimental psychology*. General, 142(4), 1277–1286. https://doi.org/10.1037/a0034024

Engelbregt, H., Meijburg, N., Schulten, M., Pogarell, O., & Deijen, J. B. (2019). The Effects of Binaural and Monoaural Beat Stimulation on Cognitive Functioning in Subjects with Different Levels of Emotionality. *Advances in cognitive psychology*, 15(3), 199–207. https://doi.org/10.5709/acp-0268-8

Fellner, M. C., Gollwitzer, S., Rampp, S., Kreiselmeyr, G., Bush, D., Diehl, B., Axmacher, N., Hamer, H., & Hanslmayr, S. (2019). Spectral fingerprints or spectral tilt? Evidence for distinct oscillatory signatures of memory formation. *PLoS biology*, *17*(7), e3000403. https://doi.org/10.1371/journal.pbio.3000403

Forsberg, A., Guitard, D. & Cowan, N. (2021). Working memory limits severely constrain long-term retention. *Psychon Bull Rev 28*, 537–547. https://doi.org/10.3758/s13423-020-01847-z

Gao, X., Cao, H., Ming, D., Qi, H., Wang, X., Wang, X., et al. (2014). Analysis of EEG activity in response to Binaural Beats with different frequencies. *International Journal of Psychophysiology*, 94(3), 399406. https://doi.org/10.1016/j.ijpsycho.2014.10.010.

Garcia-Argibay, M., Santed, M. A., and Reales, J. M. (2019a). Binaural auditory beats affect long-term memory. *Psychological Research Psychologische Forschung*, 83(6), 1124–1136. https://doi.org/10.1007/s00426-017-0959-2

Garcia-Argibay, M., Santed, M. A., and Reales, J. M. (2019b). Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: a meta-analysis. *Psychological research*, 83(2), 357–372. https://doi.org/10.1007/s00426-018-1066-8

Góes, L. G. (2018). Binaural Beats: Brain wave induction and the use of Binaural Beats to induce brainwave patterns. Current Research: Integrative Medicine, 3(02).

Gola, M., Magnuski, M., Szumska. I. & Wróbel, A. (2013). EEG beta band activity is related to attention and attentional deficits in the visual performance of elderly subjects. *International Journal of Psychophysiology*, Vol 89(3), pages 334–341. Retrieved 17:01, 16 Apr, 2020 from: https://doi.org/10.1016/j.ijpsycho.2013.05.007

Hanslmayr, S., Axmacher, N. and Inman, C.S. (2019). Modulating Human Memory via Entrainment of Brain Oscillations. *Trends in Neurosciences*, Volume 42, Issue 7, 2019, 485-499. https://doi.org/10.1016/j.tins.2019.04.004.

Hanslmayr, S., Aslan, A., Staudigl, T., Klimesch, W., Herrmann, C. S., & Bäuml, K. H. (2007). Prestimulus oscillations predict visual perception performance between and within subjects. *Neuroimage*, 37(4), 1465-1473.

Herweg, N. A., Solomon, E. A., & Kahana, M. J. (2020). Theta oscillations in human memory. *Trends in cognitive sciences*, 24(3), 208-227.

Hiwa, S., Katayama, T., & Hiroyasu, T. (2018). Functional near-infrared spectroscopy study of the neural correlates between auditory environments and intellectual work performance. *Brain and behavior*, 8(10), e01104. https://doi.org/10.1002/brb3.1104

Huang, T. L., & Charyton, C. (2008). A comprehensive review of the psychological effects of brainwave entrainment. Database of Abstracts of Reviews of Effects (DARE): Quality-assessed Reviews [Internet].

Ingendoh, R. M., Posny, E. S., & Heine, A. (2023). Binaural beats to entrain the brain? A systematic review of the effects of binaural beat stimulation on brain oscillatory activity, and the implications for psychological research and intervention. *PloS one*, 18(5), e0286023.

Ioannou, C. I., Pereda, E., Lindsen, J. P., & Bhattacharya, J. (2015). Electrical brain responses to an auditory illusion and the impact of musical expertise. *PloS one*, 10(6), e0129486.

Jazayeri, M. and Afraz, A. (2017). Navigating the Neural Space in Search of the Neural Code. *Neuron*, Volume 93, Issue 5, 2017, 1003-1014, https://doi.org/10.1016/j.neuron.2017.02.019.

Jirakittayakorn, N. & Wongsawat, Y. (2018, September 24). A Novel Insight of Effects of a 3-Hz Binaural Beat on Sleep Stages During Sleep. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6165862/

Josselyn, S. A., & Tonegawa, S. (2020). Memory engrams: Recalling the past and imagining the future. *Science* (New York, N.Y.), 367(6473), eaaw4325. https://doi.org/10.1126/science.aaw4325

Jurvanen, K. (2020). Binaural Beats and music: using theta and alpha waves in music to induce relaxation and meditation. http://urn.fi/URN:NBN:fi:aalto-202006143758

Kaneko, K. I., Fujiki, N., & Hari, R. (2003). Binaural interaction in the human auditory cortex revealed by neuromagnetic frequency tagging: no effect of stimulus intensity. *Hearing research*, 183(1-2), 1-6.

Kelly, J. M., Perseghin, A., Dow, A. W., Trivedi, S. P., Rodman, A., & Berk, J. (2022). Learning Through Listening: A Scoping Review of Podcast Use in Medical Education. Academic medicine : *journal of the Association of American Medical Colleges*, 97(7), 1079–1085. https://doi.org/10.1097/ACM.0000000000004565

Kennerly, R. (2009). An Empirical Investigation Into the Effect of Beta Frequency Binaural-beat Audio Signals on Four Measures of Human Memory , ADD / ADHD.

Kirby, J. R., Parrila, R. K., & Pfeiffer, S. L. (2003). Naming speed and phonological awareness as predictors of reading development. *Journal of Educational Psychology*, 95, 453-464.

Korjus, K., Hebart, M. N., & Vicente, R. (2016). An efficient data partitioning to improve classification performance while keeping parameters interpretable. PloS one, 11(8), e0161788

Kraus, J., and Porubanova, M. (2015). The effect of Binaural Beats on working memory capacity. *Studia psychologica*. 57. 10.21909/sp.2015.02.689.

Kuhbandner C. (2020). Long-Lasting Verbatim Memory for the Words of Books After a Single Reading Without Any Learning Intention. *Frontiers in psychology*, 11, 1780. https://doi.org/10.3389/fpsyg.2020.01780

Kuhbandner, C., Rosas-Corona, E. A., & Spachtholz, P. (2017). High-Fidelity visual Long-Term Memory within an Unattended Blink of an Eye. *Frontiers in psychology*, 8, 1859. https://doi.org/10.3389/fpsyg.2017.01859

Lafon, B., Henin, S., Huang, Y., Friedman, D., Melloni, L., Thesen, T., Doyle, W., Buzaki, G., Devisnky, O., Parra, L. & Liu, A.A. (2017). Low frequency transcranial electrical stimulation does not entrain sleep rhythms measured by human intracranial recordings. *Nat Commun 8*, 1199. https://doi.org/10.1038/s41467-017-01045-x

LeDoux, J. (2012). Rethinking the emotional brain. Neuron, 73(4), 653-676.

Leeb, H., & Pötscher, B. M. (2005). Model selection and inference: Facts and fiction. *Econometric Theory*, 21(1), 21-59.

Licklider, J. C. R., Webster, J. C., & Hedlun, J. M. (1950). On the frequency limits of Binaural Beats. *Journal of the Auditoryal Society of America*, 22, 468–473. https://doi.org/10.1121/1.1906629

Liu, H., & Cocea, M. (2017). Semi-random partitioning of data into training and test sets in granular computing context. *Granular Computing*, 2, 357-386.

May, C. P., Hasher, L., & Stoltzfus, E. R. (1993). Optimal Time of Day and the Magnitude of Age Differences in Memory. *Psychological Science*, 4(5), 326–330. https://doi.org/10.1111/j.1467-9280.1993.tb00573.x

McMurray, J. C. (2006). Binaural Beats enhance alpha wave activity, memory, and attention in healthy aging seniors. UNLV Retrospective Theses & Dissertations. 2662. Retrieved from https://digitalscholarship.unlv.edu/cgi/viewcontent.cgi?article=3661&context=rtds

Miller, G. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *The psychological review*, 63, 81-97.

Moerbeek, M. (2021). Bayesian updating: increasing sample size during the course of a study. BMC Med Res Methodol 21, 137. https://doi.org/10.1186/s12874-021-01334-6

Mujib, M. D., Hasan, M. A., Qazi, S. A., & Vuckovic, A. (2021). Understanding the neurological mechanism involved in enhanced memory recall task following binaural beat: a pilot study. *Experimental Brain Research*, 239, 2741-2754.

Obleser, J., & Kayser, C. (2019). Neural entrainment and attentional selection in the listening brain. *Trends in Cognitive Sciences*, 23(11), 913 - 926. https://doi.org/10.1016/j.tics.2019.08.004

Orozco Perez, H. D., Dumas, G., & Lehmann, A. (2020). Binaural Beats through the Auditory Pathway: From Brainstem to Connectivity Patterns. *eNeuro*, 7(2), ENEURO.0232-19.2020. https://doi.org/10.1523/ENEURO.0232-19.2020

Ortiz, T., Martínez, A. M., Fernández, A., Maestu, F., Campo, P., Hornero, R., Escudero, J., & Poch, J. (2008). Impact of auditory stimulation at a frequency of 5 Hz in verbal memory. *Actas espanolas de psiquiatria*, 36(6), 307–313. https://pubmed.ncbi.nlm.nih.gov/18985458/.

Oster, G. (1973). Auditory beats in the brain. *Scientific American*, 229(4), 94-103.

Pérez-Bellido, A., Spaak, E. & de Lange, F.P. (2023). Magnetoencephalography recordings reveal the neural mechanisms of auditory contributions to improved visual detection. *Commun Biol 6*, 12. https://doi.org/10.1038/s42003-022-04335-3

Perrott, D. R., & Nelson, M. A. (1969). Limits for the detection of Binaural Beats. *The Journal of the Auditoryal Society of America*, 46(6), 1477–1481. https://doi.org/10.1121/1.1911890

Petros, T.V., Beckwith, B.E. and Anderson, M. (1990), Individual differences in the effects of time of day and passage difficulty on prose memory in adults. *British Journal of Psychology*, 81: 63-72. https://doi.org/10.1111/j.2044-8295.1990.tb02346.x

Poldrack, R. A., Clark, J., Paré-Blagoev, E. J., Shohamy, D., Creso Moyano, J., Myers, C., & Gluck, M. A. (2001). Interactive memory systems in the human brain. *Nature*, 414(6863), 546–550. https://doi.org/10.1038/35107080

Poldrack, R.A. and Foerde, K. (2008). Category learning and the memory systems debate. *Neuroscience and Biobehavioral Reviews*, 32(2), 197-205. Retrieved from https://escholarship.org/uc/item/1gt4j18v

Rasch, B. & Born, J. (2013, April) About Sleep's Role in Memory. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/23589831

Reedijk, S. A., Bolders, A., & Hommel, B. (2013). The impact of Binaural Beats on creativity. *Frontiers in human neuroscience*, 7, 786. https://doi.org/10.3389/fnhum.2013.00786

Rogowsky, B. A., Calhoun, B. M., & Tallal, P. (2016). Does Modality Matter? The Effects of Reading, Listening, and Dual Modality on Comprehension. SAGE Open. https://doi.org/10.1177/2158244016669550

Ryan, L., Hatfield, C., & Hofstetter, M. (2002). Caffeine Reduces Time-of-Day Effects on Memory Performance in Older Adults. *Psychological Science*, 13(1), 68–71. https://doi.org/10.1111/1467-9280.00412

Samuels, S. J., & Flor, R. F. (1997). The importance of automaticity for developing expertise in reading. *Reading & Writing Quarterly: Overcoming Learning Difficulties*, 13, 107-121.

Schuett, S., Heywood, C. A., Kentridge, R. W., & Zihl, J. (2008). The significance of visual information processing in reading: Insights from hemianopic dyslexia. *Neuropsychologia*, 46, 2445-2462.

Scullin, M.K. (2013 March). Sleep, Memory, and Aging: The Link Between Slow-Wave Sleep and Episodic Memory Changes from Younger to Older Adults. Washington University in St. Louis. *Psychol Aging*. 28(1): 105–114.

Sharma, S., & Chatterjee, S. (2021). Winsorization for robust Bayesian neural networks. Entropy, 23(11), 1546.

Sharpe, R. and Mahmud, M. (2020). Effect of the Gamma Entrainment Frequency in Pertinence to Mood, Memory and Cognition. In: Mahmud, M., Vassanelli, S., Kaiser, M.S., Zhong, N. (eds) Brain Informatics. BI 2020. *Lecture Notes in Computer Science*, vol 12241. Springer, Cham. https://doi.org/10.1007/978-3-030-59277-6_5

Shekar, L., Suryavanshi, C.A. and Nayak, K.R. (2018). Effect of alpha and Gamma Binaural Beats on reaction time and short-term memory. *Natl J Physiol Pharm Pharmacol*;8(6):829-833.

Sherman, S. M., Buckley, T. P., Baena, E., & Ryan, L. (2016). Caffeine Enhances Memory Performance in Young Adults during Their Non-optimal Time of Day. *Frontiers in psychology*, 7, 1764. https://doi.org/10.3389/fpsyg.2016.01764

Stefan, A.M., Gronau, Q.F., Schönbrodt, F.D. & Wagenmakers, E.J. (2019). A tutorial on Bayes Factor Design Analysis using an informed prior. *Behav Res 51*, 1042–1058 (2019). https://doi.org/10.3758/s13428-018-01189-8

Stone, J. M. and Towse, J. N. (2015). A Working Memory Test Battery: Java-Based Collection of Seven Working Memory Tasks. *Journal of Open Research Software*, 3: e5, DOI: http://dx.doi.org/10.5334/jors.br

Trifilio, E., Tanner, J. J., Butterfield, L., Mangal, P., Maye, J. E., Marsiske, M., Price, C. C., & Bowers, D. (2020). A tale of two stories: Validity of an alternative story memory test in a sample of older adults. *The Clinical neuropsychologist*, 34(1), 158–173. https://doi.org/10.1080/13854046.2018.1538428

Tulving, E. and Thomson, D.M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychol. Rev*. 80, 352 – 373.

Varga, A.W., Ducca, E.L., Kishi, A., Fischer, E., Parekh, A., Koushyk, V., Yau, P.L., Tyler Gumb, T., Leibert, D.P., Wohlleber, M.E., Burschtin, O.E., Convit, A., Rapoport, D.M., Osorio, R.S. and Ayappa, I. (2016, June) Effects of Aging on Slow Wave Sleep Dynamics and Human Spatial Navigational Memory Consolidation. *Neurobiol Aging*. ; 42: 142–149.

Verhoeven, L., Reitsma, P., & Siegel, L. S. (2011). Cognitive and linguistic factors in reading acquisition. *Reading and Writing*, 24, 387-394

Wagner, R. K., Torgesen, J. K., Rashotte, C. A., Hecht, S. A., Barker, T. A., Burgess, S. R., ... & Garon, T. (1997). Changing relations between phonological processing abilities and word-level reading as children develop from beginning to skilled readers: a 5-year longitudinal study. *Developmental Psychology*, 33, 468.

Wais, P. E., & Gazzaley, A. (2011). The impact of auditory distraction on retrieval of visual memories. *Psychonomic Bulletin & Review*, 18, 1090-1097.

Wechsler, D., & Kodama, H. (1949). *Wechsler intelligence scale for children (Vol. 1)*. New York: Psychological corporation.

Weger Jr, H., Castle Bell, G., Minei, E. M., & Robinson, M. C. (2014). The relative effectiveness of active listening in initial interactions. *International Journal of Listening*, 28(1), 13-31.

Westerberg, C.E., Florczak, S.M., Weintraub, S., Mesulam, M.M., Marshall, L., Zee, P.C., and Paller, K.A. (2015 September). Memory Improvement via Slow Oscillatory Stimulation during Sleep in Older Adults. *Neurobiol Aging*. 36(9): 2577–2586.

Wiwatwongwana, D., Vichitvejpaisal, P., Thaikruea, L., Klaphajone, J., Tantong, A., Wiwatwongwana, A., & Medscape (2016). The effect of music with and without binaural beat audio on operative anxiety in patients undergoing cataract surgery: a randomized controlled trial. *Eye* (London, England), 30(11), 1407–1414. https://doi.org/10.1038/eye.2016.160

Wright, B. A., & Zhang, Y. (2009). A review of the generalization of auditory learning. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 364(1515), 301–311. https://doi.org/10.1098/rstb.2008.0262

Yang, J., & Li, P. (2019). Mechanisms for auditory perception: A neurocognitive study of second language learning of Mandarin Chinese. *Brain Sciences*, 9(6), 139.

Yusim, A. and Grigaitis, J. (2020) Efficacy of Binaural Beat Meditation Technology for Treating Anxiety Symptoms, *The Journal of Nervous and Mental Disease*: February 2020 - Volume 208 - Issue 2 - p 155-160. doi: 10.1097/NMD.0000000000001070

Appendix A

Quantile-to-Quantile Examination of the Measured Variables

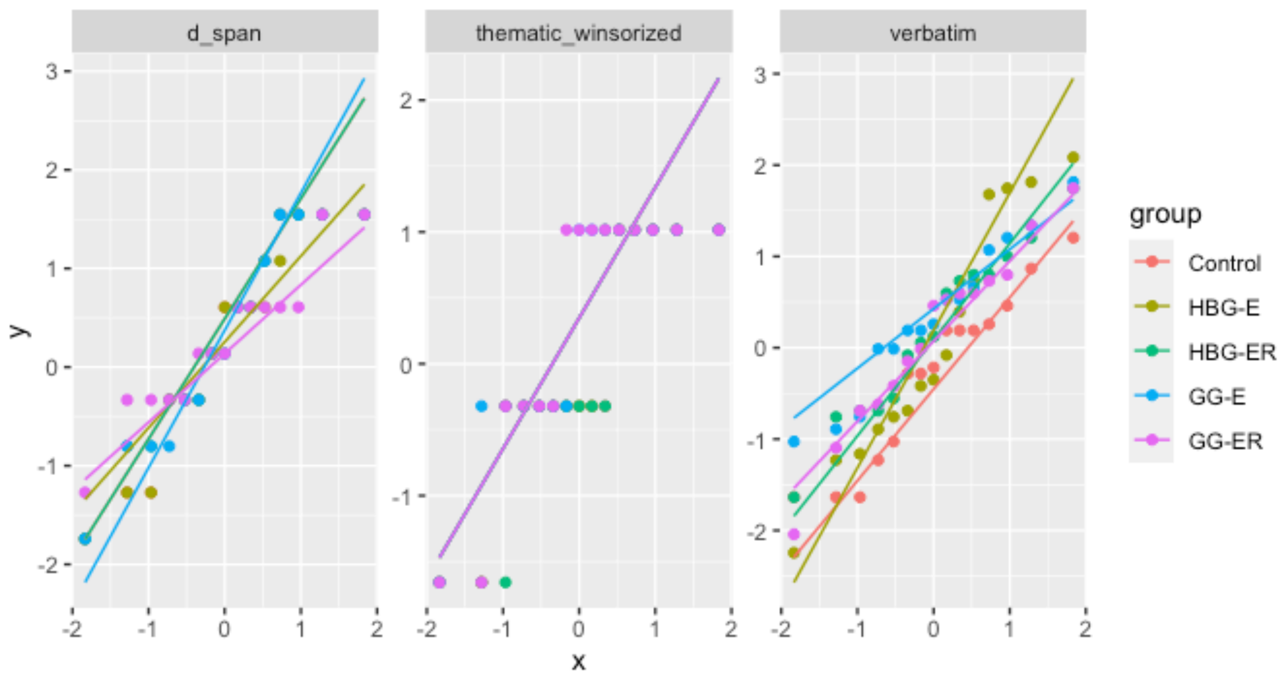
Immediate Recall with Audio Presentation. Figure A illustrates a Quantile-to-Quantile (QQ) plot contrasting observed quantiles against expected quantiles under the assumption of a normal distribution. At the median (50th percentile), a slight elevation in observed values (0.14) is noted compared to anticipated values in a normal distribution (0), suggesting nuanced central tendencies within the dataset. Throughout the interquartile range (25th to 75th percentiles), the proximity between observed and expected quantiles indicates a distributional spread akin to that expected in a normal context. However, examination of the upper percentiles (90th to 100th) reveals a consistent elevation in observed values relative to their normal distribution counterparts, signifying heavier tails and the presence of outliers. This initial analysis suggests that immediate recall scores exhibit a departure from strict normality, characterized by nuanced central tendencies, a comparable interquartile spread, and a prevalence of extreme values in the upper percentiles.

Delayed recall of target words with Audio Presentation. Notable elevation in observed values (0.14) at the median (50th percentile), relative to expected values in a standard normal distribution (0), indicates nuanced central tendencies within the dataset. Across the interquartile range (25th to 75th percentiles), close alignment between observed and expected quantiles suggests a distributional spread consistent with normal expectations. Further examination of the upper percentiles (90th to 100th) reveals a consistent upward deviation from normal distribution equivalents, indicating heavier tails and the presence of outliers (min = -1.74; max = 1.55). Consequently, participant performance in recalling target words after a delay exhibits a distribution departing from strict normality, marked by nuanced central tendencies, a distributional spread similar to normal expectations in the interquartile range, and a notable abundance of extreme values in the upper percentiles (see Figure A).

Delayed recall of Themes with Audio Presentation. At lower percentiles (0% to 30%), consistent downward deviation in observed values from expected quantiles indicates a tendency toward negative skewness in the distribution. Notably, the 50th percentile (median) exhibits a discernible upward shift in observed values (0.32) relative to the standard normal distribution (0), suggesting a central tendency that diverges from a perfectly symmetrical distribution. Within the interquartile range (31st to 69th percentiles), observed quantiles closely mirror expected counterparts, indicative of a distributional spread consistent with normal expectations. Particularly in the upper tail beyond the 70th percentile, a substantial increase in observed values leads to a notable divergence from expected quantiles, indicative of a leptokurtic distribution with heavier tails. The persistent upward deviation in tails, as evidenced by observed minimum (-1.66) and maximum (1.02) values diverging from expected extremes, underscores the presence of outliers and extreme values. Consequently, this analysis suggests that delayed recall of thematic information manifests a distribution characterized by negative skewness, nuanced central tendencies, a distributional spread akin to normal expectations in the interquartile range, and a higher concentration of extreme values in the upper percentiles (see Figure A).

Figure A1

Quantile-to-Quantile Representation of Individual Scores with Audio Presentation



Note. Legend: Immediate recall scores (“d_span”) are on the left, delayed recall (thematic) scores (“thematic_winsorized”) are in the middle, and delayed recall scores of target words (“verbatim”) are on the right, all within the context of the audio presentation. Scores are categorized by binaural beats experimental groups as follows: 'No exposure' for those not exposed to any binaural beats, 'HBG-E' for participants exposed to High-Beta binaural beats during encoding, 'HBG-ER' for participants exposed to High-Beta binaural beats during encoding and recall, 'GG-E' for participants exposed to Gamma binaural beats during encoding, and 'GG-ER' for participants exposed to Gamma binaural beats during encoding and recall.

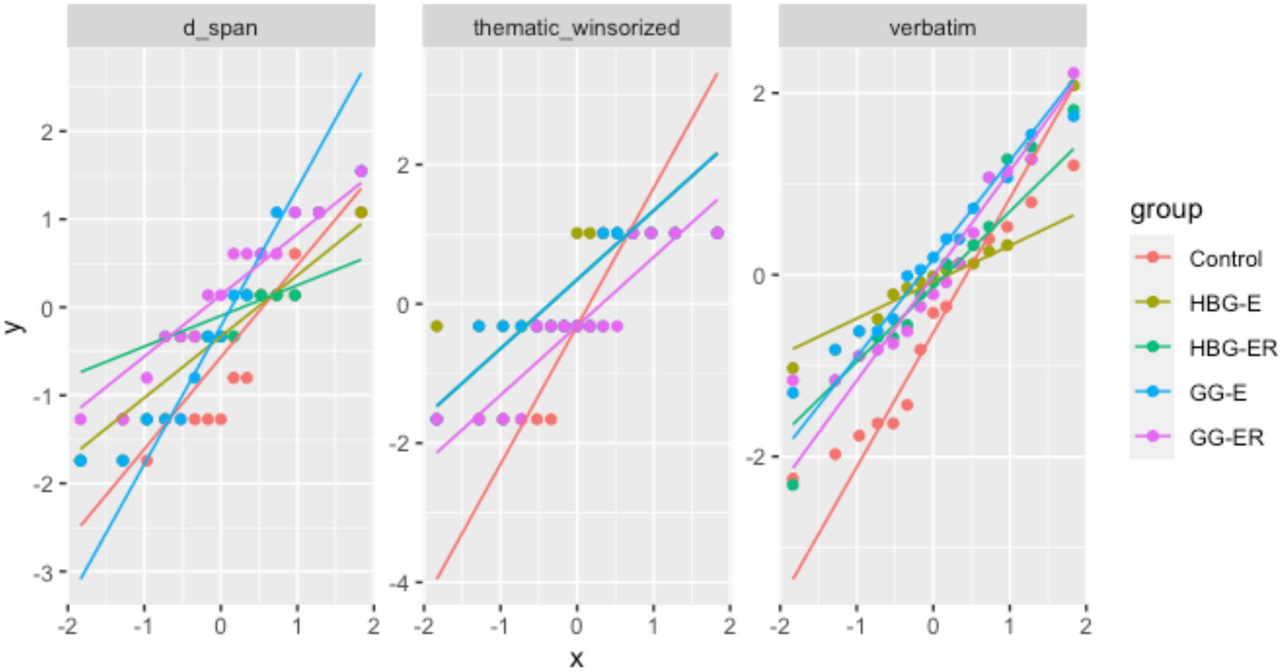
Immediate Recall with Visual Presentation. At the lower percentiles (0% to 30%), a consistent downward trend in observed values indicates negative skewness in the data. Particularly, a perceptible divergence in observed values (-1.55) from the expected quantiles is seen at the 10th percentile, suggesting a nuanced departure from the normal distribution. Within the interquartile range (31st to 69th percentiles), observed quantiles closely align with their expected counterparts, indicating a distributional spread consistent with normal expectations. However, beyond the 70th percentile, particularly in the upper tail, a substantial increase suggests a notable deviation from expected quantiles. This upward shift in the tails, surpassing the expected upper limit (max = 1.55), indicates a leptokurtic distribution in the data, implying a higher concentration of values around the mean and heavier tails than expected in a standard normal distribution. The observed skewness and kurtosis in immediate recall scores with visual presentation underscore the presence of non-normative features in the distribution, as illustrated in Figure B.

Delayed recall of target words with Visual Presentation. In the 0th to 25th percentiles, observed values demonstrate a noticeable downward trend, indicative of negative skewness in the distribution. Particularly, at the 10th percentile, a clear deviation from expected quantiles is observed, suggesting a departure from a normal distribution. Within the interquartile range (26th to 74th percentiles), observed quantiles closely align with their expected counterparts, indicating a distributional spread consistent with normal expectations. However, beyond the 75th percentile, a substantial increase in quantiles leads to a pronounced deviation from expected quantiles. This upward shift in the tails, with the observed maximum (2.22) surpassing the expected upper limit, suggests a leptokurtic distribution, implying a higher concentration of values around the mean and heavier tails than expected in a standard normal distribution. The observed skewness and kurtosis in delayed recall scores depicted in Figure B highlight non-normative features in the distribution.

Delayed Recall of Themes with Visual Presentation. In the lower percentiles (0% to 20%), observed quantiles closely align with their expected counterparts, suggesting a distribution within normal expectations. However, there is a noticeable deviation at the 18th percentile, indicating a potential slight negative skewness. Between the 21st and 62nd percentiles, a distinct downward trend in the quantiles implies a more substantial negative skewness. The deviation becomes more pronounced in the upper percentiles (> 63%), indicating a departure from a normal distribution. At the 83rd percentile, a significant shift is observed as the values surpass expected quantiles, suggesting a leptokurtic distribution with heavier tails (Figure B), indicating non-normative features in the distribution.

Figure A2

Quantile-to-Quantile Representation of Individual Scores with Visual Presentation



Note. Legend: Immediate recall scores ("d_span") are on the left, delayed recall of themes scores ("thematic_winsorized") are in the middle, and delayed recall scores of target words ("verbatim") are on the right, all within the context of visual presentation. Scores are grouped by binaural beats experimental groups as follows: 'No exposure' for those not exposed to any binaural beats, 'HBG-E' for participants exposed to High-Beta binaural beats during encoding, 'HBG-ER' for participants exposed to High-Beta binaural beats during encoding and recall, 'GG-E' for participants exposed to Gamma binaural beats during encoding, and 'GG-ER' for participants exposed to Gamma binaural beats during encoding and recall.

Appendix B

Informed Consent

University of Cape Town – Psychology Department

Different sounds and the effects on memory performance

1. **Invitation and Purpose**: You are invited to take part in a research study about memory performance while exposed to different sounds. I am a researcher from the Psychology department at the University of Cape Town.

2. **Procedures**: If you decide to take part in this study, you will randomly be assigned to a group and we will ask you to take a memory test on a digitized application. You will be asked to recall stories that you will read and hear, to the best of your ability. It will take about 90 minutes which includes a break where you will be asked to play a game. You will be provided with headphones for the duration of the experiment and there is no need to bring anything with you. You will be asked to refrain from any caffeinated drinks, or any nicotine products, for at least two hours before the trial.

3. **Risks, Discomforts & Inconveniences:** This study poses a low risk of harm to you. The audio frequencies that will be used have no known long-term side effects and the volume will be carefully monitored. The headphones will be cleaned after each use to ensure hygiene and cleanliness. We do not require any personal information, other than your initials and age. This limited information will be kept safe: anonymity is a priority.

4. **Benefits:** This study has no direct benefits to you. However, the knowledge gained from it will be used to help develop and improve policy for treatment programs for memory-related diseases, learning disabilities and learning difficulties.

5. **Privacy and Confidentiality:** We will take strict precautions to safeguard your personal information throughout the study. Your anonymized information (that is, the dataset with any identifying details removed) will be kept on a password-protected, secure server at the Department of Psychology. Only the researchers will be able to access your information.

After the study is over, the anonymized dataset will be shared on UCT's ZivaHub.

6. **Money Matters**: You will not have to pay for any part of the study. You will not be paid anything to participate in this study, but we will provide refreshments. You will however receive three (3) SRPP Points (Study Credit).

7. **Questions:** If you have questions, concerns, or complaints about the study or questions about a research-related injury, please contact:

Etienne Grobler

Tel: 061 281 9293

Email: grbeti001@myuct.ac.za

Supervisor: Dr Njomboro (Progress.Njomboro@uct.ac.za)

If you have questions about your rights as a study participant or concerns about the research, please contact the Research Ethics Committee at Rosalind.Adams@uct.ac.za or 021 650 3417.

8. Signatures

{Participant's name} ___________________________ has been informed of the nature and purpose of the procedures described above including any risks involved in its performance. He or she has been given time to ask any questions and these questions have been answered to the best of the investigator's ability. A signed copy of this consent form will be made available to the participants.

______________________________ ___________

Investigator's Signature Date

I have been informed about this research study and understand its purpose, possible benefits, risks, and discomforts. I agree to take part in this research as a participant. I know that I am free to withdraw this consent and quit this project at any time and that doing so will not cause me any penalty or loss of benefits that I would otherwise be entitled to enjoy.

______________________________ ___________

Participant Signature Date

Appendix C

Bayes Factor Classification Outline

Bayes factor	Evidence category
> 100	Extreme evidence for $\mathcal{H}_1$H1
30 - 100	Very strong evidence for $\mathcal{H}_1$H1
10 - 30	Strong evidence for $\mathcal{H}_1$H1
3 - 10	Moderate evidence for $\mathcal{H}_1$H1
1 - 3	Anecdotal evidence for $\mathcal{H}_1$H1
1	No evidence
1/3 - 1	Anecdotal evidence for $\mathcal{H}_0$H0
1/10 - 1/3	Moderate evidence for $\mathcal{H}_0$H0
1/30 - 1/10	Strong evidence for $\mathcal{H}_0$H0
1/100 - 1/30	Very strong evidence for $\mathcal{H}_0$H0
< 1/100	Extreme evidence for $\mathcal{H}_0$

Note. A heuristic classification scheme for Bayes factors BF10 (Lee and Wagenmakers, 2013, p. 105; adjusted from Jeffreys, 1961). From: A tutorial on Bayes Factor Design Analysis using an informed prior (Stefan et al, 2018).

Appendix D

Materials used during the memory test

Presented during visual Presentation: From the Newcomer Story Series, the story of Lucy Carson - Flesch-Kincaid grade level = 7.4, 61 total words, 4 total sentences, 15.25 words per sentence, 1.44 syllabus per word, and 44 total 'bits'

Lucy / Carson, / while / visiting / her / brother / in a **small** / **city** / in **Virginia**, / got **lost** / **walking** / to the **art** / **museum**. / **She / searched / her / pockets** / for the / **directions** / that had been **written** / for **her**. / **Unfortunately, / she** / had **left** / **them / sitting** / on **her** / **wooden / dresser**. / **She / then** / asked / a **bus / driver** / for **directions**, / **he / said / to / walk / north** / on **11th / Avenue** / for **five/ blocks**. /

Prompt: "A woman who went on a trip."

Presented during Audio Presentation: From the Newcomer Series, the story of Adam Jones - Flesch-Kincaid grade level = 6.4, 64 total words, 4 total sentences, 15.5 words per sentence, 1.35 syllables per word, and 44 total 'bits'

Adam / Jones' / department / store / held / an **annual** / **sale /** from **/ Tuesday** / until the **end** / of the **week**. / **Sporting / goods** / were **marked / down / 75 / per cent**, / and **winter / jackets** / were **reduced** / by / **300 / Rand. / Crowds** / of **shoppers** / **bumped / each / other, / grabbing** / for the **best / buys**. / **After / closing / time**, / when the **sale / was / over**, / the **owner** / **gave / each / employee** / a **bottle** / of/ **champagne** / for **their / hard / work**. /

Prompt: "A place that sold things".

Digit span to be used in immediate recall tests:

Test 1: 6, 13, 9, 4, 7, 12, 17, 14, 3, 1, 8, 15, 20, 11, 10

Test 2: 9, 5, 11, 4, 15, 7, 3, 12, 8, 14, 10, 6, 2, 17, 19, 13

Appendix E

Invitation email and Pre-screening Questionnaire

Dear UCT students,

I am conducting research towards my Master's Degree in Research Psychology. I am researching how audio can influence memory, and if the manner in which material is presented influences how much we remember. I would like to invite you to participate in the study.

The study aims to identify which of two audio tracks better facilitates learning and memory. We will only need about 90 minutes of your time.

This research study has been approved by the Ethics in Research Committee of the Psychology Department here at UCT.

To participate in this study you will need:

- Normal or corrected to normal vision
- No cognitive impairments
- Normal hearing
- No language related disorders i.e. aphasia or dyslexia
- No diagnosis of epilepsy

Please note that participation in this study is anonymous, voluntary, and that the choice to participate is yours alone. Furthermore, there is no consequence for not participating in this study. If you decide to participate in this study but later decide you want to withdraw, you are free to do so at any time without any consequences. To say thank you for helping us by completing this study, you will receive 3 SRPP points.

If you are interested please click over here so we can get a few details. If that doesn't work, try over here: https://redcap.link/eo8fceie

This study will take place at the Computer Lab at the Psychology Department (P.D. Hahn building, ground floor computer room). Different groups will be assessed on different days, so if you do decide to join us, be on the lookout for the specified dates and times that will be made available.

Should you have any questions, please feel free to email me at: grbeti001@myuct.ac.za, or my supervisor, Dr. Progress Njomboro : progress.njomboro@uct.ac.za

Thank you for your time and we hope to see you there!

Sincerely,

Etienne Grobler – Researcher

grbeti001@myuct.co.za

Appendix F

Debriefing Letter

Dear Student,

Thank you for taking part in this experiment. Your contribution is greatly appreciated. The experiment was designed to test the performance of both immediate and delayed recall while being exposed to High Beta or Gamma frequencies, hence asking you to write down as much as you could remember from the stories you read and the numbers you were asked to study. High Beta was played at 20Hz and Gamma at 50Hz. For the longest time there has been a debate around which one of these frequencies better supports learning and memory and with your help, we are looking to answer that question. I believe that exposure to Gamma frequencies during learning facilitates both memory and learning, making it easier to retain information. In the end, we are looking to develop programs that could help everyone with memory and learning that do not require a daily pill.

The Tower of Hanoi game was just there to distract you for a bit and to make sure that you weren't bored or repeated the information during the intermission. If you have any questions, please feel free to send me a return email and I will be happy to answer in full. If you need any more information, my full contact details are available on the consent form. Please note that your anonymity and privacy are of utmost importance and none of the information provided will be shared in any way.

Thank you again and there will be some course credit coming your way, so keep an eye out.

Kind Regards

Etienne Grobler

Appendix G

Screenshots of Application Specifically Built for this Study

Figure G1

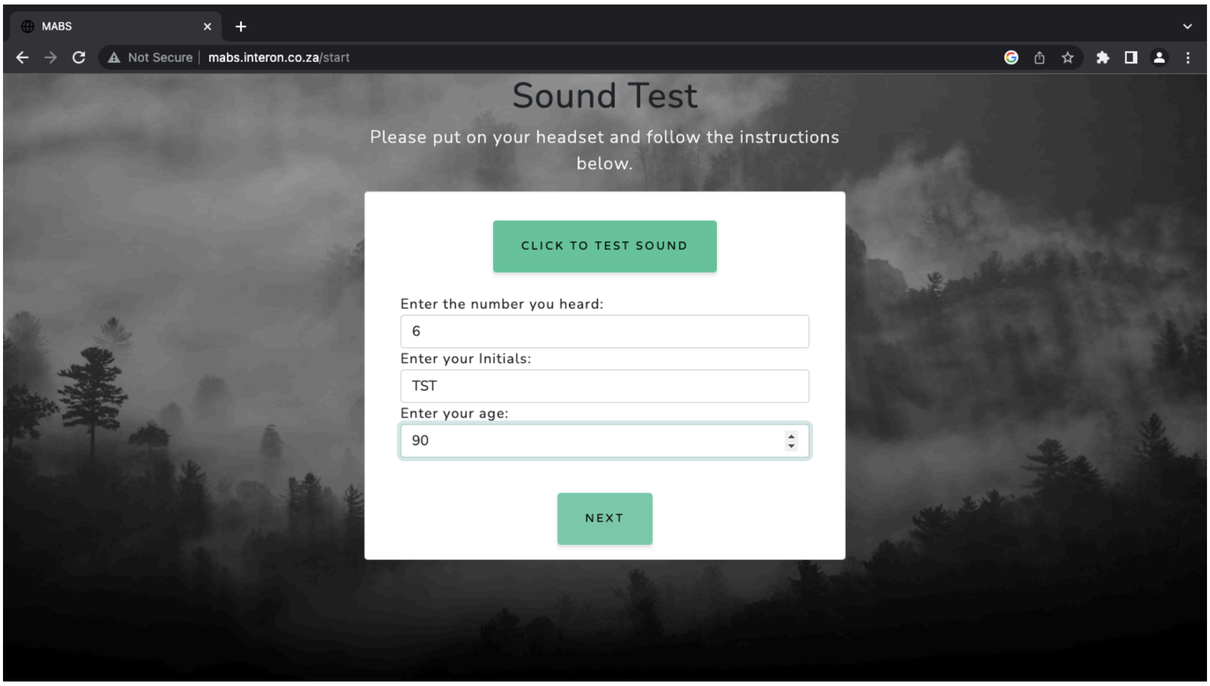


Figure G2

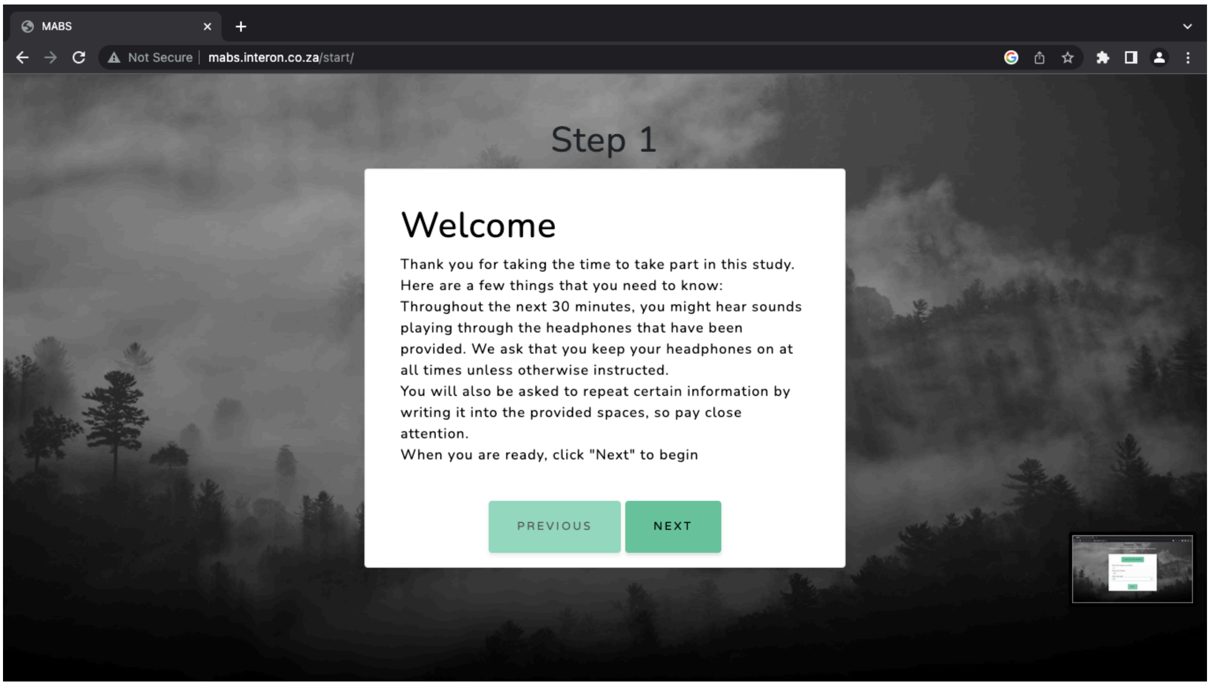


Figure G3

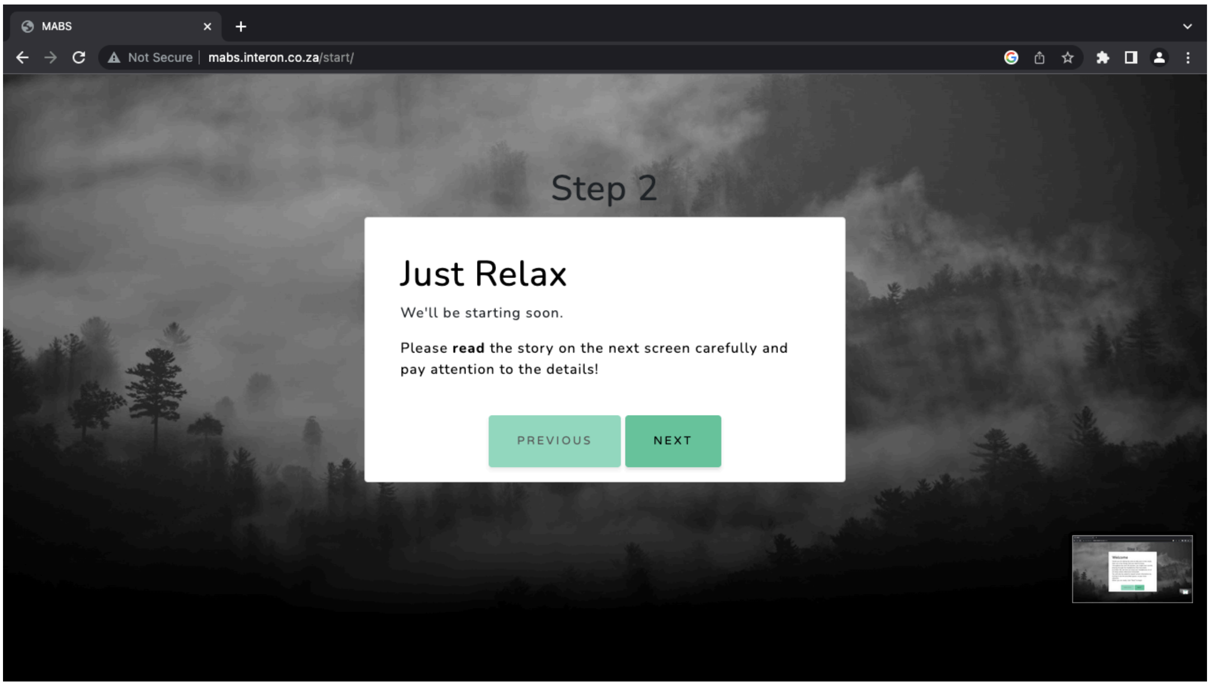


Figure G4

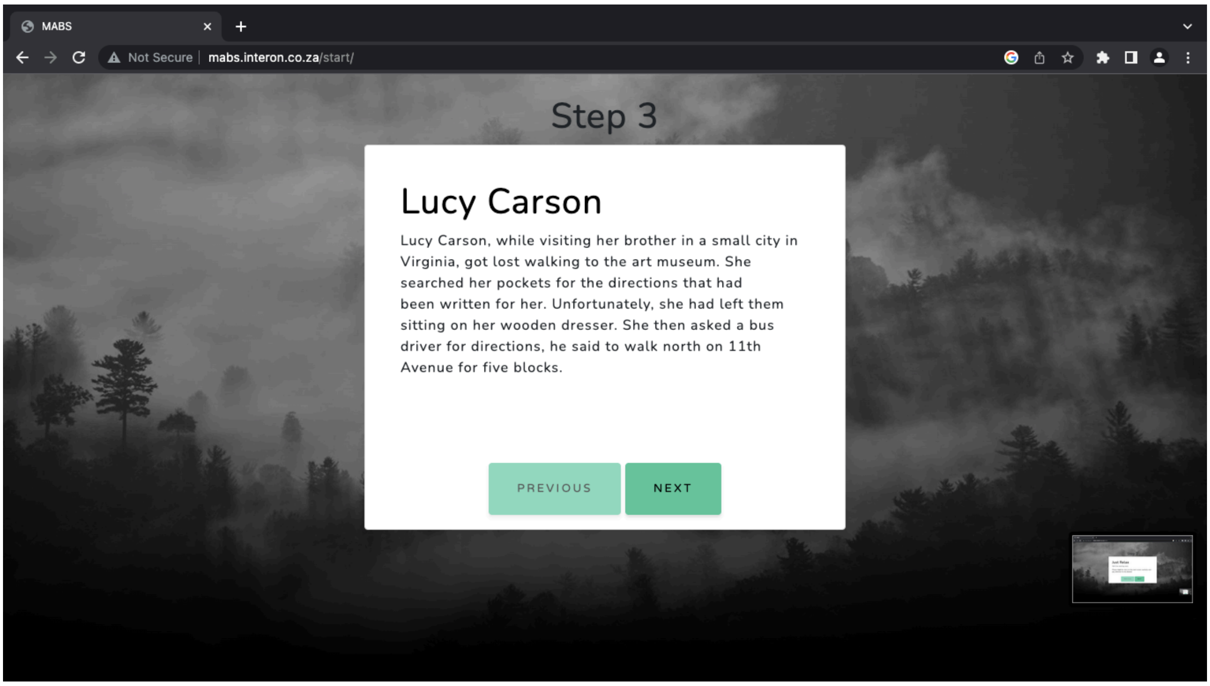


Figure G5

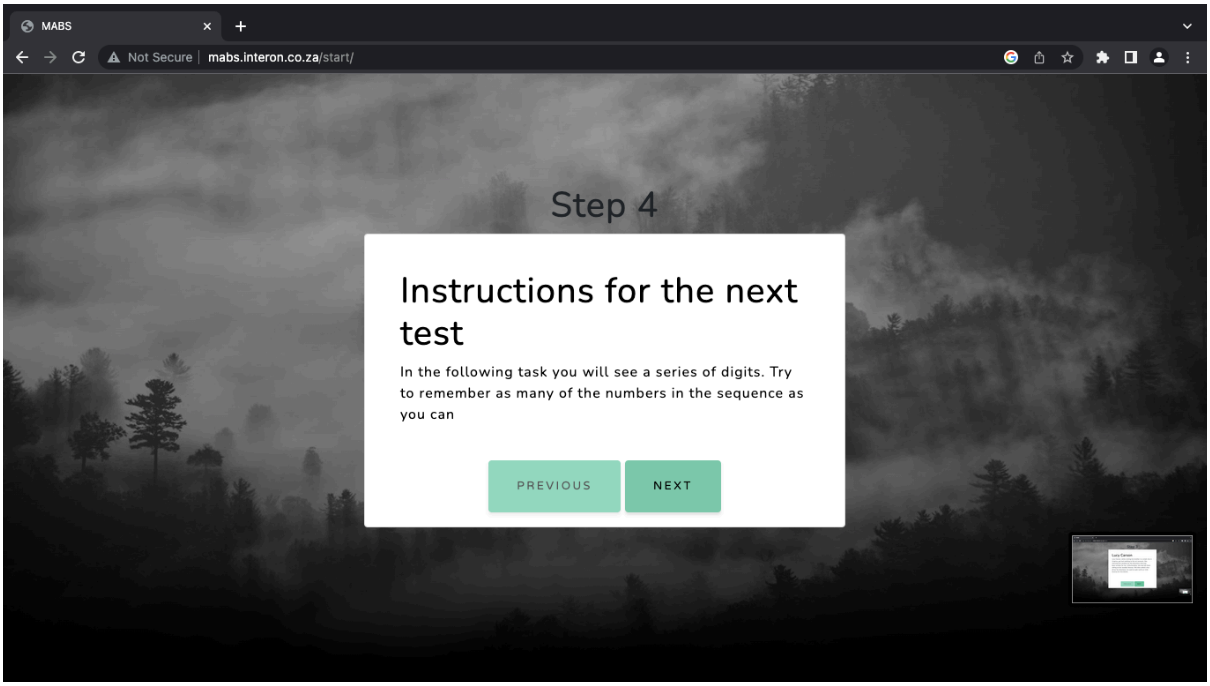


Figure G6

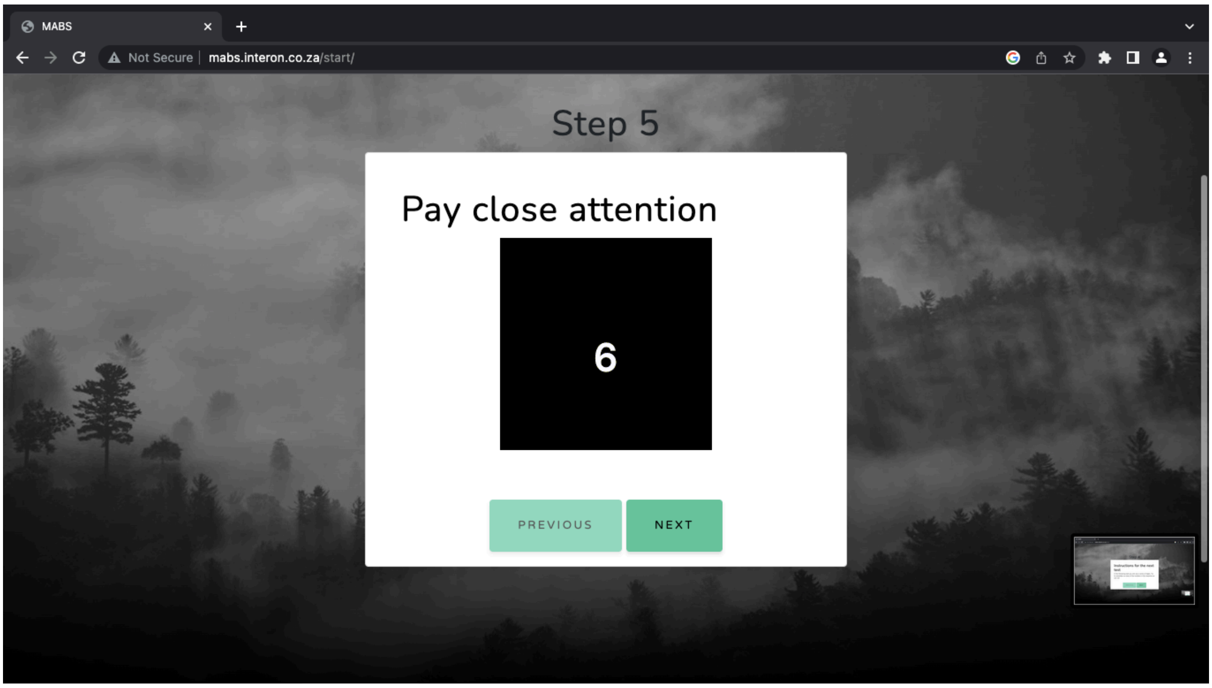


Figure G7

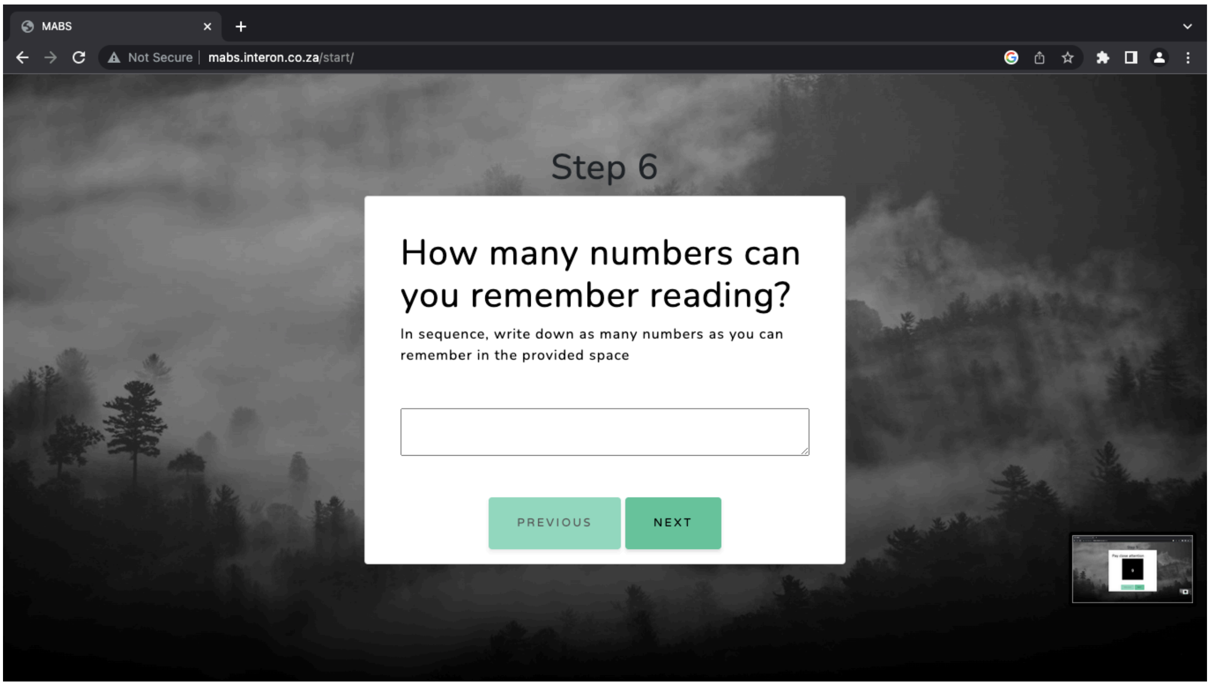


Figure G8

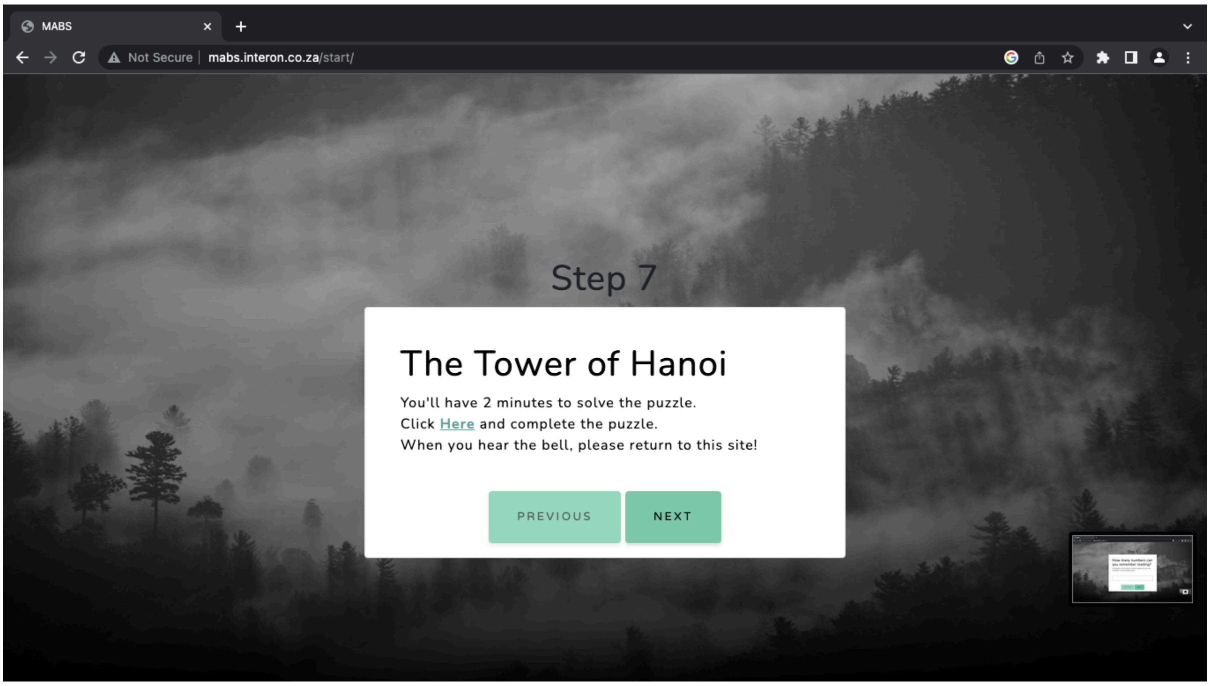


Figure G9

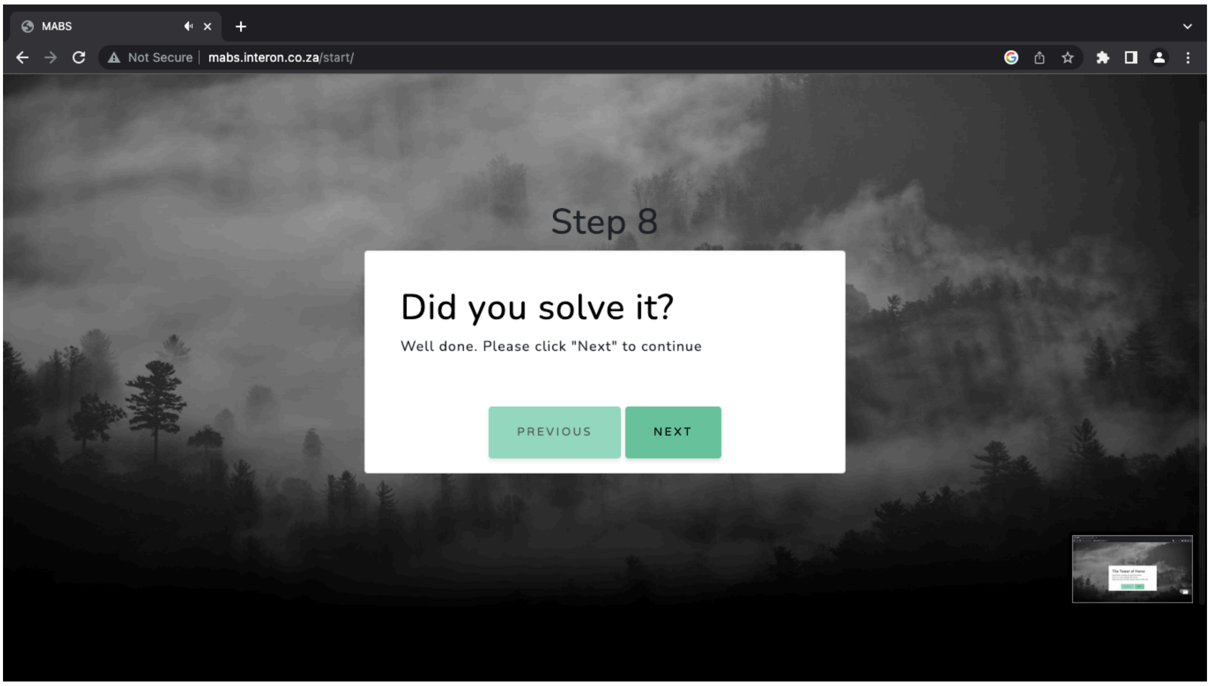


Figure G10

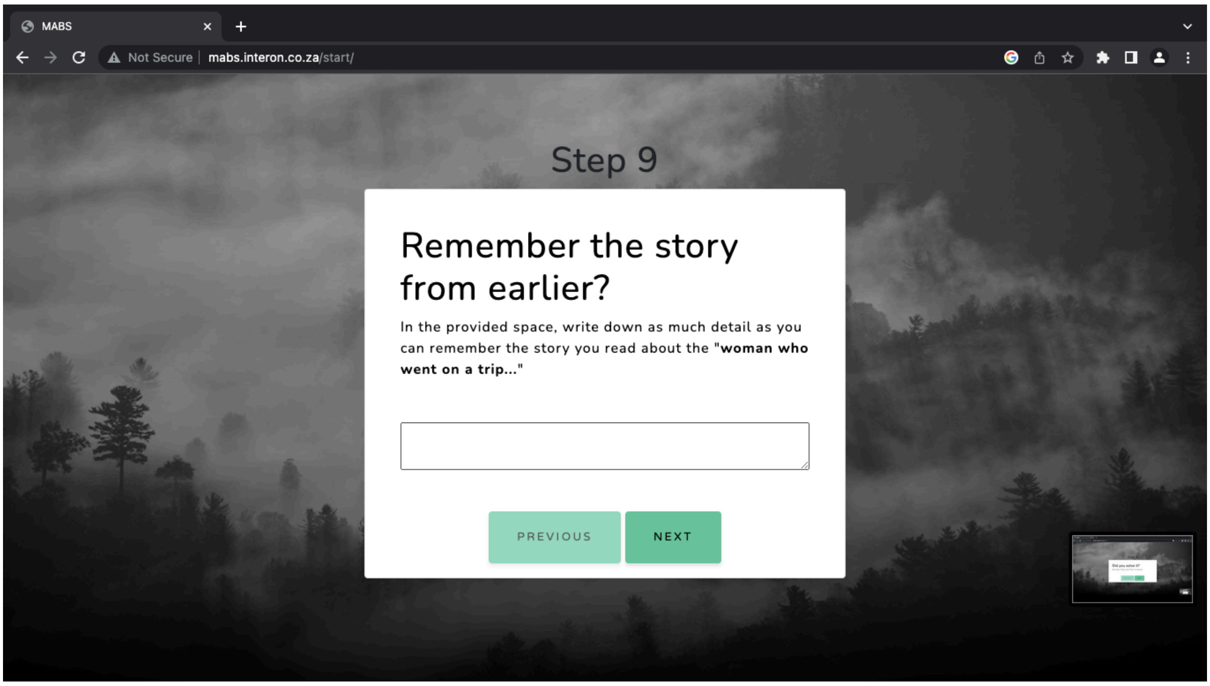


Figure G11

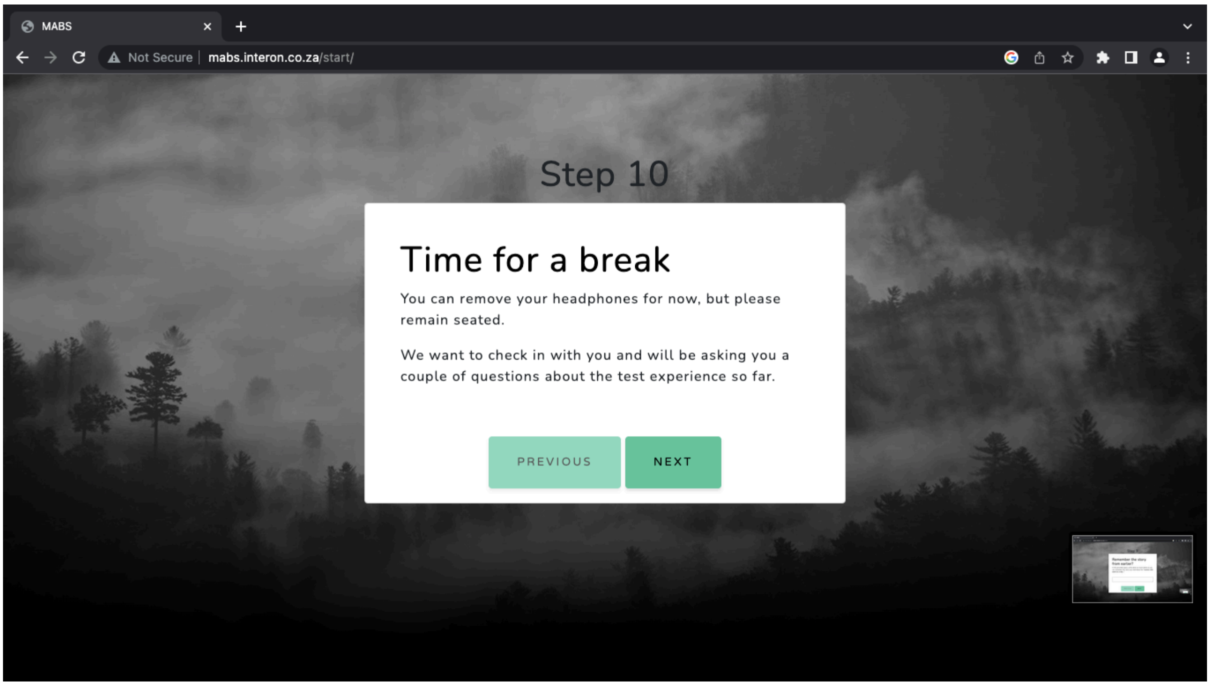


Figure G12

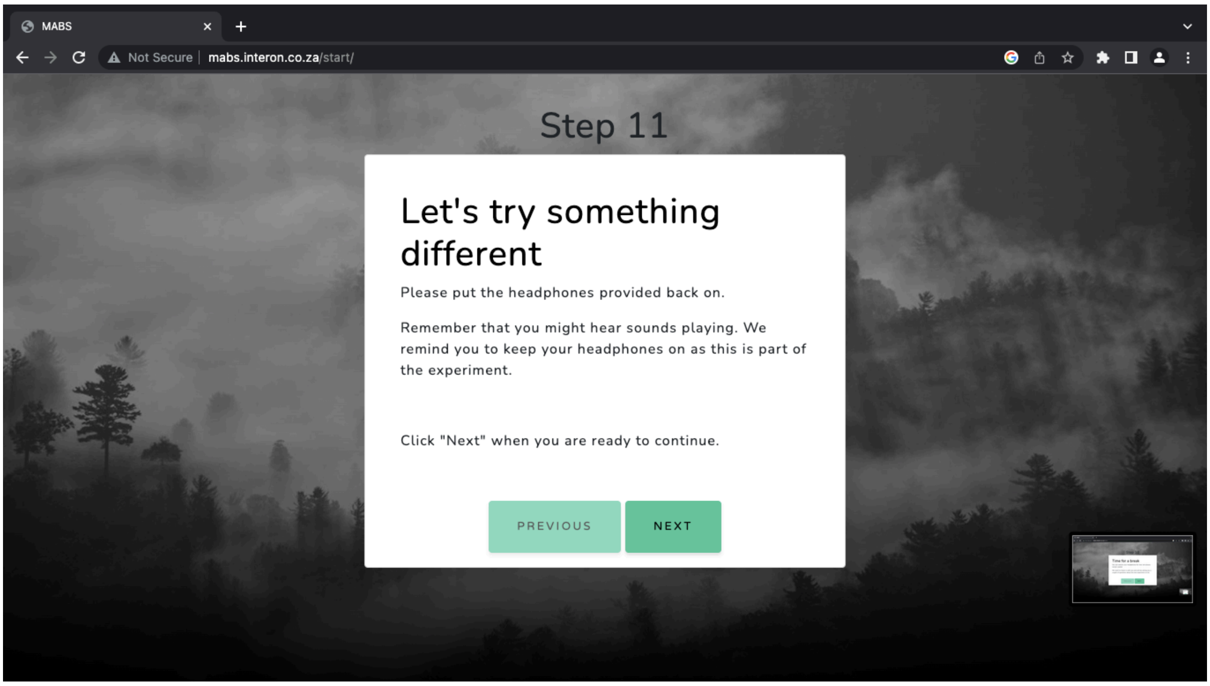


Figure G13

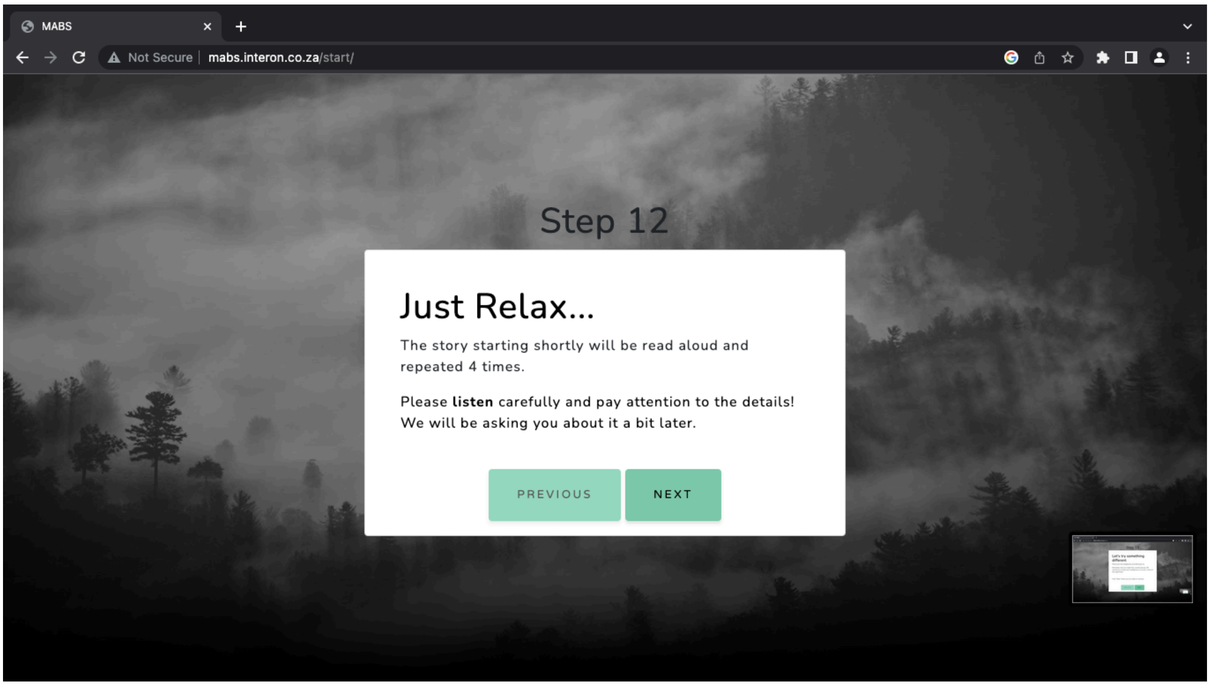


Figure G14

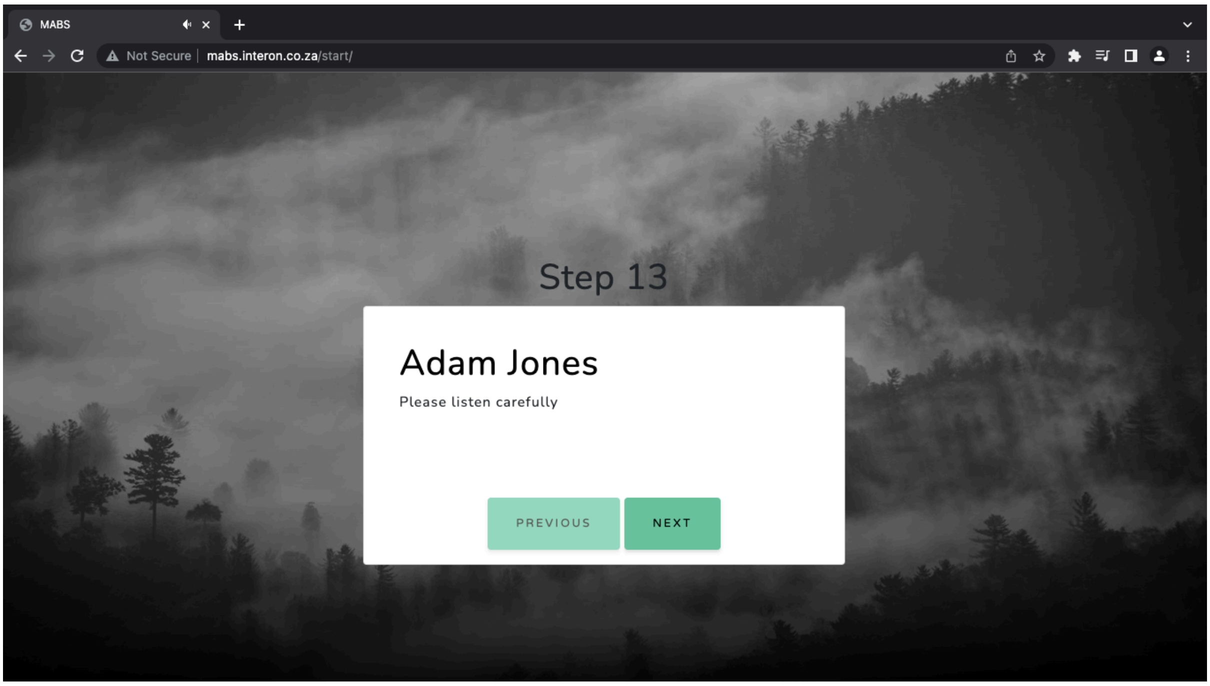


Figure G15

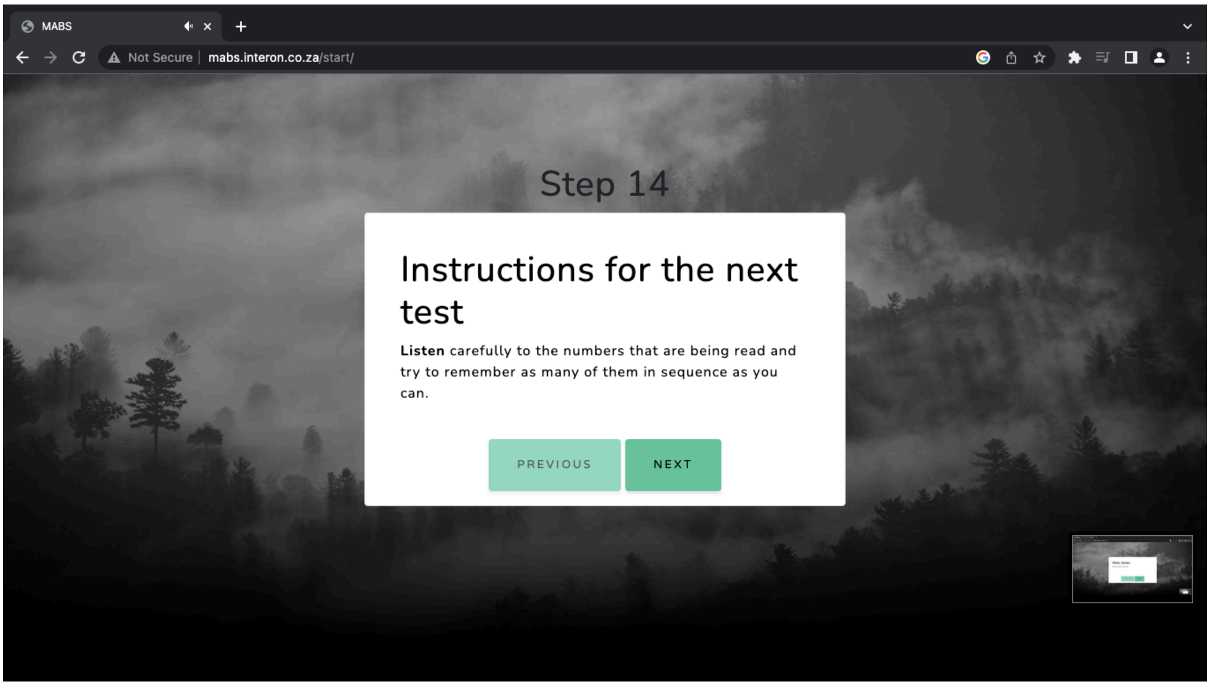


Figure G16

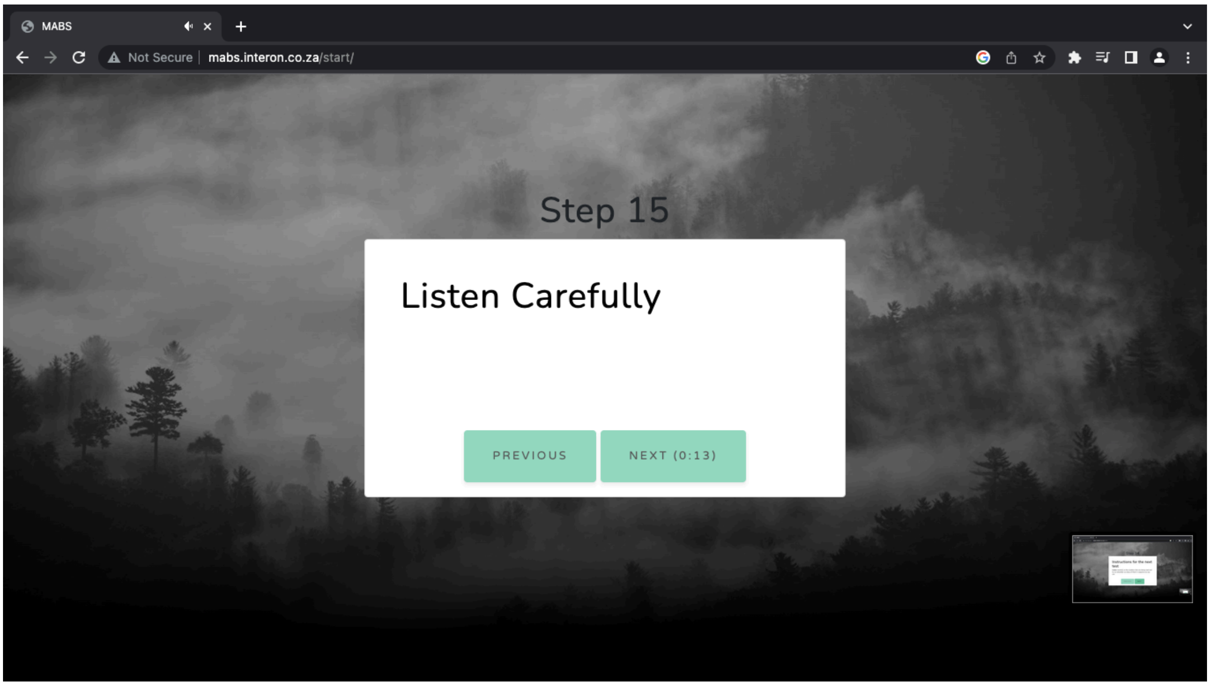


Figure G17

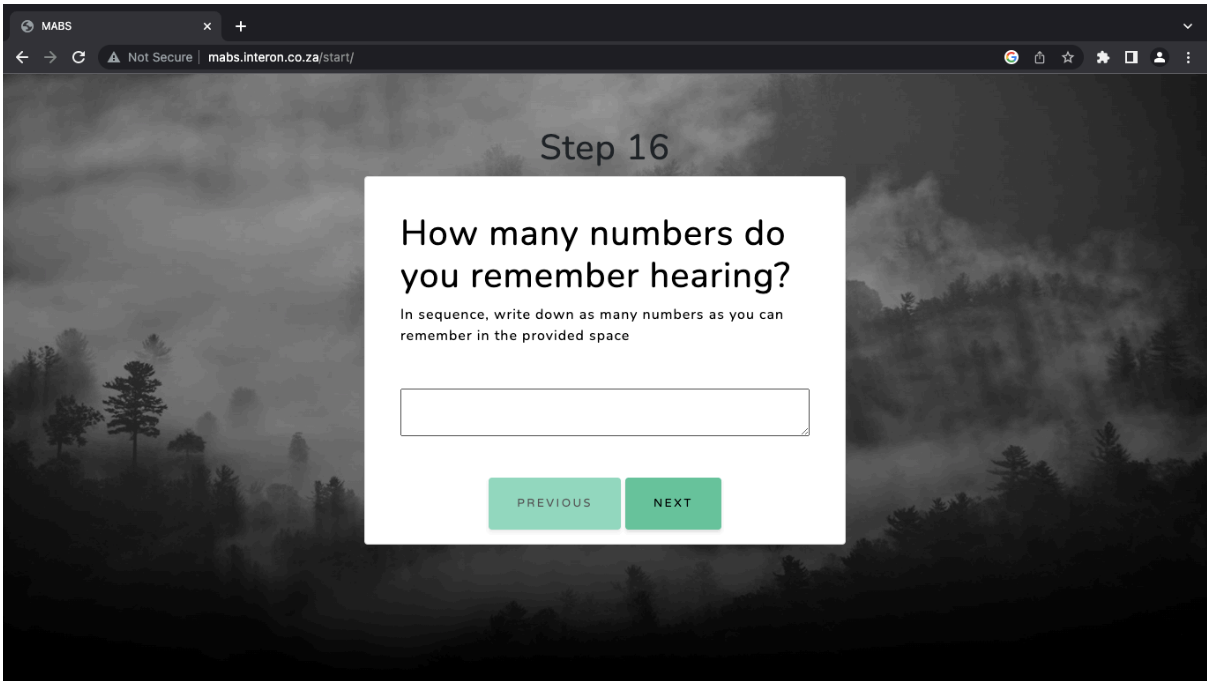


Figure G18

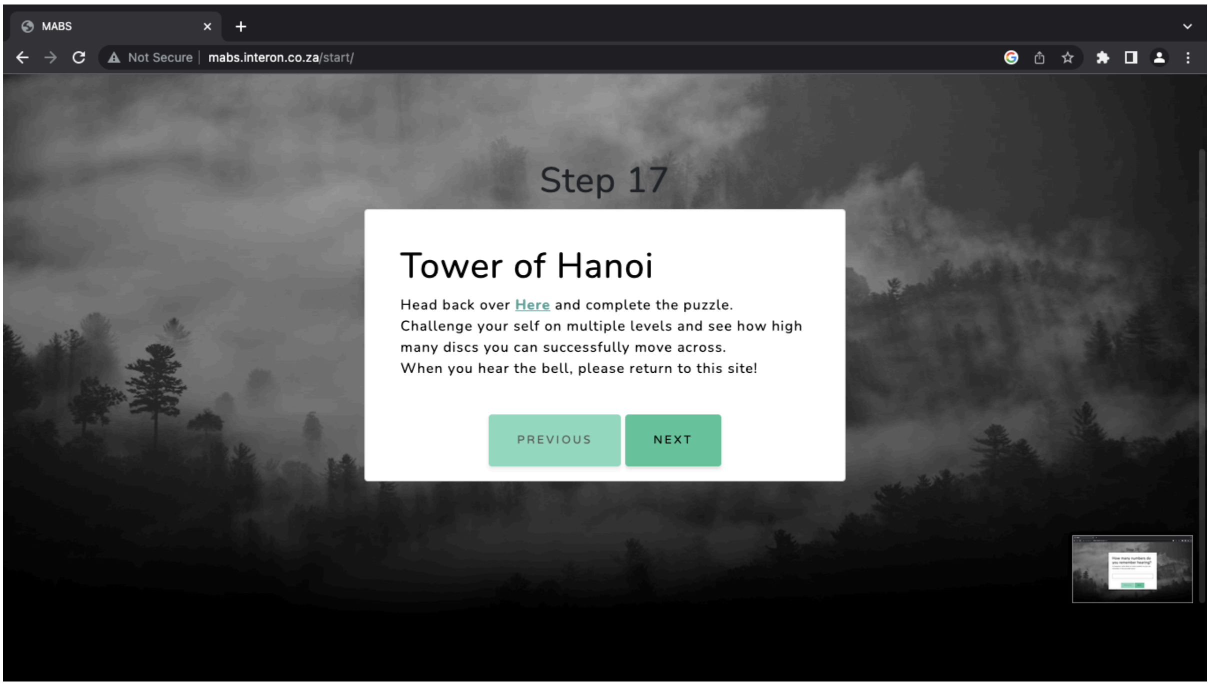


Figure G19

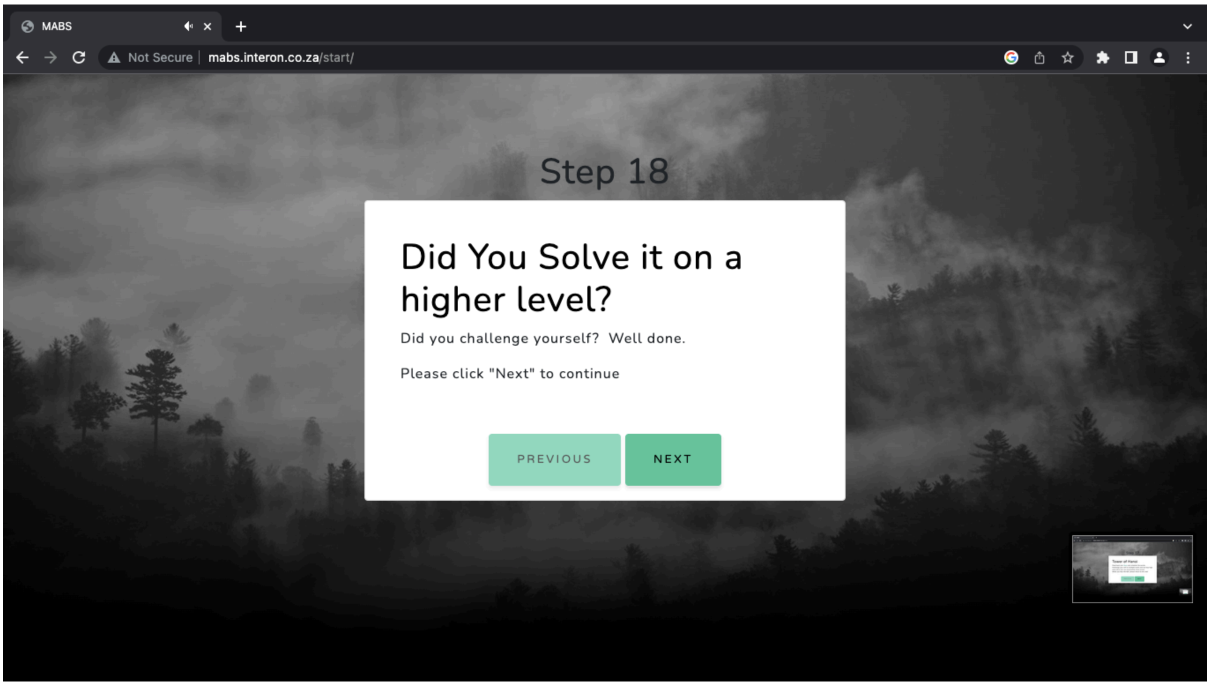


Figure G20

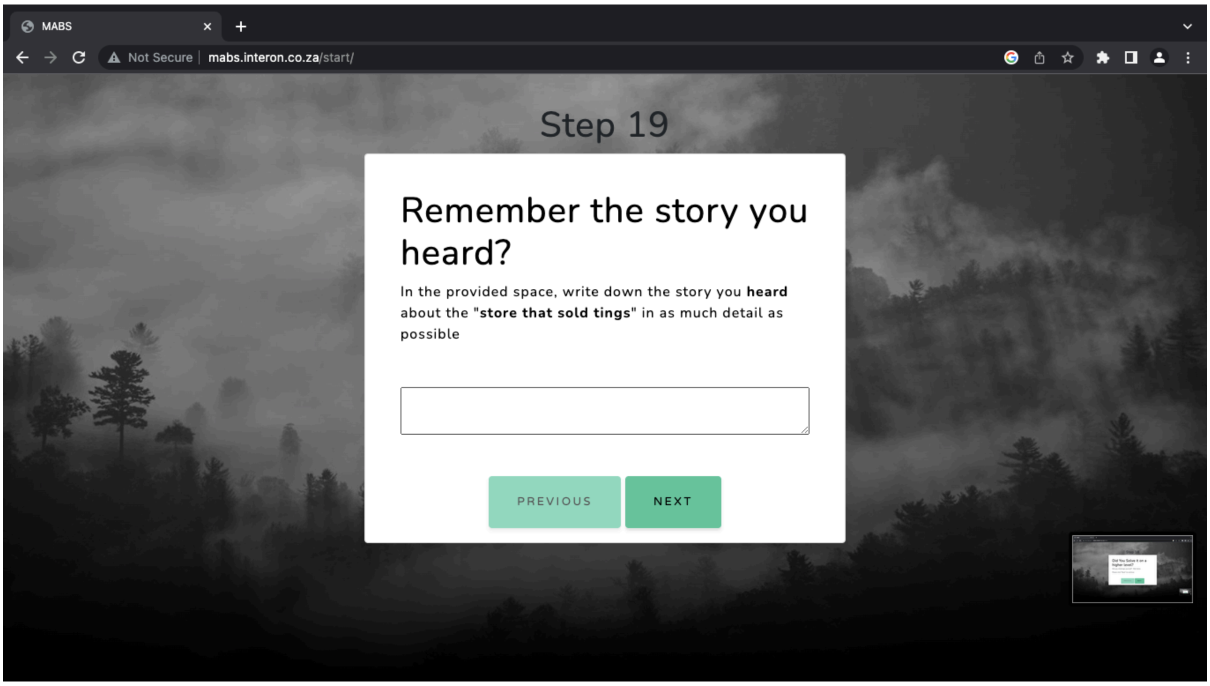
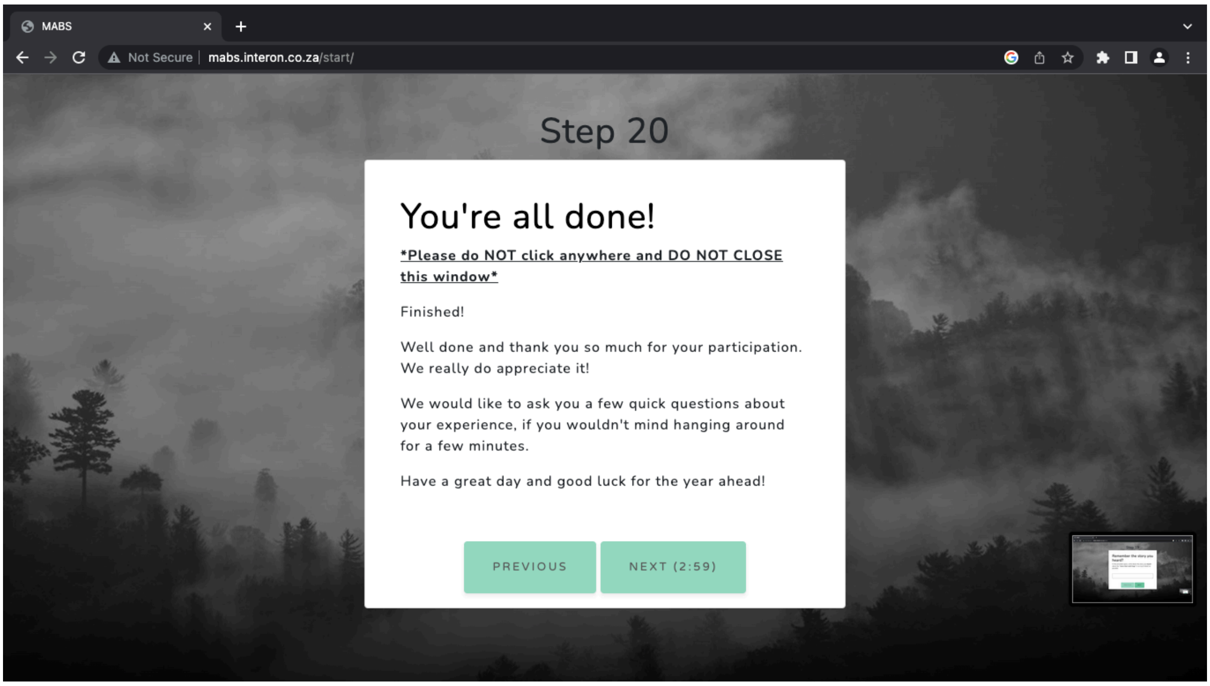


Figure G21


MABS
Not Secure | mabs.interon.co.za/start/
Step 20
You're all done!
Please do NOT click anywhere and DO NOT CLOSE this window
Finished!
Well done and thank you so much for your participation. We really do appreciate it!
We would like to ask you a few quick questions about your experience, if you wouldn't mind hanging around for a few minutes.
Have a great day and good luck for the year ahead!
PREVIOUS
NEXT (2:59)