OPTIMIZING MEMORY DISCRIMINATION USING RHYTHMIC BRAIN STIMULATION

by

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A THESIS

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This study aims to test whether theta-band sensory neural entrainment (5 Hz) can reduce memory interference and improve memory discrimination. Memory interference arises when similar memories compete, leading to confusion between related stimuli. Prior research indicates that theta oscillations play a critical role in memory encoding and retrieval, and inducing neural entrainment through sensory stimuli can modulate these processes. I hypothesized that memory accuracy would be highest when stimuli are presented at the peak (0°) phase of the entrainment echo, reflecting an optimal state for mental replay, and that correct responses are associated with increased theta power. Participants (N=100) took part in a two-part behavioral test to entrain and test their memory of similar stimuli. The current study investigates a novel, non-invasive approach to reduce memory interference, with potential implications for learning, low-cost cognitive therapy, and age-related memory decline.

Acknowledgements

I would like to thank Professor Brice Kuhl for guiding me throughout this project and allowing me to explore a novel topic that fits my personal interests. I feel blessed to have started this research position so early in my undergraduate career, as it has opened the door to amazing opportunities and helped guide my career interests. I would also like to give a big thanks to my primary mentor, Doctor Soroush Mirjalili, who has made this experience so enjoyable. Soroush helped me throughout every step of this process, from aiding in the literature review to coding the protocol and forming exploratory analyses for me to develop as a researcher. With Soroush’s help, I was able to receive great funding support and awards through this project. I must also thank Dr. Nicole Dudukovic, my major advisor, who guided me through my undergraduate planning and acted as a fantastic mentor throughout this project. In addition, I would like to thank my CHC representative, Dr. Lydia Van Dreel, for their interest in my topic through their shared love of music. Also, I would like to thank Oregon alumni Tom and Cathy Hui for their financial support, providing me the peace of mind to work on this project stress-free and feel rewarded for my research development. I also have to thank Karl Reasoner, who guided me through the Hui Undergraduate Research Scholars program, acting as an amazing mentor throughout the project. Lastly, I would like to thank my friends and family for their loving support in my development as a young researcher over the past four years.

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Introduction and Literature Review

What is Memory?

Memory can be thought of as an enormously long filing cabinet. We store some information and later retrieve it, like putting a folder into the cabinet and taking it out later. The American Psychological Association defines memory as: “the ability to retain information or a representation of experience, based on the mental processes of learning or encoding, retention across some interval of time, and retrieval or reactivation of the memory” (APA, 2018). This definition, however, fails to encapsulate the complexity of memory in both a cognitive and physiological sense.

For this reason, memory is complex, an integrative network composed of intertwining parts and connections that together form a functioning system that does more together than it would through its separated parts, like an orchestra (Raslau et al. 2014).

Memory can be divided into many subcategories, the broadest being sensory memory, short-term memory (STM), and long-term memory (LTM) (Zlotnik & Vansintjan, 2019). Sensory memory is unconscious, holding short pieces of information to either be processed further or discarded, which can be visual, auditory, haptic (touch), olfactory (smell), or gustatory (taste). STM stores information for a brief period of time, longer than sensory memory, and requires attention to further process the information. Working memory, closely related to STM, is associated with the cognitive processes for doing quick tasks that don’t need deep processing, like solving problems, having a conversation, and other cognitive strategies to achieve short-term goals (Khalili, 2024). LTM can be distinguished from STM based on its larger capacity and longer duration. Differentiating and defining STM and LTM is controversial, as both contain complex models and mechanisms.

LTM can be divided into declarative memory (explicit or conscious) and procedural memory (implicit or unconscious). Declarative memory can then be further subdivided into semantic memory and episodic memory, which is the focus of this thesis. Semantic memory includes “the memory necessary for the use of language” (Tulving, 1972), like knowing Autzen Stadium is where the Oregon Ducks play. In contrast, episodic memory is “temporally dated episodes or events, and the temporal-spatial relations” (Tulving, 1972), such as remembering your first football game. Unconscious, procedural memory includes skill learning, like learning to catch a ball, conditioning, like salivating when seeing food, and priming, like seeing a soda advertisement and later craving a soda (Raslau et al. 2014).

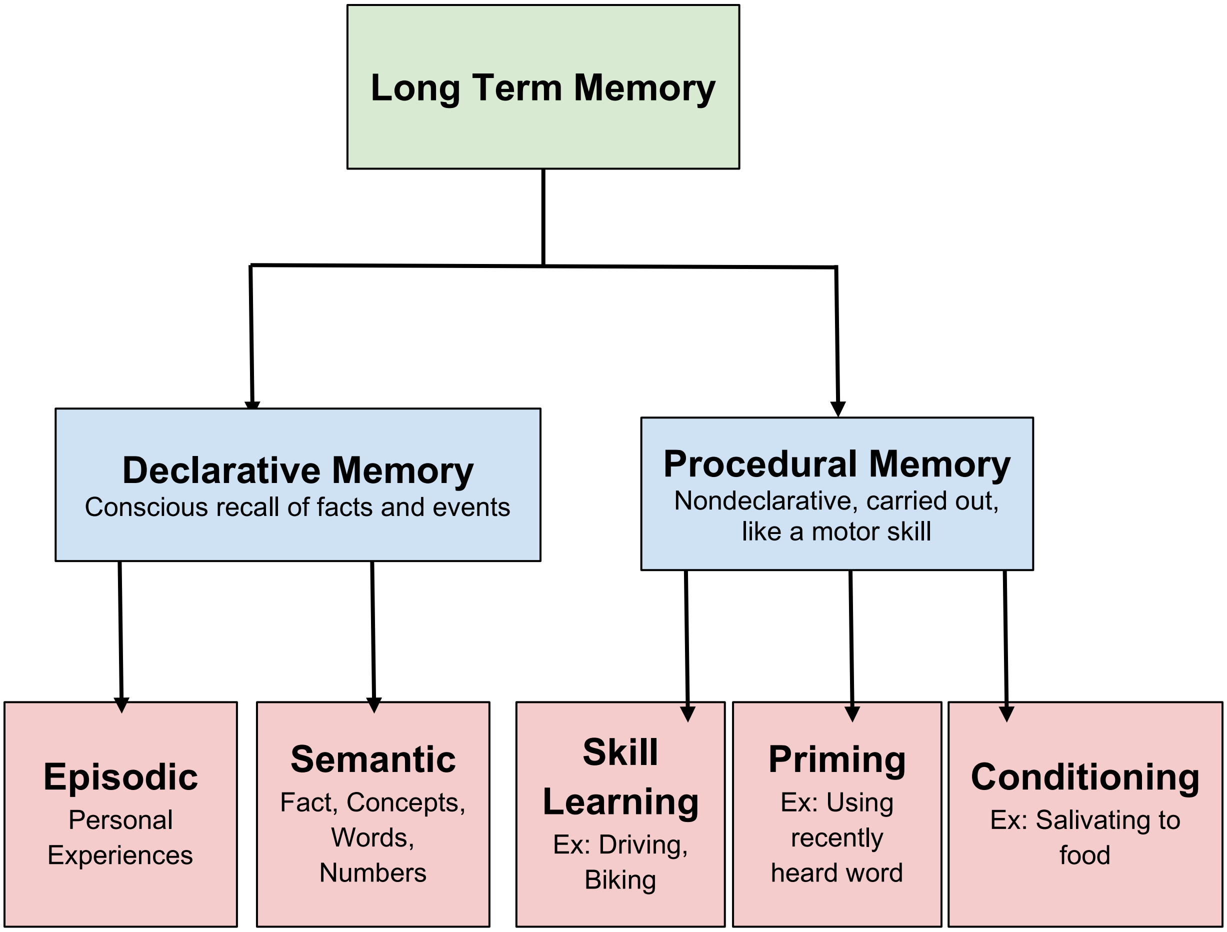


Figure 1: *Adapted from Raslau et al, 2014. A tree showing categories of memory. Showcases the relevance of episodic memory compared to other subtypes*

The Anatomy of Memory

Studying the brain's anatomy can help us understand how different areas of the brain function. For instance, researchers can understand which areas are responsible for a cognitive task by monitoring the brain's electrical activity and hemodynamic response, the rapid changes in localized blood flow volume and oxygenation. This idea can be utilized in memory tasks like encoding (forming memories), organizing, and retrieving memories (Preston & Eichenbaum, 2014). Two distinct pathways assist in these processes, the 'what' and the 'where' pathways. The 'what' pathway includes information about objects, events, and experiences we have. First, sensory pathways for vision, touch, hearing, etc., process information about the information's identity, then pass it along to cortical 'association' areas (temporal, parietal, and other cortical areas). This 'where' pathway is about the place, the spatial context of the memory. These pathways interact with the prefrontal cortex, but the streams separate en route to the hippocampus. The 'what' stream into the perirhinal cortex and the lateral entorhinal area, the 'where' stream into the parahippocampal cortex and the medial entorhinal area. The streams then converge on the hippocampus, where cohesive memories are formed, combining the quality of the event with the context in which it occurred (Preston & Eichenbaum, 2014).

One theory of the relationship between the medial prefrontal cortex (mPFC) and the hippocampus is that the hippocampus forms and retrieves memories, while the mPFC combines features of similar memories to provide context for other experiences with a memory. When the hippocampus attempts to retrieve that memory, there is a bias toward retrieving it due to the context. A study showed that different groups of neurons in the mPFC fire together in different environments (Hyman et al. 2012). There is also evidence of a bidirectional relationship between the mPFC and hippocampus, as they work together to create and retrieve memories.

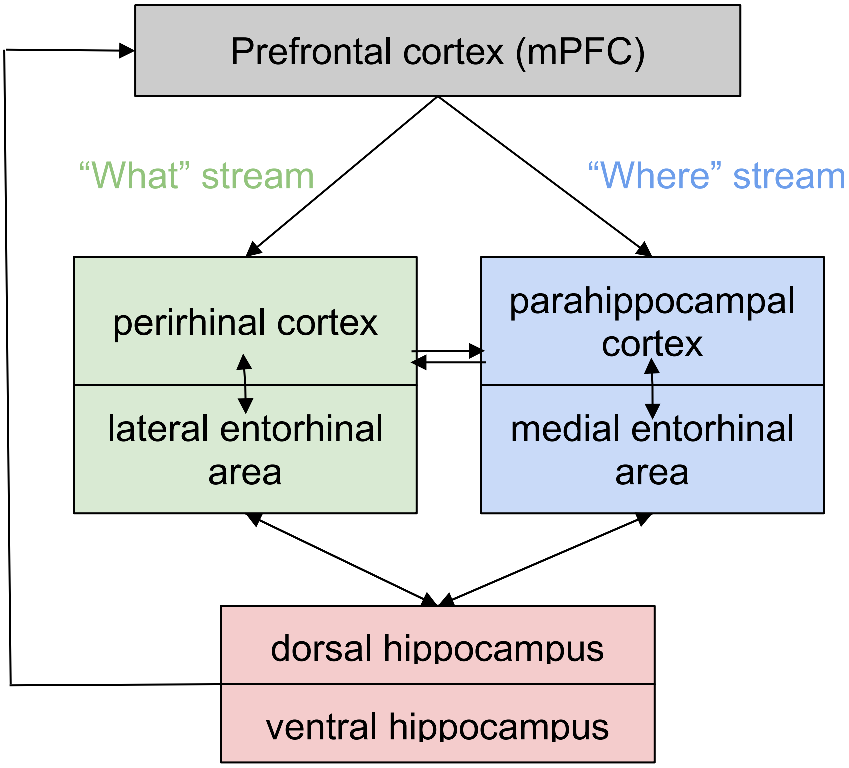


Figure 2: *Adapted from Preston & Eichenbaum, 2014. "Interplay of Hippocampus and Prefrontal Cortex in Memory". Displays the interconnectivity between the hippocampus and the prefrontal cortex*

Neural Oscillations

The brain uses electrical and chemical signals to communicate and form human cognition. The brain has rhythmic patterns with various functions in both stages of sleep and wakefulness. Neural oscillations are rhythmic patterns of electrical neural activity that play a role in many cognitive processes.

An example is the central pattern generator (CPG), a synchronized firing pattern of neurons that forms rhythmic motor patterns, such as walking, running, or swimming. Evidence of CPGs is widespread in animals (Widmer & Wiman, 2018), but has only begun to emerge in humans (Danner et al., 2015).

Oscillations can be characterized by many features, including their frequency (rate of firing per second), amplitude (magnitude of the electrical change), and period (time to complete one cycle). The oscillations themselves don’t serve specific cognitive functions, but rather these characteristics and associated brain networks do. For example, beta waves (12.5-30 Hz) are commonly associated with active thinking, problem solving, and concentration (Baumeister et al. 2013). Theta waves (4-8 Hz) specifically in the fronto-parietal network are associated with memory processes (Arkturk et al, 2022).

Theta Waves & Episodic Memory

The hippocampus has been found to produce theta wave frequencies (Sun & Bao, 2025). These hippocampal theta oscillations are synchronized with many brain regions involved in memory formation and retrieval. Many of these regions are sensory, primarily auditory and visual areas. Together, the hippocampus and the prefrontal cortex form a neural circuit in which theta oscillations convey early memory information to the PFC and synchronize theta activity between the two brain regions during memory formation and retrieval. (Zangbar et al. 2020).

Episodic memories are often multisensory events, like remembering the colors (visual) and smells (auditory) of a rose garden. Recent studies have shown that the success rate of encoding sensory information into episodic memory can be predicted by phase synchronization between visual and auditory brain regions (Wang et al. 2018). The brain receives external sensory stimuli from the environment, where the sensory cortex generates theta rhythms, leading to synchronization with the hippocampus. This synchronization improves episodic memory (Clouter et al. 2017).

The phase of the theta wave has also been connected to long-term potentiation (LTP) and long-term depression (LTD). LTP is the process of strengthening synapses, which leads to those neurons firing together more frequently. LTP plays a major role in learning. LTD is the opposite of LTP, as neuroscientists say, ‘If you don’t use it, you lose it’. The fewer synapses communicate with one another, the less likely they are to maintain those connections. LTP was discovered to be associated with the peak of the theta rhythm, and LTD with the trough of the theta waveform (Hyman et al., 2003; Heurta & Lisman, 1995).

Entrainment

Studies have shown that sensory perception and motor production are rhythmic, like in central pattern generators. These rhythms are often matched to frequencies, leading to coupling between them (Lakatos, 2019). In several cognitive measures, different senses have shown an intrinsic rhythmicity. In speech and music, across languages, a consistent frequency range of temporal modulations was discovered (Ding et al. 2017). An electroencephalography (EEG) study showed a consistent phase pattern when sustaining visual attention (Busch & VanRullen, 2010). These are just a few modalities of rhythmicity through sensory stimulation.

Scientists developed a way to modulate oscillations to test the relationship between cognitive functions and their rhythmic-like activity. Entrainment modifies naturally occurring oscillations in response to wave-like external stimuli to elucidate causality in cognitive functions such as memory and attention (Hanslymayr et al., 2019). In other words, entrainment combines two interacting oscillatory systems to synchronize their frequencies through manipulation. For instance, if you listen to an EDM song with a constant beat, some network in your brain will start firing neurons at that frequency for however long the song goes. Your motor system may prompt you to start tapping your foot or bopping your head to help predict the next beat. In this way, your brain is synchronizing, or “entraining” to that rhythm.

Initially, many single-sensory domain entrainment studies were conducted to establish which cognitive models match which frequencies, attempting to isolate a single frequency band to improve function. One of the first entrainment studies used flickering visual stimuli and found a significant increase in memory performance when entrained in the alpha frequency (10 Hz) (Williams, 2001). Using auditory rhythmic stimulation, memory performance increased when stimuli were presented in both ears at the beta frequency (20 Hz) (Argibay et al., 2017). A mouse model study found that firing hippocampal neurons at only the gamma frequency (40 Hz) reduced levels of β-Amyloid plaque, a key feature of Alzheimer’s disease (Iaccarino, 2016).

As a reminder, episodic memory involves multiple sensory domains. Acknowledging that the theta frequency (4-8 Hz) is relevant to memory formation and retrieval, especially in the multisensory domain, researchers hypothesized the role of entrainment in memory performance. Researchers turned to entrainment measures, noting the importance of the theta phase in promoting LTP. (Hyman et al., 2003; Heurta & Lisman, 1995).

In the multisensory domain, researchers presented audiovisual stimuli in which subjects made associations between the video and the audio (Clouter et al., 2017). They modulated the luminance (brightness) of the visual stimuli and the amplitude (loudness) of the auditory stimuli. The stimuli were phase-locked, meaning both the auditory and visual stimuli, and their waveforms, matched. As the video gets brighter, the volume increases; as it gets dimmer, the volume decreases. When these stimuli were presented synchronously (at the same time and phase difference of 0°) and modulated at a theta frequency (4 Hz), they had significantly better memory than at other frequencies (1.7 or 10.5 Hz) or when the visual and auditory stimuli were not in perfect synchrony, at 90°, 180°, or 270° phase differences (Clouter et al, 2017). They demonstrated a causal role of theta phase synchronization for the formation of human memories. It also showed that phase synchronization during associative multisensory memory formation was observed only at theta frequency.

Wang et al. followed up on Clouter et al.'s study by replicating its findings and building on them. They found that, on a trial-by-trial basis, phase synchrony between the different sensory cortices predicts subsequent success in encoding the association between sensory information and long-term memory (Wang et al. 2018). They also demonstrated that theta phase synchronization is important for episodic memory formation and that theta binds multisensory information. Stronger entrainment at 0° leads to successful memory, whereas strong entrainment at 180° leads to failure in episodic binding. In line with previous findings, different phases within theta either promote encoding or retrieval of episodic memories (Hasselmo et al., 2002).

Entrainment Echo

The entrainment echo is a recently discovered phenomenon where, once a neural system is fully entrained within a long enough period of time (the oscillation pattern of the external stimulus matches the internal neural firing pattern), the neural response lasts 1- 1.5 seconds after the external stimulus is removed (Hanslymayr et al, 2014; VanRulen & Macdonald, 2012). The phase and frequency are also held constant with respect to the external stimulus during the echo period, whereas the power decreases over the 1-1.5-second period. These studies were done at the alpha and beta frequency bands. Only one published study has examined the entrainment echo in the theta frequency band, which was strictly an auditory-perception study (Hermite & Zoefel, 2023). My current study sought to demonstrate the effectiveness of the entrainment echo in memory recollection with visual stimuli. I also sought to replicate the phase and frequency hold-up in the entrainment echo period in the theta band.

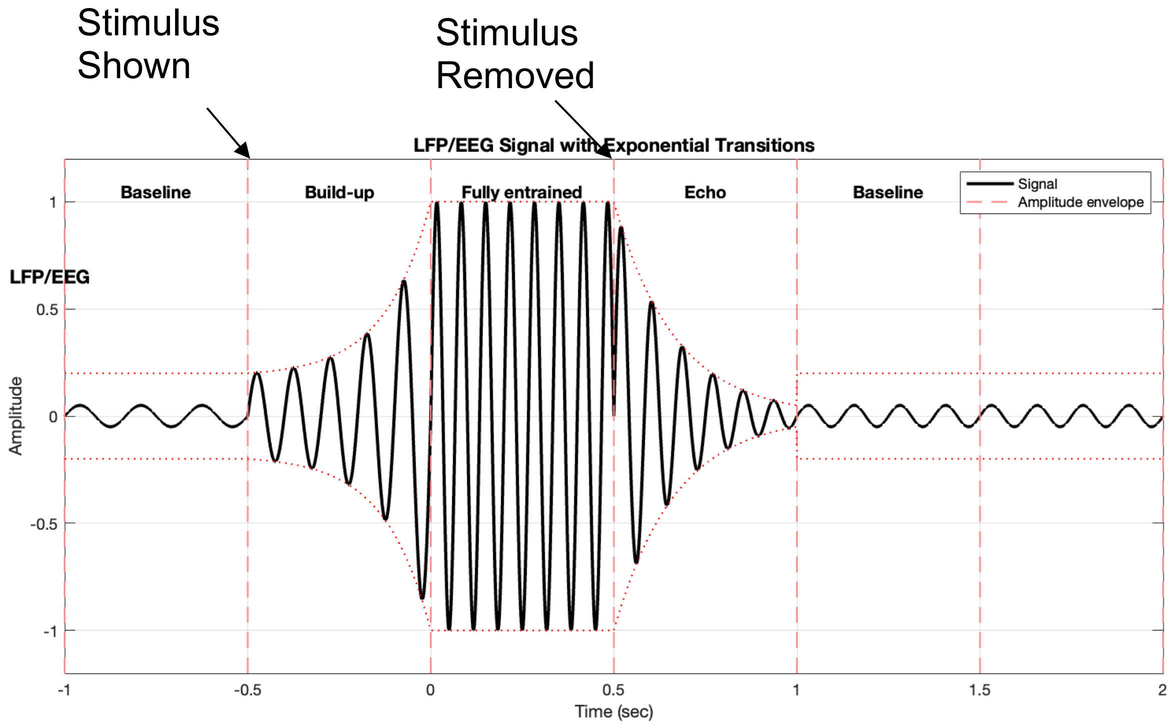


Figure 3: *Replicated from Hanslmayr et al.'s review paper "Modulating Human Memory via Entrainment of Brain Oscillations". Showcases the echo period, describes the neuronal oscillation matching that of the external stimulus, and showcases that the signal remains even after the stimulus is removed (echo period)*

Theta-Gamma Coupling

Gamma bands have also been linked to memory processes. The theta-gamma coupling network is the synchronized interaction between theta (4-8 Hz) and gamma (30-100 Hz) frequencies mediated by the hippocampus (Hanslmayr et al, 2015). Studies have shown that this theta-gamma coupling is important for many cognitive functions, such as learning, memory formation, and retrieval.

Researchers have hypothesized that theta-gamma cross-frequency phase coupling, in which gamma oscillations are locked to specific phases of theta (peak or trough), has causal effects on episodic memory. For example, applying gamma-tACS in the temporal lobe to the trough phase of the theta-tACS cycle impaired verbal episodic memory, but showed no impact at the peak phase (de Lara et al, 2018). Another study showed that stimulating gamma oscillations in the peak phase of theta improved working memory performance, whereas at the trough it showed no significance (Hanslmayr et al., 2019). A further study suggests that gamma is coupled to specific theta phasers for encoding and recall processes (Chanaz et al, 2023).

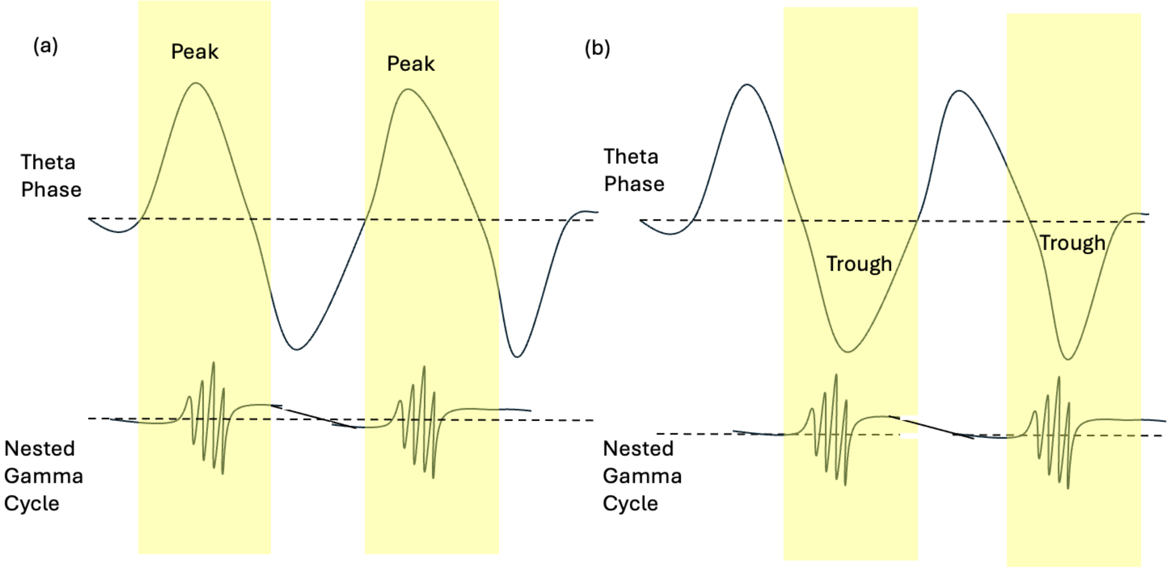


Figure 4: *Theta Gamma Cross Frequency Amplitude Coupling, Adapted From Arulchelvan et al, 2023 Review: "Promising neurostimulation routes for targeting the hippocampus to improve episodic memory" (a) Gamma oscillations nested in peak of theta phase, (b) Gamma oscillations nested in trough of theta phase*

Neurostimulation Studies

Neurostimulation techniques are emerging as promising methods for activating the hippocampus and enhancing episodic memory performance, specifically transcranial electrical stimulation (tES) (Arulchelvan & Vanneste, 2023).

tES approaches, such as transcranial alternating current stimulation (tACS) and transcranial direct current stimulation (tDCS), compared to other neurostimulation approaches such as deep brain stimulation (DBS) and transcranial magnetic stimulation (TMS), are safer, cost-effective, portable, and easier to study (Arulchelvan & Vanneste, 2023).

These approaches aim to increase the hippocampus' functional connectivity with key brain regions, strengthen synaptic plasticity (LTP), and enhance neural entrainment in the theta frequency band. Patients who suffer from amnesia, such as Alzheimer's disease, which is commonly linked to early loss of episodic memory, look to benefit from neurostimulation methods as a therapeutic technique.

Studies have shown that noninvasive, indirect stimulation measures may benefit memory formation and retrieval, specifically at the theta rhythm, and even improve memory beyond the stimulation (Arkturk et al., 2022).

A recent study showed that theta-synchronization stimulation can affect communication between brain regions and entrain the hippocampal network by stimulating the lateral temporal cortex. The boosted synchrony between these two regions lasted several minutes after stimulation, indicating sustained effects. This increased theta-synchronization power may impact network communication as a whole more than individual regions/nodes (Kragel et al, 2025).

Arulchelvan and Vanneste, in their review paper "Promising neurostimulation routes for targeting the hippocampus to improve episodic memory," suggested that although previous sensory-behavioral studies at theta frequency showed positive memory effects, gamma (40 Hz) frequency may have greater therapeutic effects. A mouse study demonstrated that all three of Alzheimer's disease's key histopathological manifestations (neuronal cell death, extracellular amyloid plaque deposits, and intracellular p-tau neurofibrillary tangles) were reduced through auditory or visual gamma frequency stimulation (Adaikkan & Tsai, 2020; Chan et al., 2022; Chen et al., 2022; Martorell et al., 2019). This supports the theta-gamma frequency model, in which each frequency band is strongly related to the others.

Neurostimulation is a promising approach for helping individuals with memory impairments strengthen connections between networks and enhance episodic memory formation and retrieval. There are still years of research before these findings translate into patient care, as optimal stimulation frequencies may vary across patients (Arulchelvan & Vanneste, 2023).

The Current Study

I aimed to replicate previous findings on theta-wave entrainment and memory performance. I then expanded on previous literature by showing the relevance of the echo period discussed in Hanslmayr's review paper. With this echo period, I hoped to show the impacts of entrainment on memory interference.

Methods

Participants

40 participants aged 18-25 (29 female) completed the first behavioral study, 43 (31 female) participants completed the second behavioral study, and 17 (12 female) participants completed the third behavioral study. Behavioral tests one and three were identical, but differentiated within our analysis as group data were collected six months apart. All participants were students from the University of Oregon. Students were recruited via the Psychology Department Human Subjects Pool. Students with a history or family history of epilepsy were excluded from this experiment. Participants provided informed consent following the University of Oregon Institutional Review Board.

Stimuli

125 distinct scenes were generated using OpenAI and Midjourney. Images were collected through Google searches. Images were selected based on distinguishability and recognizability, including familiar scenes like buildings, stores, houses, and landscapes. Each image was pasted into OpenAI's Chat GPT, where the AI was asked to create a prompt for Midjourney, a generative image artificial intelligence service. Each prompt consisted of 100-200 words, key terms in each prompt included 'hyperrealistic', 'natural lighting', 'NO people', and 'NO text'. These terminologies helped create simple art styles between scenes and prevented giveaways like people or text. The Midjourney bot in Discord generated the images for each scene. Variants that created similar scenes were generated using Midjourney's variation command on the "strong variation" setting. Each scene had four generated variants, and the three most distinct scenes were selected for usage. Each image was upscaled to 1024x1024 resolution. All steps were taken

into account to make each scene as difficult as the other between variants. However, with the current state of AI, some scenes were more easily distinguishable than others.

Behavioral Task Specifications

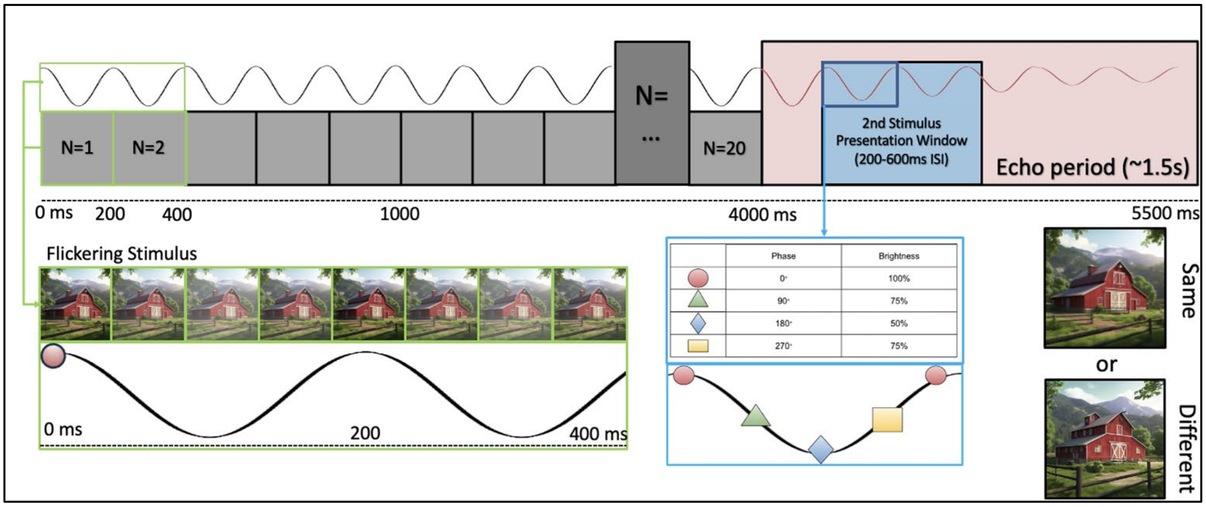
The task was presented through the PsychoPy desktop application, which was displayed on a 17-inch computer screen. Stimuli were rendered against a gray screen, and this computer had a refresh rate of 120 Hz. Participants sat approximately 100 cm away from the screen. Each scene was presented in the same, centered location of the screen. The behavioral room used was the same across participants, on the 3rd floor of the Lewis Integrative Science Building (LISB) at the University of Oregon.

Behavioral Task Procedure

The behavioral task consisted of four blocks, each divided into two phases: an entrainment phase and a memory phase. Participants were prompted with the instructions before the experiment began, via a script given by the researcher. Participants were notified that the flashing images may cause dizziness and that the experiment was accuracy-based and not reaction time-based. They were advised to take breaks between each block for this reason.

There were three total behavior tasks, consisting of 40, 43, and 17 participants, respectively. The third behavioral group mirrored the first one to check data validity. All three studies operated in the theta frequency band of 5 Hz, where the randomized break duration in the first and third tasks ranged from 200-600 ms with 50 ms intervals, and the second task ranged from 100-700 ms with 50 ms intervals.

Entrainment Phase: Within each block, 28 trials were presented (112 total trials). Each trial contained a flickering scene, followed by a still scene. The still scene was either identical to the flickering scene or a similar variant (as shown in Figure 5). Participants were prompted to select whether they thought it was identical or slightly different, selecting 1 or 2 on the keyboard, respectively. Each flickering image followed a 5 Hz cosine wave oscillatory pattern, varying in luminance (brightness) from 50-100% (Wang et al. 2018). Each scene was randomly assigned to begin at a different initial phase (0°, 90°, 180°, 270°), which is equivalent to the luminance level (100%, 75%, 50%, 75%), respectively. The flickering image oscillated at a 5 Hz frequency for 4 seconds, followed by a randomized break duration, or interstimulus interval (ISI), which was shown between the flickering scene and the still scene. The exact frequency of theta was determined by averaging several previous studies (Clouter et al., 2017; Roberts et al, 2018; Wang et al, 2018; Biba et al, 2024). In the first and third behavioral tasks (n=40, n=17), this duration ranged from 200-600 milliseconds, with intervals of 50 ms (200,250,300, etc.). In the second behavioral task (n=43), this duration ranged from 100-700 ms, with intervals of 50 ms. The second behavioral task increased the ISI range to confirm further that the differences were due to phase differences and not time, while staying within the echo period length discussed in the literature (Hanslmayr et al, 2019). These randomized measures were put into place so that each scene was randomly assigned to a total phase, which is the phase difference between the initial phase, the 4-second flickering period, and the ISI. For example, a stimulus that started at a 0° phase with a 200 ms delay would have a total phase of 0°, as one oscillation is 200 ms.



	Phase	Brightness
●	0°	100%
▲	90°	75%
◆	180°	50%
▬	270°	75%

Figure 5: *Shows the scheme of an entrainment trial. The green box shows two oscillatory cycles up close. There are 20 total cycles (5 waves per second for 4 seconds). The blue box shows the presentation window of the still stimulus, whether it is the same or a slightly different scene. As seen with the red circles, if the initial flickering stimulus was shown at 100% luminance, and then shown at 200 ms or 400 ms after the flickering stimulus disappeared, there would be a 0-degree phase difference*

<u>Memory Phase:</u> Within each block, and after each entrainment phase, participants were tested on the 28 scenes from each of the four entrainment blocks. A still image of a scene was shown, and participants were asked to identify the scene as old, similar, or new. Old referred to a stimulus seen as the second stimulus in the entrainment phase, similar referred to a stimulus similar to the second stimulus in the entrainment, a new third variant of a scene, and new referred to a completely novel stimulus, as seen in Figure 6. The initial flickering stimulus was never presented in the memory phase. Of the 28 possible scenes, 14 scenes that were truly old or similar were shown. 3 new scenes were shown in each block. Over four blocks, this totals to 68 old or similar scenes and 12 new scenes being tested per participant.

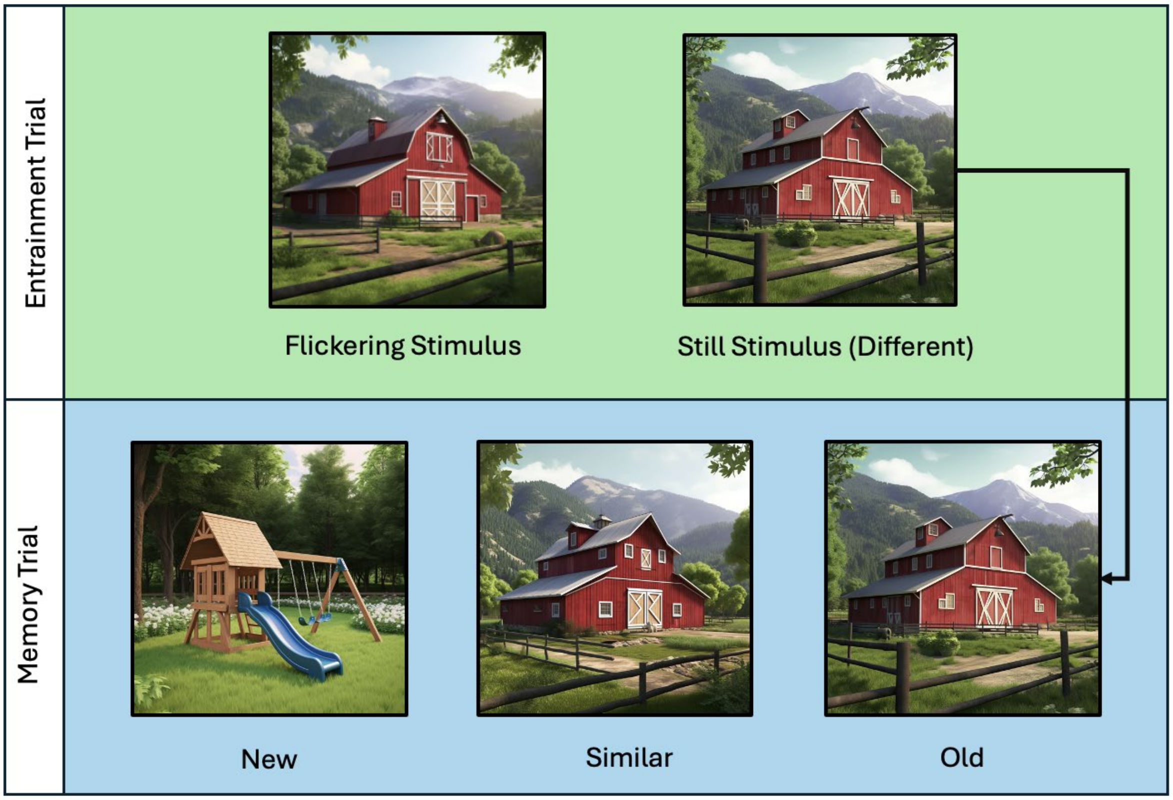


Figure 6: *This example trial shows the entrainment trial where the barn was identified as different. Then, when revisited in the memory trial, the "old" barn is the same stimulus from the entrainment trial identified as "different". If "similar", it is a new, third variant. If "new", it is a novel stimulus not seen in the entrainment trials.*

Data Analysis

Behavioral data was analyzed through R Studio. Data was pivoted by participant and total phase (initial phase + break period phase) to calculate the mean and standard error. Significance was tested using one-way repeated measures ANOVAs, followed by post-hoc within-subjects (repeated measures) t-tests, given that the ANOVAs were significant ($p < 0.05$). Plots were created using R Studio.

Comparisons were made using signal detection theory (SDT). Discrimination accuracy was calculated using (hit rate - false alarm rate). Hit rate (HR) was calculated using the simple formula (#hits/(#hits + #misses)), and false alarm rate (FA) was calculated using the formula (#false alarms/(#correct rejections + #false alarms)). Table 1 shows how each of these values is measured within the entrainment and memory phases.

Entrainment Trials

Hit: The second image shown is identical to the first, and the participant correctly identifies it as identical to the first image. (TT)

Miss: The second image shown is identical to the first, and the participant incorrectly identifies it as different from the first image. (TF)

False Alarm: The second image shown is a variant of the first, and the participant incorrectly identifies it as identical to the first image. (FT)

Correct Rejection: The second image shown is a variant of the first, and the participant correctly identifies it as different from the first image. (FF)

Memory Trials

Hit: The image shown was present in the entrainment trials, and the participant correctly identified this by selecting “old”. (oldold)

Miss: The image shown was present in the entrainment trails, and the participant incorrectly identified this by selecting “similar” or “new”. (oldsim or oldnew)

False Alarm: The image shown was not present in the entrainment trials, and the participant incorrectly identified this by selecting “old”. (simold)

Correct Rejection: The image shown was not present in the entrainment trials, and the participant correctly identified this by selecting “similar”. (simsim)

Table 1: *Operational definition of signal detection theory present in this study.*

Results

Entrainment Phase Results:

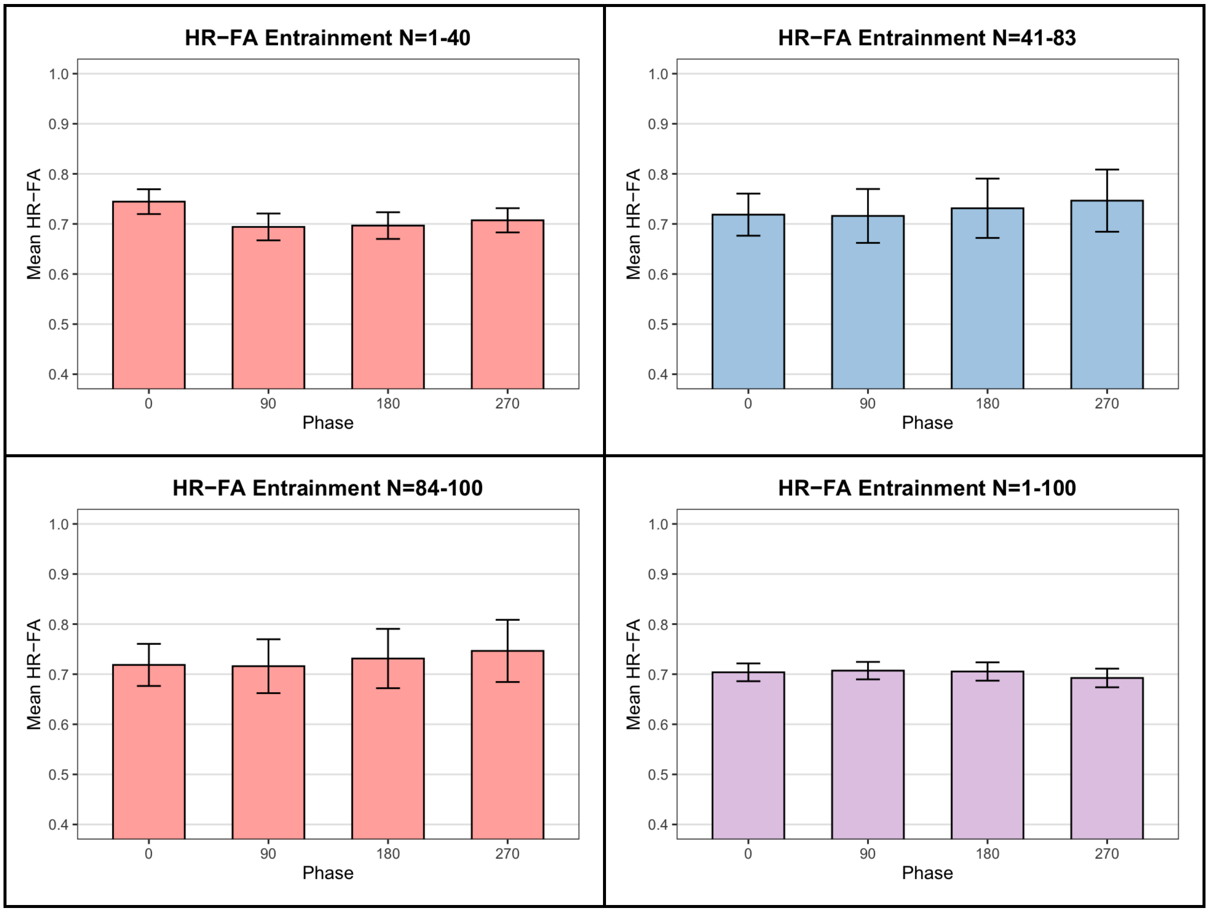


Figure 7: *Discrimination Index (hit rate – false alarm rate) for the entrainment phase. Cohort 1 (top left), cohort 2 (top right), cohort 3 (bottom left), combined (bottom right). The one-way repeated measures ANOVAs did not prompt any post-hoc t-tests, as there were no significant differences across phases for HR-FA*

Memory Phase Results

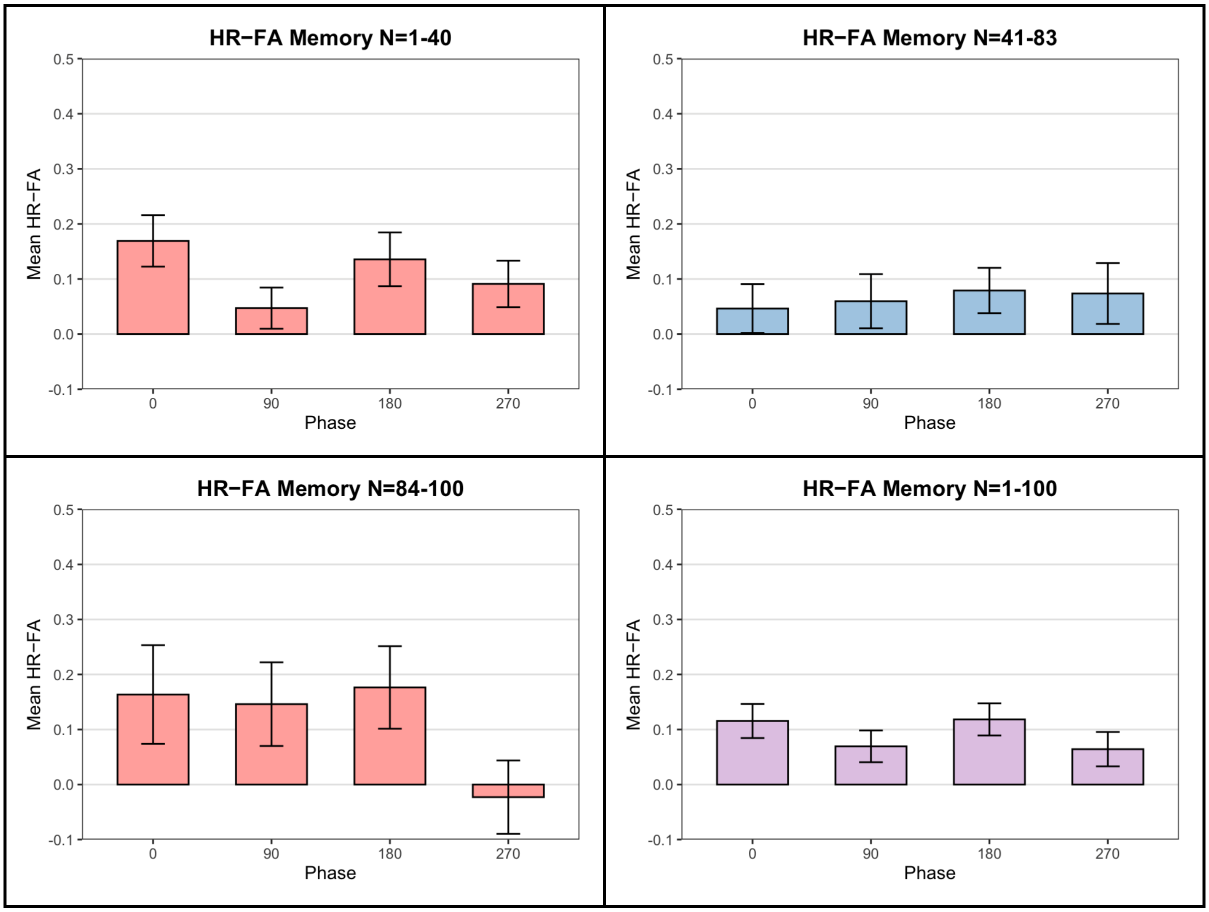


Figure 8: *Discrimination Index (hit rate – false alarm rate) for the memory phase. Cohort 1 (top left), cohort 2 (top right), cohort 3 (bottom left), combined (bottom right). The one-way repeated measures ANOVAs did not prompt any post-hoc t-tests, as there were no significant differences across phases for HR-FA*

Statistics

Entrainment	ANOVA (p value)	ANOVA (F value)
N = 1-40	0.306	1.218
N = 41-83	0.075	2.360
N = 84-100	0.856	0.257
N = 1-100	0.150	0.266
Memory	ANOVA (p value)	ANOVA (F value)
N = 1-40	0.180	1.662
N = 41-83	0.054	0.124
N = 84-100	0.198	1.614
N = 1-100	0.341	1.120

Table 2: *Provides the results of the one-way repeated measures ANOVAs and post-hoc within-subjects (repeated measures) t-tests, no ANOVA test suggested significance*

Entrainment Results Discussion: The one-way repeated measures ANOVAs did not prompt any post-hoc t-tests, as there were no significant differences across phases for HR-FA

Memory Results Discussion: The one-way repeated measures ANOVAs did not prompt any post-hoc t-tests, as there were no significant differences across phases for HR-FA

Discussion

The results of this experiment failed to support previous findings of a phase-dependent relationship between sensory theta entrainment and memory performance (Clouter et al. 2017, and Wang et al. 2018). However, these previous studies were done in a multisensory domain (audiovisual), whereas the current one only operated within the visual domain. The current study was also one of the first attempts to incorporate the topics of the echo period and memory interference within the protocol. Through these new additions, we hoped to showcase that the echo period can be detectable through a behavioral paradigm, as well as display how memory interference is phase-dependent.

Within the memory segment of the experiment, we hypothesized that previous on-phase trials within the entrainment phase would later improve distinguishability and reduce memory interference, leading to the creation of separate, distinct memories. Since our entrainment trials fell short of improving memory performance, this secondary memory test also failed to show significant findings.

One possible explanation for the lack of significant findings is the interpersonal differences in visual processing delays. Under this experiment's paradigm, it was assumed that participants had no visual processing delays. A slight delay, from observing the image on your retina to encoding the image as a memory, would cause a phase difference that our program did not account for. A zero phase difference, meaning the second image in entrainment was shown following the same brightness and cosine pattern as the first image, may actually be several degrees off, assuming visual processing delays are present. Although our sample population (college-aged psychology students) all likely have similar visual processing delays, there may be slight variations between participants, making it difficult to analyze the data accurately. If, for example, Participant A is observing a stimulus with a hypothesized 0° phase difference at a physiological 15° phase difference, and Participant B observes the same stimulus at a physiological -7° phase difference, it is difficult to compare between participants and form conclusions.

One limitation present in the current study is that the only frequency band of theta studied was 5 Hz. There may be a more ideal frequency within the theta band (4-8 Hz) that is more applicable to this study's design. 5 Hz was chosen for this study based on a calculated average of the theta-related studies used in the literature review. A frequency of 4 Hz, closer to this study's core inspirations, may have been a more ideal choice. The ideal frequency may also be subject-dependent, adding further complications to making an optimal version of this study.

Another possible limitation is the assumption that entrainment was reached within 4000 milliseconds (4 seconds) to elicit the echo period phenomenon. Entrainment does not occur instantaneously, but takes a varied amount of time, dependent on the stimulation intensity (Hanslmayr, 2017). The target population of neurons may have required a greater amount of time to properly become phase-aligned and fully entrain to the stimulus. It is also possible that the visual stimulation was not intense enough for the neuron populations to reach full intensity, and a multisensory stimulation, such as audiovisual, is required to reach full signal intensity and elicit the echo phenomenon.

Further studies may want to investigate these limitations addressed, such as looking at other frequencies within the theta band and conducting longer entrainment time periods. Other important next steps would be to investigate what is physiologically occurring within this protocol. Electroencephalography (EEG) or magnetoencephalography (MEG) may give insight into the ongoing neural mechanisms. These tools, with high temporal resolution, may help understand the questions at hand, such as interpersonal visual processing delays and the effectiveness of our entrainment protocol.

However, these tools have poor spatial resolution, since these theta waves originate deep within the brain, in the hippocampus, they would not be ideal for understanding the origins of these oscillations. A possible solution would be intracranial recordings and stimulations to investigate deep brain regions, but there are several ethical concerns and barriers to this investigation. However, it would be unethical to install invasive recording materials into human participants to study sensory phenomena.

Reflections

Although my study led to insignificant findings, being a member of the Clark Honors College and having the opportunity to work on this project has been extremely valuable in my development as a student and researcher.

This study came to fruition as a result of my interest in oscillatory patterns and music, a subject I grew fond of in a 200-level Clark Honors College class titled “The Science of Music”, taught by Professor Rebecca Altman. The topics spanned from the physics of sound waves to the biology of sound processing. Through this class, I was quickly inspired to purchase my first guitar, a hobby that has remained extremely important to me for the last three years. The guitar has served as a great therapeutic, critical thinking, and creative tool to improve on in my downtime from school and lab work.

I brought these newfound interests in music to my principal investigator, Dr. Brice Kuhl, who formulated this project for me, which would bring together aspects of his lab’s interests with mine. Combining his own interest in memory interference with mine in oscillatory patterns and the hippocampus. Throughout the planning of the project and protocol, I became super fascinated by the topics of plasticity and circuits. This drove me towards an internship at UC San Diego with Dr. Douglas Nitz, where I got to explore the role of hippocampal place cells within rat models. Over the course of my summer internship, I became more aware of where my true interests lie within the realm of neuroscience, specifically in systems and cellular-level neuroscience, with an emphasis on electrophysiology. I spent the next two summers interning at other labs at UC San Diego, where I learned to conduct ex vivo electrophysiology studies, using patch-clamp and field recording techniques on hippocampal slices. The first of these two summers, I worked with Dr. William Mobley to investigate plasticity changes within Down Syndrome mouse models. The following summer, I worked alongside Dr. Kim Dore on my hands-on technique, looking at plasticity changes within Alzheimer's disease mouse models.

Since these experiences, an electrophysiologist, Dr. Lila Wollman, has opened a lab at the University of Oregon, where I continue to work as a researcher and electrophysiologist. Until I begin a doctoral program in neuroscience, likely this fall, I will be working with Dr. Wollman to study how nicotine exposure impacts the intrinsic breathing signals originating in the brainstem. Within my future doctoral program, I hope to work with neurodegenerative rodent models to continue studying plastic changes and cellular-level changes in aging models.

This thesis project has been a very important experience in developing my research interests and skills. I learned basic research skills in conducting literature reviews, writing hypotheses, and collecting and analyzing data. I had great opportunities to work alongside members of the Kuhl Lab to develop my collaborative and communicative skills, including my primary mentor, Dr. Soroush Mirjalili. Hitting the ground early as a researcher made the transition into numerous other labs seamless, already possessing the necessary basic skills to excel in other environments. Most importantly, I've gained a great appreciation for research and look forward to further developing within the scope of neuroscience research in whatever opportunity presents itself next.

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