THETA-GAMMA PHASE-AMPLITUDE COUPLING DURING NATURALISTIC MEMORY ENCODING: A COMPARISON OF REAL-WORLD AND 2D EXPERIENCES

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DEDICATION

To my amazing wife, my loving family, and my kind friends, your support, patience, and belief in me have carried me every step of this journey, especially in the moments when I doubted myself the most.

To all the brave people of my homeland, Iran, whose resilience and strength continue to inspire me every day.

This work is for all of you.

ABSTRACT

Episodic memory allows individuals to recall personal experiences by integrating perceptual, emotional, and contextual information over time. Previous research suggests that episodic memory depends on the coordination of neural activity across different frequency bands, particularly through theta-gamma phase-amplitude coupling (PAC). However, most studies have examined these mechanisms using simplified laboratory tasks, with limited attention to how they operate in more naturalistic contexts. The present study investigated how encoding context influences neural dynamics during episodic memory formation by comparing a real-world performance with a two-dimensional (2D) version of the same narrative. Sixty-two young adults were assigned to either a real-world or 2D condition. Neural activity was recorded using electroencephalography (EEG) during encoding, and PAC between frontal theta (4-8 Hz) and parietal gamma (30-100 Hz) oscillations was computed. Following encoding, participants completed a free verbal recall task.

The results showed a significant effect of encoding condition on PAC, with higher theta-gamma coupling observed in the 2D condition compared to the real-world condition. Despite these neural differences, recall performance did not differ significantly between conditions. There was a significant positive correlation between PAC and memory recall performance only observed in the 2D condition. Furthermore, PAC was not consistently related to general cognitive measures, suggesting that it reflects task-specific neural processing rather than stable cognitive ability. These findings show that the neural coordination underlying memory encoding is influenced by the context in which information is experienced, even when similar levels of memory performance are achieved across different conditions. In other words, increased PAC in the 2D condition may reflect greater reliance on internally driven processing when external

structure is reduced. Overall, this study highlights the importance of using naturalistic paradigms to better understand how memory operates in real-world settings and suggests that PAC should be interpreted as a flexible, context-dependent neural mechanism rather than a general measure of memory performance.

ETHICS STATEMENT

Work described in this thesis received research ethics approval from the university of Alberta Research Ethics board, Project Name “Neural and Behavioral Differences in Episodic Memory Encoding Across Real-World and 2D Stimuli”, No. Pro00146097, October 22, 2024.

USE OF GENERATIVE AI

I used generative AI tools in a limited way to support the writing of this thesis. Their main use was to help improve grammar, clarity, and overall flow of the text, and to make the writing more academically polished. This was especially helpful as English is my second language. In some cases, I used AI to rephrase sentences or improve the organization of paragraphs. However, I did not use AI to generate research ideas, design the study, analyze data, or interpret the results. All research decisions, analyses, and conclusions are my own. I carefully reviewed and edited the AI-assisted text to make sure it accurately reflects my work and meaning. I take full responsibility for the content of this thesis, including the accuracy of all information and citations.

PREFACE

This thesis was developed from my interest in understanding how memory works in real-world situations, beyond simplified laboratory tasks. During my undergraduate in Psychology and my master's in Neuroscience studies and my work with EEG, I became interested in how our brain processes continuous, natural experiences, and whether the mechanisms identified in controlled experimental settings apply in more realistic contexts. This led to the idea of comparing memory encoding in a real-world performance with a recorded version of the same experience. The project was carried out in the Ekstrand Neuroimaging Laboratory at the University of Lethbridge. It involved designing a naturalistic paradigm, coordinating real-world performances, collecting EEG data, and developing the pipeline for phase-amplitude coupling (PAC) analysis. Throughout this process, I was involved in all aspects of the research, including study design, data collection, analysis, and interpretation of the findings. This work reflects my effort to bridge controlled experimental research with more ecologically valid approaches to studying memory. It also represents an important step in my academic journey as I continue to explore how neural processes support cognition in real-world settings.

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PAC	Phase-amplitude coupling
EEG	Electroencephalography
ICA	Independent component analysis
ROI	Region of interest
MI	Modulation Index
GLM	General linear model
2D	Two-dimensional
MoCA	Montreal Cognitive Assessment
PSM	Picture Sequence Memory
LSWM	List Sorting Working Memory
DCCS	Dimensional Change Card Sort
ORR	Oral Reading Recognition
PC	Pattern Comparison
PV	Picture Vocabulary

CHAPTER 1: GENERAL INTRODUCTION

1.1 EPISODIC MEMORY: FOUNDATIONS AND SIGNIFICANCE

Episodic memory is a fundamental component of human cognition that enables individuals to recall personally experienced events, including details about what, where, and when they occurred. Episodic memory allows individuals to re-experience past events by integrating perceptual, emotional, and contextual details (Tulving, 2002). This ability supports learning from past experiences and guides decision-making across time (Conway, 2005). Beyond these functions, episodic memory is particularly sensitive to aging and neurological disorders, making it a critical domain for understanding both typical and impaired cognition (Nyberg et al., 2012). It also plays an important role in maintaining a coherent sense of identity across time and supports the ability to imagine and plan for future events (Addis et al., 2007; Schacter et al., 2008). A defining feature of episodic memory is its reliance on the integration of multiple elements of experience, including sensory details, emotional context, and temporal structure, into a unified representation (Rubin, 2006; Tulving, 2002). In contrast to semantic memory, which involves the storage of general knowledge and facts independent of context, episodic memory is inherently tied to specific spatiotemporal contexts and personal experience (Tulving, 2002). This distinction highlights the unique role of episodic memory in enabling individuals to mentally relive past events. Understanding how these complex, multi-component representations are formed requires examining both the neural systems involved and the mechanisms by which information is integrated over time.

1.2 NEURAL SYSTEMS SUPPORTING EPISODIC MEMORY

Episodic memory encoding and retrieval rely on the coordinated activity of distributed cortical and subcortical brain systems that interact to support the integration of information. The

hippocampus plays a central role in binding perceptual and contextual inputs into cohesive memory representations, while the prefrontal cortex is involved in organizing and monitoring perceptual, contextual, and temporal information to support goal-directed encoding and retrieval processes (Cabeza et al., 2016). Importantly, these regions interact dynamically during both encoding and retrieval, with the hippocampus supporting the binding of information, the prefrontal cortex guiding goal-directed processing, and parietal regions contributing to attentional and reconstructive processes (Ranganath & Ritchey, 2012). During encoding, these systems work together to integrate incoming perceptual and contextual information into structured memory representations, whereas during retrieval, they support the reconstruction and reactivation of stored experiences (Cabeza et al., 2016; Ranganath & Ritchey, 2012). Parietal regions further contribute to the integration of attentional and spatial information that supports the vivid re-experiencing of past events (Vilberg & Rugg, 2008). The coordinated interaction of these regions enables the transformation of continuous experience into structured, retrievable episodes, highlighting the importance of large-scale network dynamics in episodic memory processing. These systems contribute to maintaining a sense of self across time and support goal-directed behaviour, navigation, and social communication (Rubin, 2006).

Aging is associated with well-documented declines in episodic memory, reflected in reduced ability to encode and retrieve contextually rich, temporally ordered experiences (Nyberg et al., 2012). At the neural level, these deficits have been linked to reduced functional connectivity between the hippocampus and prefrontal cortex during encoding, regions that are central to the binding and organization of episodic memories (Grady et al., 2003). Beyond connectivity changes, aging is also associated with reductions in the synchronization of slow oscillatory brain activity involved in memory encoding, which may compromise the temporal

precision needed for effective episodic encoding (Reinhart & Nguyen, 2019). The specific nature of these oscillatory changes and their relevance to memory will be discussed in detail in the following sections. Across these individual regions, episodic memory also depends on the precise temporal coordination of neural activity across the hippocampus, prefrontal cortex, and parietal cortex, a coordination that unfolds dynamically over time (Jensen & Colgin, 2007).

1.3 NEURAL OSCILLATIONS AND MEMORY ENCODING

In addition to the spatial organization of memory systems, episodic memory encoding and retrieval depend on the precise timing of neural activity across brain regions (Jensen & Colgin, 2007; Ranganath & Ritchey, 2012). These processes are supported by neural oscillations, which provide a temporal framework for organizing information flow within and across distributed neural systems (Buzsáki & Draguhn, 2004). Neural oscillations span multiple frequency bands, including delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), gamma (30-220 Hz), each associated with distinct cognitive and perceptual functions (Buzsáki & Draguhn, 2004; Esghaei et al., 2022). While multiple frequency bands contribute to cognitive processing, theta and gamma oscillations are particularly relevant for episodic memory due to their role in organizing and integrating information across time (Jensen & Colgin, 2007; Lisman & Jensen, 2013). Theta oscillations (particularly in the hippocampus and frontal cortex) are thought to temporally organize neural firing patterns that support the sequential encoding of experience (Jensen & Colgin, 2007). In contrast, gamma oscillations reflect the synchronous activation of neuronal populations encoding specific perceptual features or item-level details (Canolty et al., 2006). Effective communication between the hippocampus and cortical regions during episodic memory encoding depends on the coordinated interaction of these neural rhythms (Jensen & Colgin, 2007; Lisman & Jensen, 2013). This interaction between frequency

bands provides the foundation for more complex forms of cross-frequency coordination, such as phase-amplitude coupling (PAC), which enables the integration of information across temporal and spatial scales.

1.4 EEG AS A TOOL FOR INVESTIGATING NATURALISTIC MEMORY

EEG has an extremely high temporal resolution for examining the neural dynamics underlying cognitive functions, allowing it to capture transient fluctuations in neural activity that support information integration (Cohen, 2014). Compared to other neuroimaging techniques (e.g., fMRI) which captures slow hemodynamic changes, EEG measures electrical activity at the millisecond timescale, aligning directly with the real-time dynamics of oscillatory coordination during encoding (Cohen, 2014; Mathewson et al., 2024). This temporal precision makes EEG particularly well suited for tracking cross-frequency coordination during memory encoding, providing direct insight into how distributed neural populations synchronize and integrate information in real time (Cohen, 2014; Jensen & Colgin, 2007). Furthermore, EEG is highly compatible with naturalistic settings, making it especially valuable for paradigms that go beyond simple trial-based designs and allowing for the continuous recording of oscillatory dynamics during extended, ecologically valid experiences (Gramann et al., 2014; Mathewson et al., 2024).

1.5 PHASE-AMPLITUDE COUPLING AS A MECHANISM OF MEMORY INTEGRATION

PAC is a form of cross-frequency interaction in which the amplitude of a higher-frequency oscillation, such as gamma, is systematically modulated by the phase of a lower-frequency oscillation, such as theta (Canolty & Knight, 2010; Esghaei et al., 2022). This coupling represents a key mechanism by which neural oscillations coordinate activity across temporal and spatial scales, allowing the fast, detail-rich information carried by gamma

oscillations to be organized within the slower rhythmic framework provided by theta oscillations, supporting information flow within and across brain regions (Lisman & Jensen, 2013). For example, intracranial electroencephalography (EEG) studies have shown that successful memory encoding is associated with increased theta activity and stronger theta-gamma PAC within medial temporal lobe structures, which predicts subsequent memory performance (Lega et al., 2016). Such coupling facilitates the integration of contextual and sensory information across distributed cortical regions.

While theta-gamma PAC has been consistently observed in association with memory encoding across a range of studies, it is important to recognize that this coupling is not exclusive to memory and has also been observed across a range of cognitively demanding contexts (Esghaei et al., 2022; Papaioannou et al., 2022). Theta-gamma coupling has been associated with the active maintenance and organization of information over time, particularly under conditions that require sustained attention or increased processing demands (Daume et al., 2024; Lisman & Jensen, 2013). In this context, stronger coupling may not necessarily indicate more efficient encoding, but rather increased neural effort required to organize and integrate information under more demanding conditions. Research in the memory domain supports the idea that PAC between theta and gamma oscillations integrates perceptual details into temporally ordered episodes (Lisman & Jensen, 2013). Further, the strength of theta-gamma coupling during memory encoding predicts later recall performance (Heusser et al., 2016; Lega et al., 2016). Specifically, stronger frontal theta to posterior gamma coupling during encoding has been shown to index successful memory formation in scalp-recorded EEG, suggesting that this oscillatory relationship is detectable with non-invasive methods and generalizes across stimulus types (Friese et al., 2013). Köster et al. (2014) illustrated that better recognition of pictorial stimuli is

associated with a stronger coupling between the phase of frontal theta and the amplitude of parietal gamma. Zheng et al. (2024) further demonstrated using intracranial recordings that hippocampal theta phase aligns spike timing and high-frequency activity to encode sequential experience. This finding supports the functional role of phase precession in human episodic memory.

Importantly, the neural systems that support theta-gamma PAC are also among those most vulnerable to age-related decline. Given that theta-gamma PAC depends on the functional integrity of precisely these frontal-hippocampal systems (Lisman & Jensen, 2013), age-related degradation of this connectivity may directly reduce the oscillatory coordination available to support episodic encoding. Consistent with this, interventions that restore rhythmic synchrony between prefrontal and temporal regions have been shown to improve working memory performance in older adults, suggesting that oscillatory coupling represents a functionally relevant and potentially modifiable mechanism in aging (Reinhart & Nguyen, 2019). However, direct evidence on how theta-gamma PAC during episodic encoding is modulated across the adult lifespan remains limited, representing a meaningful gap in the literature. Establishing the neural oscillatory mechanisms that support naturalistic episodic encoding in healthy adults is therefore an important foundational step toward understanding how these mechanisms may change with age and contribute to the memory declines observed in older populations.

1.6 NATURALISTIC AND REAL-WORLD ENCODING OF MEMORY

Despite these advances in understanding the neural and oscillatory mechanisms of episodic memory, the overwhelming majority of this foundational research has been conducted using highly simplified laboratory tasks such as word-list learning, picture recognition, and paired associate learning that bear little resemblance to how memory operates in everyday life

(Hasson et al., 2008; Sonkusare et al., 2019). These paradigms, while valuable for isolating specific processes, lack contextual, sensory and emotional richness that characterize real-world experiences and may therefore fail to capture the full complexity of episodic encoding (Hasson et al., 2008). In the past 15 years, researchers have increasingly turned to naturalistic paradigms, such as using films, narratives, and immersive real-world tasks, to study memory encoding under more ecologically valid conditions (DuPre et al., 2020; Grall & Finn, 2022). Real-world experiences unfold continuously, integrating multimodal information, social interactions, and emotional salience in ways that controlled laboratory stimuli cannot replicate (Hasson et al., 2008; Jääskeläinen et al., 2021).

Naturalistic stimuli elicit widespread and coordinated brain activation spanning perceptual, emotional, and hippocampal regions involved in episodic encoding (Hasson et al., 2008; Jääskeläinen et al., 2021). When the same movie is shown to different people, neural activity tends to align temporally and spatially between them, reflecting shared cognitive processing of the narrative (Chen et al., 2017). This inter-subject alignment shows that the human brain encodes complex and multimodal experiences in a structured and comparable manner even outside the controlled laboratory environment. Naturalistic paradigms therefore provide a critical link between tightly controlled laboratory experiments and the complexity of real-world cognitive processes (Hasson et al., 2008; Sonkusare et al., 2019). Importantly, the ecological richness of naturalistic stimuli also appears to modulate neural coupling during encoding. Multisensory environments engage distributed perceptual, attentional, and hippocampal networks simultaneously, placing greater demands on the cross-frequency coordination that organizes incoming information into coherent memories (Jääskeläinen et al., 2021; Marucci et al., 2021). This suggests that the degree of environmental richness during

encoding may directly modulate the strength of theta-gamma PAC, with more immersive, multisensory contexts driving greater oscillatory coupling than less immersive, screen-based presentations.

Collectively, these findings point to a broader question: do the oscillatory mechanisms established in controlled laboratory settings actually operate when memory encoding occurs in richer, more complex environments? Recent intracranial evidence suggests they do. Zheng et al. (2024) demonstrated that theta-phase precession, the mechanism by which neuronal firing shifts progressively to earlier phases of ongoing theta oscillations, contributes to the encoding and retrieval of naturalistic experiences during movie watching in humans. Importantly, this temporal coding mechanism was not simply a product of simplified task conditions, but generalized to the dynamic, continuously unfolding nature of real-world-like narratives. These findings suggest that precise theta-organized timing helps structure the continuous flow of experience into coherent episodic memories and directly motivate an investigation of theta-gamma PAC in a similarly naturalistic encoding context. Critically, if theta-organized coupling supports memory formation during naturalistic experiences, individual differences in PAC strength during encoding should predict the completeness of subsequent recall- a relationship that remains to be examined in the context of real-world versus 2D encoding.

In naturalistic contexts, experiences unfold over time as a stream of perceptual, social, and contextual information, and memory encoding is often organized around meaningful narrative units. Research shows that people segment ongoing experiences into discrete episodes, which provide a structural framework for subsequent recall (Zacks et al., 2007). The boundaries between these narrative units are psychologically meaningful: they mark points of heightened attention and increased memory encoding that shape how the experience is later retrieved (Zacks

& Swallow, 2007). From a neural perspective, encoding extended narratives requires the integration of information across longer timescales, spanning seconds to minutes. Theta-gamma PAC has been proposed as a mechanism that supports the integration of information across these extended timescales (Lisman & Jensen, 2013).

1.7 THE PRESENT STUDY AND HYPOTHESES

Based on the theoretical and methodological foundations reviewed above, the present thesis investigates how neural oscillatory coupling supports episodic memory encoding in ecologically valid contexts. This study specifically compares PAC between frontal theta (4-8 Hz) and parietal gamma (30-100 Hz) during the encoding of a real-world, narrative-driven vignette versus a video recording of the same performance. The Real-world condition involved a live theatrical performance staged within a controlled laboratory environment, while the 2D condition presented a video recording of the same narrative. Unlike 2D screen-based presentations, real-world interactions involve rich multimodal cues (including spatial depth, physical movement, and direct interpersonal engagement) that are thought to enhance attentional focus and emotional salience during encoding (Hasson et al., 2008; Marucci et al., 2021). These differences in perceptual richness may modulate the degree of theta-gamma coordination during encoding, with the Real-world condition expected to place greater demands on the cross-frequency integration mechanisms that support episodic memory formation. After encoding, participants were asked to verbally recall everything they remembered from the vignette. By linking oscillatory coupling during encoding to recall performance, the study aims to identify electrophysiological markers of successful real-world memory formation. Based on this evidence, two primary hypotheses were formulated:

1. Theta-gamma PAC between the frontal and parietal regions of the brain will be stronger in the Real-world condition than in the 2D condition, reflecting greater neural integration in more immersive and socially rich context.

2. Memory recall performance will positively correlate with PAC strength, suggesting that greater theta-gamma coordination supports more complete and coherent recollection of naturalistic events.

Clarifying these relationships will contribute to a broader understanding of how oscillatory dynamics enable the transformation of continuous sensory experience into structured episodic memory. In addition to refining theoretical accounts of neural integration, this work provides a foundation for future studies of naturalistic memory and its potential modulation through non-invasive stimulation or clinical interventions.

CHAPTER 2: METHODOLOGY

2.1 OVERVIEW

The current thesis seeks to examine how real-world experience influences neural dynamics during episodic memory encoding. Specifically, we investigated whether encoding a narrative through a real-world performance produces different patterns of theta-gamma PAC compared to encoding the same narrative in a 2D format. To examine whether immersive, real-world encoding impacts neural dynamics, participants were assigned to one of the two experimental groups: 1) a real-world encoding condition, where they viewed a live theatrical performance played by actors or 2) a 2D encoding condition, where participants passively viewed a recorded 2D presentation of the same narrative on a projector screen. EEG was used to capture the real-time neural activity with millisecond-level temporal resolution, which allowed us to precisely examine oscillatory interactions (specifically PAC) during encoding.

2.2 PARTICIPANTS

A total of 62 healthy young adults (age range = 18-39) participated in the current study. Thirty-two participants were assigned to the Real-world encoding condition and thirty to the 2D encoding condition. The Real-world condition included participants aged 18-39 years (M = 22.34, SD = 6.46), whereas the 2D condition included participants aged 19-33 years (M = 22.03, SD = 3.80). In the Real-world condition, 17 participants identified as female and 15 as male, whereas in the 2D condition, 21 participants identified as female and 9 as male. One individual attended a testing session but was unable to participate due to difficulties fitting the EEG net and was therefore not included in the sample. No participants withdrew after data collection began, and all recorded datasets (N = 62) were included in the final analyses.

Participants were recruited from the University of Lethbridge community through campus-wide flyers, departmental announcements, and advertising in classes. Participants were screened for any neurological (including seizures in the past 5 years) or vision conditions that would prevent them from performing the tasks in this study. Five participants self-identified as left-handed, and no participants were excluded based on handedness. Participants provided written informed consent prior to beginning the experiment and received compensation of either course credit (1% course credit per hour up to a total of 2%), or monetary compensation ($15 CAD for the session). The experimental protocol was approved by the University of Alberta Research Ethics Board 2 (Pro00146097).

2.3 EXPERIMENTAL PROCEDURE

Participants were assigned to one of two encoding conditions: Real-world or 2D. Prior to EEG electrode placement, participants were asked to remove all metallic objects, including jewelry, watches, earrings, and mobile phones, to minimize electrical interference and signal artifacts. The EEG net was then fitted according to the manufacturer's guidelines, with alignment based on standard anatomical landmarks. At the beginning of the encoding phase, PsychoPy (Version 2021.2.1) was initiated, and a trigger signal was sent to the EEG recording system to mark the start of the procedure. A second trigger was sent immediately before the vignette began. At this time, a one-second beep sound was played through two Altec Lansing ACS5 computer speakers positioned in the room. In the Real-world condition, participants observed a short, scripted narrative vignette performed live in front of them by two actors. In the 2D condition, participants watched a video recording of the same vignette. In the Real-world condition, this beep cued the actors to begin the performance. In the 2D condition, the same beep was presented immediately before the video onset to maintain a consistent temporal structure across conditions.

At the end of the performance, the experimenter terminated the encoding segment of the task, after which participants completed two memory recall tasks. The first recall task consisted of a free recall phase where participants were asked to verbally report everything they could remember about the narrative they had just viewed. Instructions for the recall task were presented both verbally and visually on the computer screen. Participants were allowed to speak for as long as they wished while describing the events of the scene they viewed in the encoding phase. A trigger signal was sent to the EEG recording system at the start of the free recall phase, and another trigger was sent when the recall period ended. Verbal recalls were recorded using a Sony ICD-UX670 digital audio recorder. Throughout the recall phase, instructions and cue presentation were displayed on a 24-inch LCD monitor positioned approximately 68 cm from the participant. Within PsychoPy, the display resolution was set to 1500 x 1000 pixels.

Following the free recall phase, participants completed a cued recall task designed to probe memory for specific events within the vignette. During this phase, visual cues from the vignette were presented to them on the computer screen one at a time in random order using PsychoPy. The specific objects used as retrieval cues are listed in Appendix A. Each cue presentation was accompanied by a one-second beep sound. Participants were asked to verbally recall any additional information related to the event associated with that object that they had not already mentioned during the free recall phase. No time limit was imposed during the cued recall task, and participants were allowed to provide as much detail as they wished for each object.

Following the completion of the EEG recording and memory recall tasks, participants underwent a series of cognitive and demographic assessments. This included the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) as a brief screening measure of general cognitive functioning along with a demographic questionnaire and a comprehensive set of tasks

from the NIH Toolbox Cognitive Battery (Weintraub et al., 2013). All NIH Toolbox Cognitive Battery scores were calculated using age-adjusted standard scores in accordance with established scoring procedures, allowing for standardized comparison across individuals.

2.4 STIMULI AND EXPERIMENTAL SETUP

The vignette performance lasted approximately nine minutes and depicted a conversational interaction structured as a romantic date in a park between two individuals. The full script of the vignette ("Over the Moon") is provided in Appendix A. As the original script was previously written by a professional script writer (Arnone, 2024), the dialogue was modified by the research team to resemble a continuous natural conversation rather than a sequence of clearly segmented events. This structure was intended to preserve the ecological characteristics of everyday social interactions and allow participants to experience the vignette as a coherent and continuous unfolding episode rather than as a discrete experimental stimulus.

The Real-world performance area was arranged to maintain visual consistency across sessions while also limiting the movement of actors within the scene. A solid background wall was placed behind the actors and the park bench to visually separate the performance area from the rest of the experimental room. To maintain consistent spatial boundaries during the Real-world performances, a yellow line was placed on the floor to indicate the limits of the actors' movement area. The distance between the park bench and the yellow boundary line was approximately 85 cm, which limited the actors' movement and ensured that the performance remained within a stable visual frame across sessions. Participants were seated facing the performance area during the encoding phase at a distance of approximately 170 cm from the scene.

Each real-world performance was recorded with an Insta360 camera on a tripod positioned approximately 210 cm away from the stage area, placed next to where participants were seated. The camera was aligned with the right shoulder of the seated participant so that the participant was not captured in the recording frame. Because the narrative was performed for each participant in the Real-world condition, a total of thirty-two videos were recorded. These recordings were later used to generate the stimuli for the 2D condition. To ensure consistency across video stimuli, the beginning and ending segments of the recordings were edited using Adobe Premiere Pro (version 25.6).

Participants in the 2D condition viewed video recordings that had been captured during the real-world performances. Each participant viewed one unique recording, and recordings from the Real-world condition were randomly paired with participants in the 2D condition. In the 2D condition, the recorded vignette was projected onto the same background wall that was used behind the actors during the real-world performances. The projection surface measured approximately 242 cm in length and 202 cm in height. A TOPTRO LCD projector (lens size 188 mm, 1/2.9) was used to display the video stimulus. The projector was positioned approximately 115 cm from the participant and approximately 178 cm above the ground. The presentation of the video stimuli was controlled using PsychoPy (Version 2021.2.1), which was also used to manage experimental timing and event triggers during both Real-world and 2D sessions. Visual representations of the experimental setup for both encoding conditions are provided in Appendix D.

The vignette included several objects that were embedded in the narrative and later used as cues during memory retrieval. These objects were physically present in the real-world performance and were integrated into the narrative interaction between the actors. Images of the

cue objects used during the cued recall task are presented in Appendix A.1. These objects were selected because they appeared at different moments within the play and could therefore serve as cues associated with specific events during later recall.

2.5 EEG ACQUISITION

EEG data were recorded using a high-density 128-channel HydroCel Geodesic Sensor Net connected to a Geodesic EEG System 400 (GES 400). Data acquisition was controlled using Net Station software (version 5.5.0). The HydroCel net consists of evenly distributed electrodes across the scalp, allowing for relatively higher spatial sampling of the electrical activity and improved characterization of large-scale neural dynamics. Electrode impedances were monitored and maintained between tasks to keep them below acceptable thresholds as recommended for high-impedance EEG systems to ensure stable signal acquisition. Continuous EEG data were recorded throughout the encoding and recall phases of the experiment. Event markers were sent from the PsychoPy experimental script to the EEG recording system to precisely synchronize behavioural events with the brain-recorded signals. These markers included the start of the experiment, the onset of the encoding phase, the beginning and the end of the free recall phase, and the onset of each cued recall event. This synchronization allowed for accurate temporal alignment between neural activity and task events during subsequent analyses.

2.6 EEG PREPROCESSING

EEG preprocessing was done using MATLAB (version 2024b) in combination with EEGLAB (version 2025.0.0), a plug-in tool under MATLAB. EEGLAB provides a widely used open-source framework for the EEG signal processing and has been extensively validated for electrophysiological data analysis (Delorme & Makeig, 2004). Continuous EEG data were first imported into Net Station Review and visually inspected to ensure data quality and identify any

electrodes with major recording issues. Raw EEG data was then imported into EEGLAB for preprocessing, which included band-pass filtering (0.1 to 100 Hz) and notch filtering (60 Hz, power grid) to remove slow drifts and high-frequency noise while preserving the frequency bands relevant to subsequent analyses. To verify that the notch filter was correctly applied, power spectral density was computed before and after filtering. The PSD confirmed substantial attenuation of power at 60 Hz following notch filtering, indicating that line noise was effectively removed prior to subsequent analyses. Linear-phase finite impulse response (FIR) filters were applied to minimize temporal distortions in the signal, which is important for analyses that rely on precise phase estimation, like PAC (Widmann et al., 2015). Marked bad channels were interpolated prior to re-referencing to avoid propagating noise from bad electrodes, which had excessive noise or signal dropout or consistent abnormal activity patterns, into the reference signal (Delorme & Makeig, 2004). EEG data were then re-referenced to the average of all electrodes. Average referencing is usually used in high-density EEG recordings, like the 128-channel recording that is used in this study, and helps reduce spatial bias seen by a single reference electrode while improving the comparability across channels (Luck, 2014).

Artifact removal was performed using independent component analysis (ICA), which decomposes the EEG signal into temporally independent components representing underlying neural and non-neural sources. ICA is a standard method in EEG preprocessing for separating brain activity from artifacts such as eye movements, muscle activity, cardiac signals, and line noise (Delorme & Makeig, 2004). After ICA decomposition, components were automatically classified using the ICLabel algorithm, which assigns probabilistic labels to independent components based on their spatial, spectral, and temporal characteristics (Pion-Tonachini et al., 2019). In the current study, components were flagged for removal if they were classified with a

probability of 90% or greater as belonging to non-brain categories, including muscle activity, eye activity, heart activity, line noise and channel noise. Components classified as “brain” or “other” were retained, as these categories may contain meaningful neural signals and were not considered artifacts for the purposes of this analysis. After artifact rejection, the preprocessed and cleaned EEG data were retained in continuous form for subsequent analyses. Maintaining continuous data was essential for the PAC analysis, as PAC quantifies the temporal relationship between oscillatory phase and amplitude over extended time periods (Canolty & Knight, 2010). The preprocessing pipeline was therefore designed to balance effective artifact removal with preservation of the temporal and spectral characteristics of the neural signals of interest.

2.7 PHASE-AMPLITUDE COUPLING ANALYSIS

PAC analysis was used to measure the interaction between the low-frequency theta phase (4-8 Hz) and high-frequency gamma amplitude (30-100 Hz) during the encoding phase of the experiment. PAC was computed using the Tensorpac toolbox implemented in Python within the MNE framework (Combrisson et al., 2020). This toolbox provides a standardized implementation of cross-frequency coupling metrics, including the Modulation Index (MI) first introduced by Tort et al. (2010). A synthetic validation of the PAC analysis pipeline is provided in Appendix B. This analysis is focused on the coupling between frontal theta oscillations (4-8 Hz) and parietal gamma activity (30-100 Hz), based on prior literature demonstrating that theta-gamma interactions play an important role in memory encoding and the integration of distributed neural information (Canolty & Knight, 2010; Köster et al., 2014; Lisman & Jensen, 2013). Frontal and parietal regions were selected as regions of interest (ROIs) to capture large-scale coordination between higher-order cognitive control processes and perceptual integration systems. This selection was supported by the EEG studies showing that activity within frontal

and parietal regions is closely linked to memory-related processes and cognitive functions (Bian et al., 2014).

Preprocessed EEG data were imported into Python and analyzed using MNE-Python (Gramfort et al., 2013). Data corresponding to the encoding phase were selected for further analysis. Frontal and parietal ROIs were defined based on predefined electrode groupings. Signals from electrodes within each ROI were extracted and averaged to generate representative regional time series for each participant. This regional averaging approach reduces channel-level noise and facilitates the analysis of large-scale neural interactions (Cohen, 2014).

To capture the temporal dynamics of coupling during encoding, the continuous EEG signal was segmented into overlapping time windows. Sliding epochs 20 seconds in duration with 10-second overlap were extracted across the encoding period. This window length ensured stable estimation of low-frequency phase while maintaining sensitivity to temporal changes across recording (Cohen, 2014; Tort et al., 2010). Within each epoch, the phase of the theta band was extracted from the frontal signal and the amplitude envelope of the gamma band was extracted from the parietal signal using the Hilbert transform applied to band-limited data (Cohen, 2014). The strength of coupling between theta phase and gamma amplitude was then quantified using the Modulation Index (MI) method (Tort et al., 2010). The MI is based on the Kullback-Leibler divergence, which measures how much the observed distribution of gamma amplitude across theta phase bins deviates from a uniform distribution. The key formula for MI is:

$$MI = \frac{D_{KL}\left(P \parallel U\right)}{\log\left(N\right)}$$

where P represents the observed distribution of gamma amplitude across phase bins, U represents a uniform distribution, N is the number of phase bins, and D_{KL} is the Kullback-Leibler

divergence between the two distributions. This measure captures how strongly gamma amplitude is modulated by the phase of the theta oscillation. If gamma amplitude is evenly distributed across all phases of theta, the distribution approximates uniformity and the MI approaches zero, indicating no coupling. In contrast, if gamma amplitude is consistently higher at specific phases of the theta cycle, the distribution deviates from uniformity, resulting in a higher MI value. Therefore, the MI provides a normalized measure of the strength of cross-frequency coupling by quantifying the degree of phase-dependent modulation of amplitude.

To control for spurious coupling arising from noise or signal properties, surrogate-based normalization was applied. For each epoch, surrogate datasets were generated by randomly shifting the phase time series relative to the amplitude time series, thereby disrupting their temporal alignment while preserving their individual spectral characteristics. A total of 200 permutations were computed for each segment to generate a null distribution and converted to z-scored values, providing a normalized estimate of coupling strength relative to chance (Dvorak & Fenton, 2014). Multiple comparison correction across frequency components was implemented using a maximum statistics (maxstat) approach within Tensorpac. This method evaluates observed coupling values relative to the maximum surrogate distribution and provides a consecutive control for false positives (Combrisson et al., 2020). Finally, PAC values were averaged across all epochs for each participant to obtain a single summary measure of frontal theta and parietal gamma coupling during the encoding phase.

In addition to participant-level PAC values, frequency-resolved coupling patterns were visualized using comodulograms. These plots display the strength of PAC across a range of phase and amplitude frequencies. Group-averaged comodulograms were generated by averaging normalized PAC values across participants within each condition, and difference comodulograms

were computed to visualize relative changes in coupling strength between conditions. These visualizations complemented the statistical analyses by providing a descriptive overview of frequency-specific coupling patterns across conditions. These values were used in subsequent statistical analyses to examine differences between the Real-world and 2D conditions and to assess relationships between neural coupling and behavioural measures of memory performance. To confirm that the observed PAC differences were not attributable to condition-related differences in raw signal power, supplementary analyses of theta and gamma band power were conducted across the Real-world and 2D conditions, supporting the interpretation that the PAC effects reported in the Results reflect genuine cross-frequency coupling rather than differences in underlying signal power. Full results are reported in Appendix C..

2.8 BEHAVIOURAL SCORING

Behavioural memory performance was assessed using both free and cued recall tasks following the encoding phase. Participant verbal responses were audio-recorded and subsequently transcribed using Whisper, an open-source automatic speech recognition tool developed by OpenAI (Radford et al., 2023), which was run locally to ensure that participant data were not uploaded to any external servers or cloud-based platforms. All transcriptions were then manually reviewed by the primary researcher, who listened to each audio recording and corrected any errors or omissions in the automated transcription prior to scoring. The scoring procedure was designed to capture episodic memory performance by focusing on the recall of event-specific details embedded within the narrative rather than general semantic or gist-based information. The vignette used in the experiment was structured into five major events. Each event was associated with a distinct object that appeared during the performance and was

integrated into different moments of the vignette. This structure allowed the recall process to be anchored to meaningful event segments while maintaining the natural flow of the story.

Recall performance was quantified using a predefined scoring rubric with a maximum possible score of 12 points. The event segmentation framework and scoring rubric are provided in Appendix E. Detailed event descriptions are listed in Appendix E.1, and the full scoring rubric is presented in Appendix E.2. The rubric was designed to capture the presence and completeness of event-specific information across the five vignette segments. Each participant's score reflected the extent to which they successfully reconstructed the structure and the content of the narrative based on the episodic details. Scoring was conducted by the primary researcher to ensure consistency across participants. Although participants also completed a cued recall task following the free recall phase, only free recall responses were included in the present analysis. The cued recall task was used to support retrieval by providing structured access to event-specific cues, which helped participants re-engage with the narrative and retrieve additional details. However, to maintain consistency with the study's focus on spontaneous episodic memory processes, only unprompted recall performance was used as the primary behavioural measure. This scoring approach was informed by prior work on naturalistic memory and event segmentation (Zacks et al., 2007).

2.9 STATISTICAL ANALYSIS

Statistical analyses were completed using IBM SPSS Statistics (version 27). The primary objective of the statistical analysis was to examine differences in neural and behavioural measures between the Real-world and 2D encoding conditions and to assess the relationship between PAC and memory performance. Group differences in neural measures were assessed using analyses of covariance (ANCOVA) comparing normalized (z-scored) PAC values between

the Real-world and 2D conditions, while also controlling for sex. This analysis was used to determine whether frontal theta and parietal gamma coupling differed as a function of encoding condition. Sex was included as a covariate because the Real-world and 2D groups were not evenly distributed by sex. Behavioural differences between conditions were evaluated using an independent-samples *t*-test comparing free recall scores between the Real-world and 2D groups. To examine the relationship between neural and behavioural measures, Pearson correlation analyses were conducted between participant-level PAC values and free recall scores separately within each condition. Additional correlation analyses were performed to assess the association between PAC values and cognitive measures, including NIH Toolbox Cognitive Battery scores and MoCA scores, separately within each condition. All statistical tests were conducted as two-tailed tests with a significant threshold of $\alpha = 0.05$.

CHAPTER 3: RESULTS

3.1 OVERVIEW

This chapter presents the results of the statistical analyses examining differences in neural oscillatory coupling during episodic memory encoding across Real-world and 2D conditions. Based on the major role of PAC in the present study, the analyses first focus on condition-related differences in PAC. The following sections will examine recall performance, the relationship between PAC and recall, and a series of control analyses assessing whether the observed effects are associated with general cognitive functioning, including MoCA and NIH Toolbox Cognition Battery measures.

3.2 CONDITION DIFFERENCES IN PAC

An ANCOVA was conducted to examine the differences in PAC between the Real-world and 2D conditions, with sex included as a covariate. Results show a significant main effect of condition on PAC, $F(1, 59) = 5.44$, $p = .023$, indicating that neural oscillatory coupling differed between encoding conditions. Examination of estimated marginal means showed that PAC was higher in the 2D condition ($M = 0.29$, $SD = 0.46$) compared to the Real-world condition ($M = 0.10$, $SD = 0.32$; see Figure 3. 1). These findings indicate that encoding condition significantly modulates PAC, with stronger theta-gamma coupling observed during 2D encoding relative to Real-world encoding.

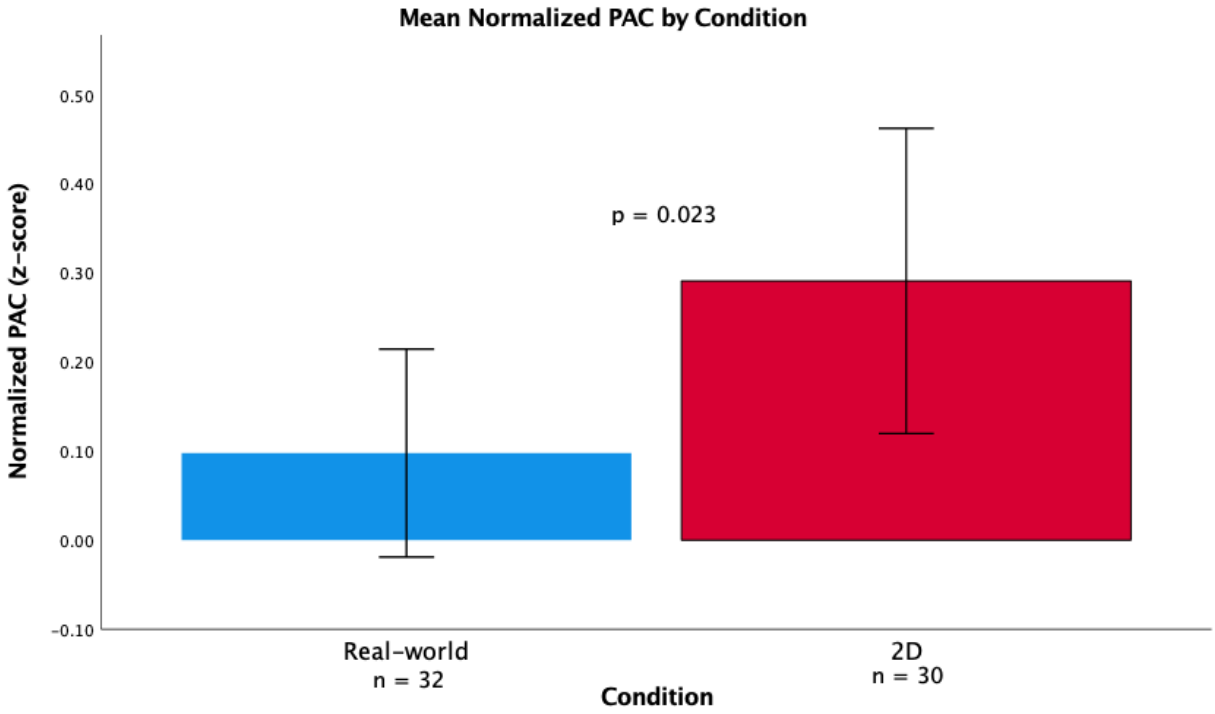

Figure 3. 1: Mean normalized PAC (z-scored) as a function of encoding condition (Real-world vs. 2D). Error bars represent standard error of the mean.

3.3 FREQUENCY-SPECIFIC PAC PATTERNS

To provide a descriptive visualization of the observed condition effect in the PAC, PAC patterns across phase and amplitude frequencies were examined using a group-level comodulogram. Figure 3.2 shows the group-averaged comodulograms for the Real-world and 2D conditions separately. In both conditions, coupling was broadly distributed across theta-gamma frequencies, with the 2D condition showing visibly stronger modulation within the theta phase (4-8 Hz) and gamma amplitude (30-100 Hz) range.

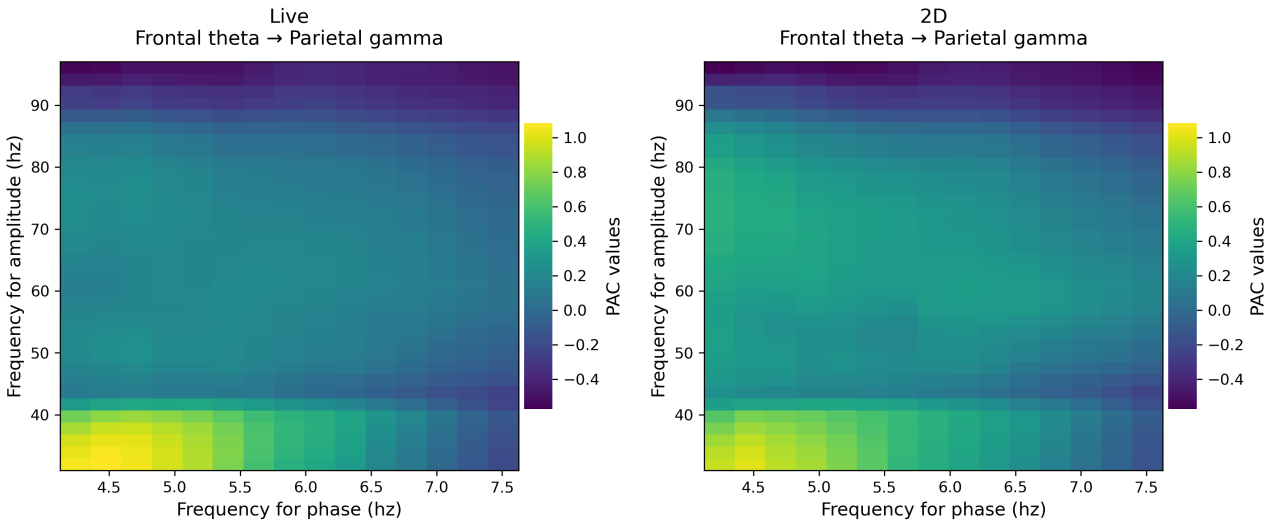

Figure 3. 2: Group-averaged comodulograms for both Real-world and 2D conditions

A difference comodulogram was computed to visualize the distribution of PAC values across frequencies, calculated as the subtraction of Real-world from 2D encoding (2D – Real-world). As shown in Figure 3. 3, the difference heatmap showed that PAC was generally higher in the 2D condition across a range of phase and amplitude frequencies. In particular, increased coupling was observed within the theta phase range (4-8 Hz) and gamma amplitude range (30-100 Hz), indicating stronger theta-gamma interactions during 2D encoding. These patterns are consistent with the statistical results reported above, further illustrating that the observed condition differences in PAC are not uniform across frequencies but are localized within the theta-gamma coupling range. This pattern is in line with the significant main effect of condition observed in the ANCOVA, $F(1, 59) = 5.44$, $p = .023$, suggesting that the overall increase in PAC in the 2D condition is primarily driven by activity within the theta-gamma frequency range.

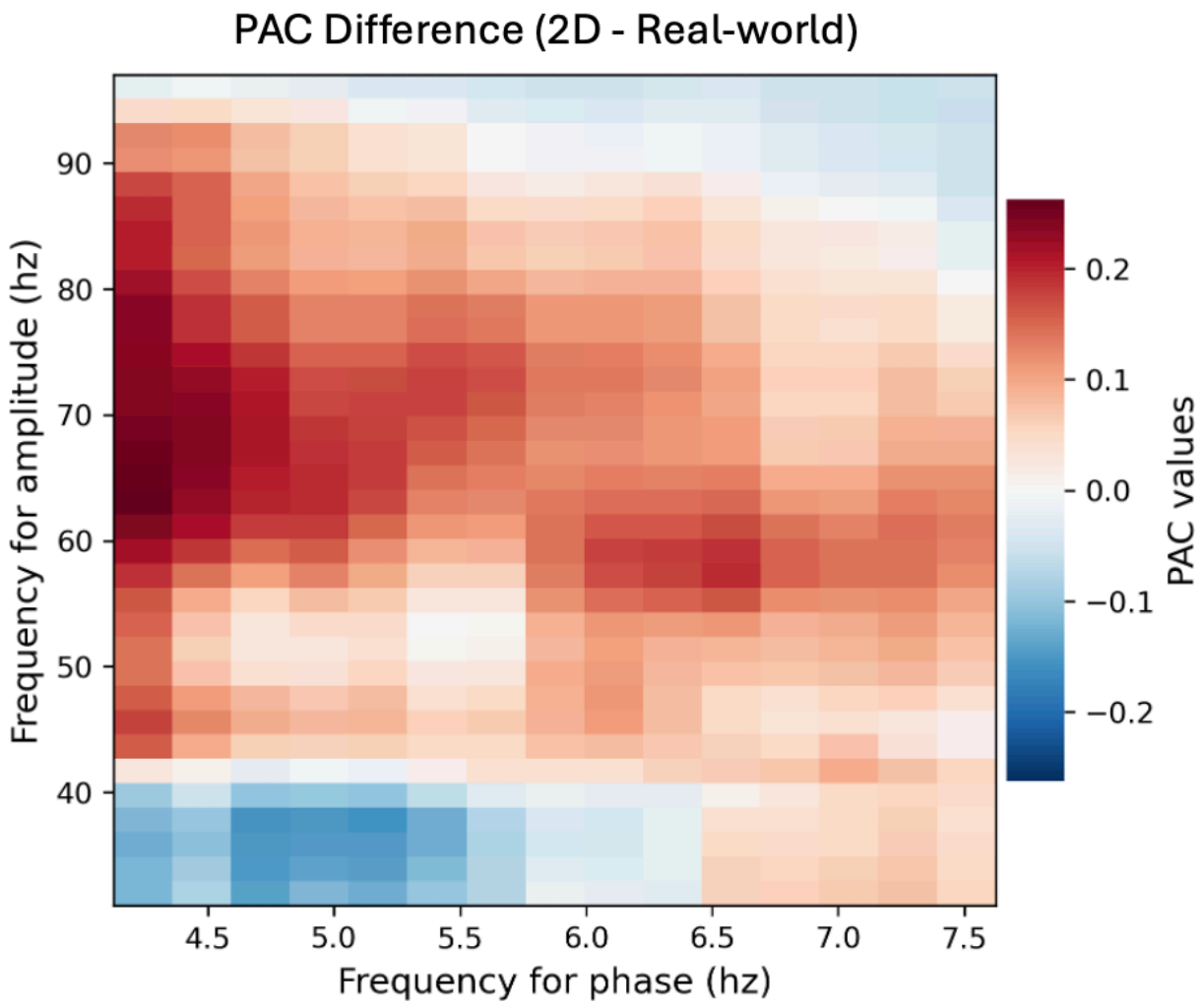

Figure 3. 3: Differences in PAC between conditions (2D – Real-world) across phase (theta) and amplitude (gamma) frequencies.

3.4 CONDITION DIFFERENCES IN RECALL

To identify whether there were significant differences in free recall memory performance between the Real-world and 2D encoding conditions, we conducted an ANCOVA, with sex included as a covariate. Results indicated that there was no significant main effect of condition on recall performance, $F(1, 59) = .716$, $p = .401$. Descriptive statistics showed that mean recall

performance was comparable between the 2D condition (M = 5.03, SD = 1.89) and the Real-world condition (M = 4.73, SD = 1.81; see Figure 3. 4). These findings indicate that memory performance did not significantly differ as a function of encoding condition.

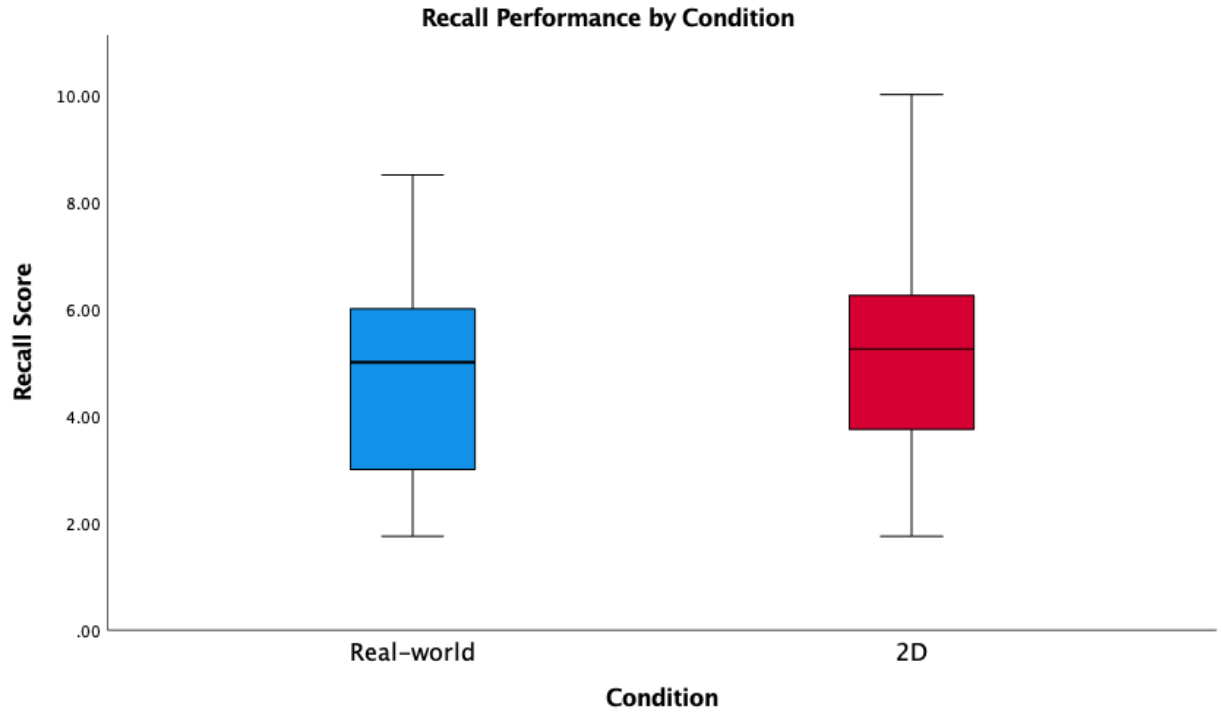

Figure 3. 4: Recall performance by encoding condition (Real-world vs. 2D). Boxes represent interquartile range, with median indicated by the horizontal line. Whiskers extend to the minimum and maximum values. No significant differences were observed between conditions.

3.5 PAC-RECALL RELATIONSHIP

To examine the relationship between PAC and episodic memory recall performance, Pearson correlation analyses were conducted between PAC values and recall scores separately for the Real-world and 2D encoding conditions. In the Real-world encoding and recall condition,

no significant relationship was observed between PAC and episodic memory recall performance, $r(30) = -.12$, $p = .499$ (see Figure 3.5). In contrast, a significant positive correlation was observed between the 2D encoding and recall condition, $r(28) = .40$, $p = .031$, indicating that higher PAC was associated with better memory recall performance during the 2D condition. These findings suggest that the functional relationship between neural coupling and memory performance varies as a function of encoding context.

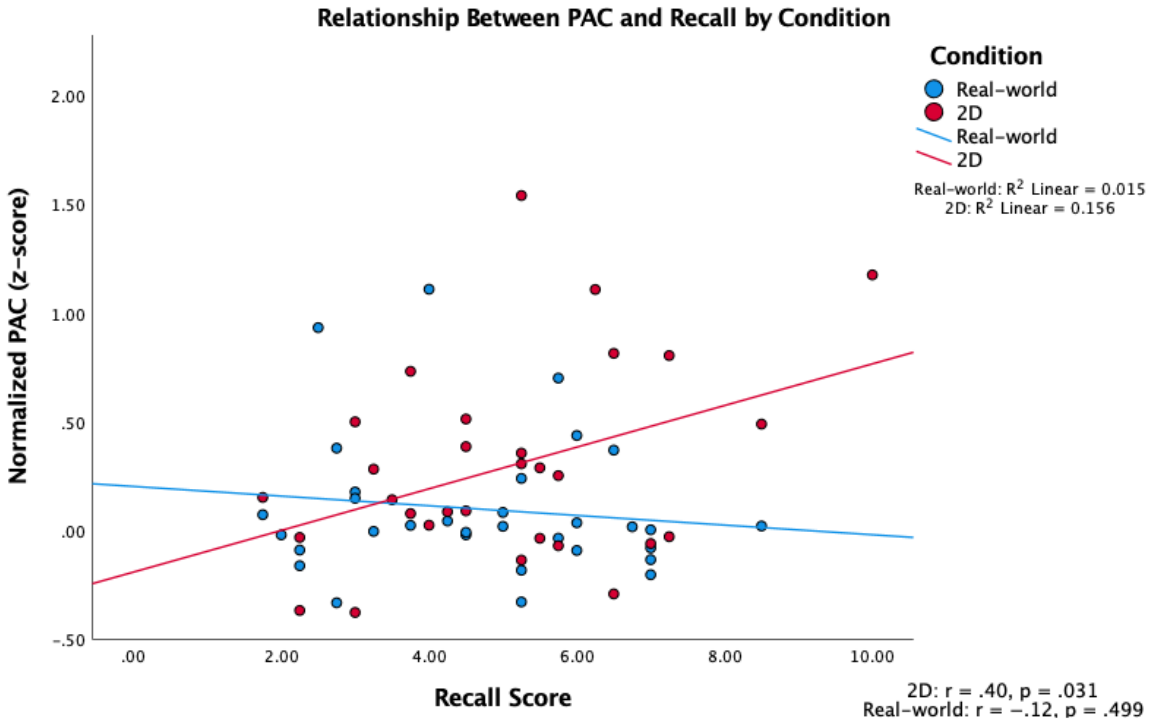

Figure 3. 5: Relationship between PAC and recall performance by condition. Lines represent linear fits for Real-world and 2D conditions.

3.6 ASSOCIATIONS BETWEEN PAC, RECALL AND COGNITIVE MEASURES

To examine whether PAC was associated with general cognitive functioning, Pearson correlation analyses were conducted between PAC and cognitive measures, including MoCA

(Nasreddine et al., 2005) and NIH Toolbox Cognition Battery (Weintraub et al., 2013) measures (specifically the Picture Sequence Memory (PSM), Flanker, List Sorting Working Memory (LSWM), Dimensional Change Card Sort (DCCS), Oral Reading Recognition (ORR), Pattern Comparison (PC), and Picture Vocabulary (PV) tasks), separately for both Real-world and 2D conditions.

Prior to examining these associations, independent-samples t-tests were conducted to assess whether the Real-world and 2D groups differed significantly on any cognitive measure at baseline. Results indicated that the two groups were largely comparable in general cognitive functioning. At the uncorrected level, PV scores showed a significant difference, $t(60) = 2.39$, $p = .020$, $d = .61$, with the Real-world group scoring higher ($M = 107.31$, $SD = 12.52$) than the 2D group ($M = 99.20$, $SD = 14.15$). Additionally, several measures approached significance, including LSWM, $t(60) = -1.94$, $p = .057$, $d = -.49$, PSM, $t(60) = 1.87$, $p = .067$, $d = .47$, and PC, $t(60) = 1.76$, $p = .083$, $d = .45$. However, after applying the Benjamini-Hochberg false discovery rate correction for multiple comparisons across all eight cognitive measures, none of these differences remained statistically significant (all $p_{adj} > .05$; see Table 3. 1). These results indicate that the Real-world and 2D groups did not significantly differ on cognitive functioning prior to the main analyses, supporting the comparability of the two groups.

Table 3. 1

Group differences in cognitive measures between Real-world and 2D conditions. Means and standard deviations are presented for each group. BH-adjusted p-values reflect Benjamini-Hochberg false discovery rate correction across all eight comparisons. For MoCA, Levene's test indicated unequal variances (F = 6.31, p = .015); corrected degrees of freedom are reported.

Variable	Real-world *M (SD)*	2D *M (SD)*	*t*	*df*	*p*	p_{adj}	*d*
MoCA	27.69 (1.40)	27.03 (2.16)	1.41	49.27	.166	.248	.36
PSM	107.09 (13.02)	100.80 (13.52)	1.87	60	.067	.166	.47
Flanker	98.59 (9.44)	96.73 (10.50)	0.73	60	.466	.533	.19
LSWM	100.06 (13.07)	106.27 (11.99)	−1.94	60	.057	.166	−.49
DCCS	100.09 (13.09)	98.20 (12.87)	0.57	60	.568	.568	.15
ORR	98.91 (13.77)	104.40 (18.37)	−1.34	60	.186	.248	−.34
PC	100.91 (14.19)	94.03 (16.50)	1.76	60	.083	.166	.45
PV	107.31 (12.52)	99.20 (14.15)	2.39	60	**.020**	.160	.61

In the Real-world condition, a significant negative correlation was observed between PAC and MoCA scores, $r(30) = -.43$, $p = .015$, indicating that higher PAC values were associated with lower overall cognitive performance (see Figure 3. 6). In contrast, no significant association was found between PAC and MoCA in the 2D condition, $r(28) = .13$, $p = .497$. Furthermore, PAC was not significantly correlated with any NIH Toolbox Cognition Battery measures in either encoding condition (all $p > .05$; see Table 3. 2), although the correlation between PAC and PSM in the Real-world condition approached significance, $r(30) = -.35$, $p = .052$, suggesting a possible negative association between coupling strength and sequential memory performance that warrants further investigation. Overall, these findings indicate that PAC was not systematically related to general cognitive functioning, suggesting that the observed condition differences in PAC are unlikely to be explained by general cognitive functioning.

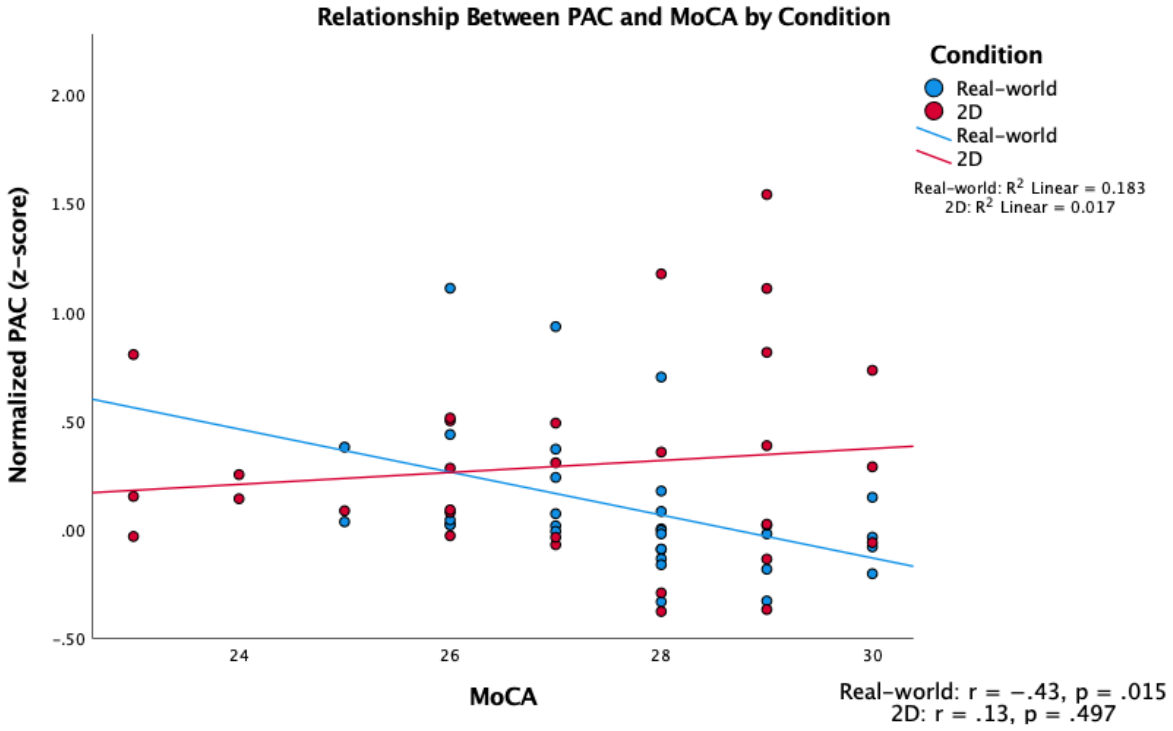

Figure 3. 6: Relationship between PAC and MoCA by condition (Real-world vs. 2D). Lines represent linear regression fits for each condition. A significant negative association is observed in the Real-world condition, whereas no relationship is evident in the 2D condition.

Table 3. 2

Pearson correlation coefficient (r) between PAC and cognitive measures (MoCA and NIH Toolbox variables) across real-world and 2D conditions. Values in parentheses represent two-tailed p-values. Significant correlations ($p < .05$) are indicated with an asterisk (*). Sample sizes were n = 32 for the Real-world condition and n = 30 for the 2D condition.

Variable	Real-world PAC r (p)	2D PAC r (p)
MoCA	**−0.43 (.015)***	0.13 (.497)
PSM	−0.35 (.052)	0.09 (.652)
Flanker	0.08 (.665)	−0.21 (.264)
LSWM	−0.11 (.540)	−0.11 (.580)
DCCS	0.04 (.846)	0.23 (.223)
ORR	0.03 (.881)	0.01 (.939)
PC	−0.09 (.607)	-0.17 (.364)
PV	−0.12 (.508)	0.16 (.394)

To further assess whether recall performance was influenced by the general cognitive ability, Pearson correlation analyses were conducted between recall scores and MoCA (Nasreddine et al., 2005) and NIH Toolbox Cognition Battery scores (Weintraub et al., 2013). In the Real-world condition, recall performance was not significantly correlated with MoCA, $r(30) = .08$, $p = .660$, or with any NIH Toolbox Cognition Battery measures, including PSM, Flanker, LSWM, DCCS, ORR, PC, and PV (all $p > .05$). Similarly, in the 2D condition, no significant associations were observed between memory recall scores and MoCA scores, $r(28) = .25$, $p = .192$, or between memory recall scores and any NIH Toolbox Cognition Battery measures (all $p > .05$). As summarized in Table 3. 3, recall performance was not systematically related to cognitive measures in either condition. These findings indicate that memory recall performance was not driven by individual differences in general cognitive functioning.

Table 3. 3

Pearson correlation coefficient (r) between recall scores and cognitive measures (MoCA and NIH Toolbox variables) across Real-world and 2D conditions. Values in parentheses represent two-tailed p-values. Sample sizes were n = 32 for the Real-world condition and n = 30 for the 2D condition.

Variable	Real-world Recall r (p)	2D Recall r (p)
MoCA	0.08 (.660)	0.25 (.192)
PSM	0.03 (.861)	0.31 (.100)
Flanker	0.27 (.139)	−0.13 (.489)
LSWM	0.21 (.246)	0.11 (.567)
DCCS	−0.18 (.313)	0.10 (.582)
ORR	0.12 (.513)	0.02 (.930)
PC	0.01 (.963)	−0.08 (.667)
PV	0.21 (.244)	0.14 (.453)

CHAPTER 4: DISCUSSION

4.1 OVERVIEW OF THE STUDY AND MAIN FINDINGS

The present thesis examined how real-world experiences influence the neural dynamics underlying episodic memory encoding, particularly in terms of changes in PAC between frontal theta and parietal gamma oscillations. Based on a theoretical framework that focuses on the role of cross-frequency coupling in coordinating distributed neural processing (Canolty & Knight, 2010; Lisman & Jensen, 2013), this study was designed to examine whether encoding a vignette in a real-world and immersive context would enhance neural coordination compared to encoding the same vignette in a 2D recorded format. In addition to neural measures, this study examined behavioural memory performance and the relationship between neural coordination and recall, as well as possible correlations with broader cognitive functioning.

To address these questions, participants were assigned to one of two encoding conditions that differed based on ecological realism: a Real-world condition, in which a narrative vignette was performed in real time by two actors, or a 2D condition, in which participants watched a recorded version of the same performance. EEG was used to capture neural activity during both memory encoding conditions. PAC was then computed to measure how strongly the phase of frontal theta oscillations modulated the amplitude of parietal gamma oscillations. Following encoding, participants completed recall tasks, which allowed us to examine both neural and behavioural indices of episodic memory formation.

The initial hypothesis predicted higher PAC during the Real-world encoding than during 2D encoding because the Real-world condition offered greater sensory richness, social presence, and ecological validity. This prediction was based on the literature suggesting that more naturalistic and multimodal experiences engage broader neural systems and support richer

memory processing (Gramann et al., 2014; Hasson et al., 2008; Jääskeläinen et al., 2021). However, results from the ANCOVA comparing PAC across the two encoding conditions showed a significant main effect of condition in the opposite direction. Specifically, PAC was significantly higher in the 2D condition compared to the Real-world condition. These effects were observed within the theta (4-8 Hz) and gamma (30-100 Hz) frequency ranges, which are indicated in the literature as supporting the episodic memory process (Jensen & Colgin, 2007; Köster et al., 2014; Lisman & Jensen, 2013). These findings indicate that the format in which an experience is encoded, whether it is real-world performance or 2D, modulates the strength of cross-frequency neural interactions during memory formation.

Interestingly, behavioural results did not show a significant difference in recall performance between the two encoding conditions. Participants in both the Real-world and 2D groups demonstrated comparable levels of memory recall, suggesting that the observed differences in neural coordination did not translate into measurable differences in behavioural performance. This suggests that comparable levels of memory performance can be supported by varying degrees of neural coordination depending on the encoding context, rather than fundamentally different processes.

Further analyses examining the relationship between PAC and recall performance showed a condition-specific pattern. In the 2D condition, higher PAC was associated with better memory recall performance, indicating that stronger neural coordination between theta and gamma oscillations was functionally related to memory encoding success in this condition. On the other hand, no correlation was found in the Real-world condition, suggesting that the role of PAC in supporting memory performance may differ depending on the nature of the encoding environment. These findings point to a context-dependent relationship between neural dynamics

and behavioural outcomes, emphasizing the importance of considering ecological factors when interpreting neural measures of memory.

Additional analyses were done to determine whether the observed neural and behavioural effects could be explained by general cognitive functioning. Although a significant negative correlation between PAC and MoCA scores was observed in the Real-world condition, there was no comparable relationship found in the 2D condition. Also, PAC was not significantly associated with any NIH Toolbox Cognition Battery measures in either condition. Furthermore, recall performance was not significantly correlated with MoCA or NIH Toolbox Cognitive Battery measures across the two conditions. Taken together, these findings suggest that the condition-related differences in PAC are unlikely to be driven by general cognitive ability and instead reflect differences in neural processing associated with the encoding context itself.

Overall, the results of the present study demonstrate that encoding context modulates neural coordination during episodic memory encoding, but not necessarily behavioural memory performance. Although memory recall was similar in both conditions, PAC was higher in the 2D condition, suggesting that more immersive experiences do not always produce stronger neural coordination. Instead, these results suggest that increased neural coupling may reflect greater processing demands or compensatory mechanisms engaged under less naturalistic conditions, an interpretation that will be explored further in the following sections. This interpretation provides a critical foundation for the subsequent sections of the discussion, which will examine the theoretical and methodological implications of these findings in more detail.

4.2 HIGHER PAC IN 2D THAN REAL-WORLD: INTERPRETATION OF THE MAIN NEURAL FINDING

One of the main findings of the current thesis was that PAC between frontal theta and parietal gamma oscillations was significantly higher in 2D encoding condition compared to the Real-world condition. Our initial hypothesis predicted that stronger neural coordination or coupling between the phase of frontal theta and the amplitude of parietal gamma would be observed during the Real-world encoding condition due to its greater ecological validity and sensory richness. This prediction was grounded in prior work suggesting that theta-gamma coupling supports the integration and temporal organization of information during memory encoding, and that more naturalistic, multimodal experiences engage broader neural systems involved in memory processing (Hasson et al., 2008; Jääskeläinen et al., 2021; Lisman & Jensen, 2013). This unexpected finding requires careful interpretation in the context of existing research on neural oscillations, episodic memory, and cognitive processes.

A common interpretation in the literature is that theta-gamma PAC is involved in the temporal organization of information and the representation of multiple elements within a sequence (Jensen & Colgin, 2007; Köster et al., 2014; Lisman & Jensen, 2013). Within this framework, theta oscillations are thought to provide a temporal structure that organizes neural activity over time, while gamma oscillations are associated with local neuronal processing and the representation of item-level information (Buzsáki & Draguhn, 2004; Jensen & Colgin, 2007). The coupling between these frequencies has been proposed as a mechanism for integrating information over time (Lisman & Jensen, 2013), and has been linked to successful episodic memory encoding in human EEG studies (Köster et al., 2014). From this perspective, it might be expected that a more immersive and naturalistic encoding context, such as the Real-world condition, would enhance this coordination and result in stronger PAC.

However, the present findings challenge this straightforward interpretation. Even though the Real-world encoding condition provided a more immersive and sensory-rich experience, PAC was significantly lower compared to the 2D condition. This suggests that a higher PAC value does not necessarily reflect more efficient or successful encoding. Instead, an alternative interpretation is that increased PAC may reflect greater demands on neural coordination, particularly in contexts that require more active organization of incoming information, as cognitive load has been shown to modulate prefrontal-parietal network engagement and neural efficiency in an inverted-U manner (Gkintoni et al., 2026). In the 2D condition, participants viewed a recorded video of the same vignette, which likely imposed additional processing demands compared to the Real-world condition (Hasson et al., 2008; Sonkusare et al., 2019). Unlike real-world encoding, where the narrative is presented in a physically present and socially engaging environment, the 2D format may require participants to rely more heavily on internally driven cognitive processes to maintain attention, structure the narrative, and integrate information over time. In this context, higher theta-gamma coupling may reflect increased top-down control and active organization of information, as cross-frequency coupling has been shown to be sensitive to attentional and cognitive control demands rather than memory processes alone (Esghaei et al., 2022; Papaioannou et al., 2022; Voytek et al., 2010), particularly under increased cognitive load conditions (Gkintoni et al., 2026).

This interpretation is consistent with evidence suggesting that, although theta-gamma PAC has been proposed as a mechanism supporting memory encoding, cross-frequency coupling more broadly is also sensitive to cognitive control and attentional demands (Daume et al., 2024; Esghaei et al., 2022; Papaioannou et al., 2022; Voytek et al., 2010). Importantly, recent evidence shows that theta-gamma PAC is not specific to memory processes but is also observed across a

range of non-memory tasks, indicating that it reflects broader cognitive mechanisms such as attention and control (Papaioannou et al., 2022). In particular, theta-gamma coupling has been proposed to support the temporal organization and representation of multiple items, processes that are often associated with working memory (Lisman & Jensen, 2013).

Within this framework, the lower PAC observed in the Real-world encoding condition may reflect a reduced need for internally driven coordination due to the inherent structure and richness of the environment. Recent autobiographical memory research shows that memories experienced from a first-person perspective are associated with richer scene-related representations, whereas observer-like perspectives are linked to reduced vividness and increased reconstructive processing (St. Jacques, 2024). Naturalistic experiences are known for their continuous, multimodal, and temporally structured inputs that can guide perception and memory encoding in a more externally supported manner (Hasson et al., 2008; Jääskeläinen et al., 2021; Sonkusare et al., 2019), and multisensory integration has been shown to improve performance and reduce workload under higher perceptual demands (Marucci et al., 2021). In the present study, the Real-world condition involved real-time interaction and dynamic and rich sensory input, which may have reduced the need for internally generated coordination processes during encoding.

On the other hand, the 2D condition may have required participants to engage more strongly in internally driven processes to organize and integrate the narrative, as reduced sensory richness and immersion may limit externally provided structure for processing (Hasson et al., 2008; Sonkusare et al., 2019). This engagement may manifest as increased PAC, reflecting the additional coordination required to organize incoming information, as cross-frequency coupling has been shown to be sensitive to attentional and cognitive control demands rather than memory

processes alone (Papaioannou et al., 2022), and to vary as a function of cognitive load (Gkintoni et al., 2026). Importantly, this interpretation is supported by the behavioural findings of the present study that showed no significant difference in the memory recall performance between the two conditions. Despite the differences in neural coordination and PAC, participants achieved similar levels of episodic memory recall performance, suggesting that similar behavioural outcomes can be supported by different neural processes depending on the encoding context. This is consistent with research showing that neural activity can vary across conditions despite comparable behavioural performance, particularly in naturalistic and cognitively demanding tasks (Hasson et al., 2008).

Additional support for this interpretation comes from the condition-specific correlation between PAC and memory recall performance. In the 2D encoding condition, higher frontal theta and parietal gamma PAC was positively correlated with better recall performance, indicating that increased neural coordination was functionally relevant for encoding in this context. In contrast, no such relationship was found in the Real-world encoding condition, suggesting that PAC may play a less important role when the encoding environment provides stronger external structure. This is consistent with evidence that neural activity is strongly shaped by stimulus structure and task context in naturalistic settings (Hasson et al., 2008), and that richer and more immersive environments can support more efficient processing with reduced reliance on internally driven coordination (Marucci et al., 2021). Taken together, these findings suggest that PAC should not be interpreted as a direct marker of encoding success. Instead, PAC appears to reflect a flexible neural mechanism that is modulated by task demands and environmental context (Canolty & Knight, 2010; Papaioannou et al., 2022; Voytek et al., 2010). Higher coupling may indicate increased engagement of coordination processes when external support is limited, whereas lower

coupling may reflect encoding that is supported by richer and multimodal environmental structure.

These findings have important implications for understanding the neural basis of episodic memory. Rather than assuming that stronger neural coupling is always useful and beneficial, the present results highlight the importance of considering how environmental context and elements shape the neural dynamics. In naturalistic settings, where experiences are structured, immersive, and multimodal, encoding may rely less on internally generated coordination mechanisms (Hasson et al., 2008; Sonkusare et al., 2019). In more constrained and less immersive contexts, stronger neural coordination may be required to support the organization of information over time. Overall, the increased PAC between frontal theta and parietal gamma found in the 2D condition is best interpreted not as evidence of stronger and better encoding, but as an indicator of increased demands on neural coordination required to achieve similar behavioural outcomes.

Importantly, this interpretation aligns with findings from aging research showing that reductions in theta-gamma coupling and disrupted network synchronization are associated with poorer memory performance, and that when such coupling is disrupted, it may lose its behavioural relevance for supporting cognitive performance (Reinhart & Nguyen, 2019). Thus, increased neural activity has been proposed to serve a compensatory function. For example, the Hemispheric Asymmetry Reduction in Older Adults (HAROLD) model demonstrates that older adults show increased bilateral prefrontal recruitment during cognitive tasks compared to younger adults, interpreted as compensatory engagement to maintain performance in the face of declining neural efficiency (Cabeza, 2002). Similarly, the Posterior-Anterior Shift in Aging (PASA) model suggests that age-related increases in prefrontal activity are positively correlated with better performance during both episodic retrieval and visual perception tasks, suggesting

that greater frontal engagement can compensate for reduced posterior processing resources (Davis et al., 2008). Drawing a parallel to the present findings, the higher PAC observed in the 2D condition may reflect a similar compensatory upregulation of frontal-parietal coordination, not indicative of superior encoding, but rather increased neural effort recruited to achieve outcomes comparable to those supported more efficiently by the richer real-world environment. This framing suggests that PAC may function as a flexible, context-sensitive mechanism that scales with processing demands, whether those demands arise from age-related neural decline or from reduced ecological richness in the encoding context.

4.3 MATCHED RECALL PERFORMANCE ACROSS CONDITIONS

One of the most theoretically significant findings of the present study is that recall performance was comparable across Real-world and 2D encoding conditions, despite clear differences in neural activity during encoding. This suggests that equivalent memory outcomes can be achieved through different degrees of neural coordination depending on the encoding context. One interpretation of this comparable performance is that the two conditions shared many key features of the task, including the same narrative structure, event sequence, and memory cues, despite differing in ecological realism. Both groups encoded the same scripted narrative, both experienced the narrative as a continuous unfolding episode, and the 2D stimuli were created from the video recordings of the real-world performance rather than from a separate or simplified stimulus set. In addition, the procedure was designed to preserve temporal consistency across conditions: the same cueing structure was used, the same wall served as the background or projection surface, and the actors' movements were constrained so that the real-world performance remained within a stable visual frame across sessions. Furthermore, the

sample consisted of young, healthy adults with above-average cognitive functioning, which may have reduced variability in performance and supported comparable recall across conditions.

This interpretation is consistent with research on event segmentation, which suggests that individuals naturally organize continuous experience into meaningful events and tend to identify similar event boundaries when observing the same activity (Sasmita & Swallow, 2022; Zacks & Swallow, 2007). This shared organization of experience can provide a common structure that supports memory for events. In the current study, both encoding conditions preserved the same narrative event structure and the same object-event relationships used as retrieval cues. As a result, participants in both groups may have relied on a similar underlying event structure during encoding and retrieval, which may have contributed to the comparable recall performance observed across conditions. Importantly, the comparable recall performance observed across conditions should not be interpreted as a null finding, but rather as evidence that both encoding contexts were equally effective in supporting episodic memory formation. This finding underscores the importance of measuring both neural and behavioural indices when studying memory in naturalistic settings, as relying on behavioural data alone would have obscured the meaningful differences in neural processing revealed by the PAC analyses.

4.4 CONDITION-SPECIFIC PAC-RECALL RELATIONSHIP

While section 4.3 established that recall performance was comparable across conditions, the relationship between PAC and recall showed a markedly different pattern, one that was specific to the 2D encoding condition. In the 2D condition, stronger frontal theta to parietal gamma coupling during encoding was positively associated with better recall performance, suggesting that neural coordination was functionally relevant for memory formation in this

context. In contrast, no such relationship was observed in the Real-world condition, pointing to a context-dependent role of theta-gamma PAC in supporting episodic memory.

PAC quantifies the degree to which gamma amplitude is systematically modulated by theta phase, and at the functional level this coupling has been proposed to reflect the coordination of neural activity across temporal scales, such that item-level representations are structured within the phase of ongoing theta oscillations (Canolty & Knight, 2010; Friese et al., 2013; Heusser et al., 2016; Lega et al., 2016; Lisman & Jensen, 2013). In this framework, theta oscillations are thought to structure information over time, while gamma activity represents more local, item-level processing.

To contextualize this finding within the existing literature, it is important to consider studies demonstrating that theta-gamma coupling supports memory formation, while acknowledging that its functional role depends on task context. In scalp EEG, Friese et al. (2013) found increased cross-frequency coupling between frontal theta and posterior gamma oscillations during successful memory encoding, suggesting that this interaction is related to the formation of new memories. In an intracranial EEG study, Lega et al. (2016) found that slow-theta-to-gamma PAC in the human hippocampus was associated with successful episodic encoding during a free-recall word-list task in which participants encoded and later recalled lists of words. Similarly, Heusser et al. (2016) showed that participants encoded items presented in sequences, where items in different positions were associated with gamma power at distinct phases of theta oscillation, with this phase-based organization relating to successful temporal-order memory. Together, these findings suggest that theta-gamma coupling supports the organization of information over time during encoding, particularly in tasks that require maintaining and structuring sequential information. For example, Köster et al. (2014) reported prefrontal theta-

parietal gamma coupling during successful episodic retrieval, which supports the relevance of this frontal-parietal coupling but does not directly explain the condition-specific encoding effect found in the current research. More broadly, Papaioannou et al. (2022) showed that cortical theta-gamma PAC is not specific to memory, but is also observed in tasks involving attention and perceptual processing. This suggests that PAC reflects a general mechanism of coordinating neural activity, rather than a process unique to memory encoding. As a result, the relationship between PAC and behaviour is likely to depend on the extent to which a task relies on this type of coordination.

Applied to the present findings, this framework suggests that in the 2D condition, where external structure was reduced and participants may have relied more heavily on internally driven neural coordination, theta-gamma PAC was directly engaged in organizing incoming information into retrievable memories. In the Real-world condition, by contrast, the richness of the environment may have provided sufficient external scaffolding to support encoding without requiring the same degree of internally generated oscillatory coordination, resulting in a weaker association between PAC and recall performance. This interpretation is consistent with the broader argument developed in section 4.2, in which higher PAC in the 2D condition was proposed to reflect increased cognitive demands rather than superior encoding efficiency.

4.5 PAC, MOCA, AND BROADER COGNITION

Another goal of this study was to examine whether the observed PAC effects could be explained by differences in general cognitive ability or whether they were specific to the encoding context. Although one measure, Picture Vocabulary, showed a nominally significant difference between groups at the uncorrected level, this did not survive Benjamini-Hochberg false discovery rate correction across all eight cognitive comparisons, and no other measure

approached significance. Nevertheless, the nominal difference in Picture Vocabulary should be considered when interpreting the findings, as it is possible that subtle differences in crystallized verbal ability between groups may have contributed to some of the observed effects (Weintraub et al., 2013). To examine this, correlations were calculated between PAC and broader cognitive measures, including the MoCA and NIH Toolbox Cognition Battery scores. These included Picture Sequence Memory, Flanker, List Sorting Working Memory, Dimensional Change Card Sort, Oral Reading Recognition, Pattern Comparison, and Picture Vocabulary. Overall, PAC was not consistently related to cognitive performance across the sample. The only significant finding was a negative correlation between PAC and MoCA in the Real-world condition. In contrast, no such relationship was found in the 2D condition. This pattern suggests that PAC does not reflect stable differences in general cognitive ability, but instead reflects task-specific neural processing during encoding.

One possible way to interpret the negative correlation between PAC and MoCA scores in the Real-world condition is that it reflects increased effort in participants with lower cognitive scores. In other words, participants with lower MoCA scores may have relied more on the neural coordination during encoding, which resulted in higher PAC values. This interpretation is consistent with the broader view developed in this study that PAC reflects coordination between the neural processes rather than memory performance alone (Papaioannou et al., 2022). It is also important that this pattern was only observed in the Real-world condition and not in the 2D condition. Therefore, the negative PAC and MoCA correlation in the real-world condition is best interpreted as a context-specific pattern rather than a general link between PAC and cognitive ability. Taken together, these results suggest that the main PAC effects observed in this study are unlikely to be driven by the overall cognitive ability. Even though a condition-specific

relationship was observed between PAC and MoCA scores, it did not generalize across conditions or across cognitive measures. Instead, the findings suggest that PAC is more closely related to task-specific processing during encoding, rather than reflecting the stable differences in general cognitive performance.

4.6 METHODOLOGICAL IMPLICATIONS

The findings of this study also have several methodological implications for research on memory and brain activity. One of the main contributions is using a well-matched naturalistic design that compares real-world and 2D recording versions of the same narrative. This approach allows for more direct examination of how encoding context affects neural activity, while keeping the content constant. By controlling the narrative structure across conditions, this study was able to examine differences related to the mode of presentation rather than the differences in the material being remembered. Future studies aiming to examine the effect of context or presentation format should consider using matched stimuli across conditions in order to isolate the influence of the encoding environment from differences in content, an approach that has been advocated in naturalistic neuroscience as a means of balancing ecological validity with experimental control (Jääskeläinen et al., 2021; Sonkusare et al., 2019).

Another important methodological point is the use of PAC as a neural measure in a naturalistic task. Much of the previous work on PAC has been conducted using simplified or highly controlled paradigms, such as discrete trial-based tasks involving word lists or sequential item presentations, where stimuli are presented in isolation and timing is tightly controlled (Heusser et al., 2016; Köster et al., 2014). These designs allow for precise manipulation of encoding conditions but do not reflect the continuous and dynamic nature of real-world experiences. In contrast, the current study demonstrates that PAC can be measured during

continuous, narrative-based encoding that closely resembles real-world memory formation. Importantly, the findings show that PAC did not relate to memory performance in a uniform way across conditions, suggesting that its functional relevance depends on task demands rather than reflecting a general marker of memory strength. This also highlights the importance of combining the behavioural and neural measures. If only verbal free recall performance had been measured, the conditions would have appeared similar, despite differences in neural processing. Taken together, these findings suggest that researchers should both interpret PAC in a context-dependent manner and integrate neural and behavioural measures when studying memory in naturalistic settings, as relying on a single measure type may lead to incomplete or misleading conclusions. More broadly, these findings suggest that the ecological validity of the paradigm is not simply a methodological consideration but a factor that fundamentally shapes the neural dynamics under investigation and the conclusions that can be drawn from them.

More broadly, the results highlight an important consideration for cognitive neuroscience: experimental design does not simply influence outcomes, but can shape the relationship between neural activity and behaviour itself. Even when the same material is used, changing only the mode of presentation altered whether PAC was behaviourally relevant, despite identical content. This suggests that conclusions about neural mechanisms derived from simplified or controlled paradigms may not directly translate to more naturalistic settings. As a result, incorporating ecologically valid designs is not only a methodological consideration, but a necessary step for understanding how memory operates outside the laboratory.

4.7 LIMITATIONS AND FUTURE DIRECTIONS

While this study provides useful insight into how encoding context affects neural activity and memory, several limitations should be considered when interpreting the results. These

limitations also point to clear directions for future studies. One limitation is the use of a single narrative stimulus. In this study, participants encoded one vignette presented in two formats. While this allowed for strong control over the content, it limits how much the findings can be generalized. Different types of narratives, emotional contexts, or complexity may lead to different patterns of neural activity and memory performance. Future research should test a wider range of naturalistic stimuli to determine whether the present findings generalize across different contexts.

The present thesis focused specifically on PAC between frontal theta and parietal gamma activity as a measure of neural coordination during encoding. While this approach was theoretically motivated and aligned with the study's objectives, it captures only one aspect of neural dynamics. Future research could expand on this by incorporating additional measures, such as functional connectivity or activity across different frequency bands, to provide a more comprehensive understanding of the neural processes supporting memory in different contexts. Similarly, our behavioural measure focused on event-based scoring of free recall, which provided a structured way to evaluate memory for the narrative. However, this approach primarily captured whether key events were remembered and did not directly assess other aspects of memory, such as richness, level of detail, or subjective experience. Future studies could include additional measures, such as ratings of vividness or confidence, to capture these dimensions fully. Additionally, the present findings are based on a sample of young, healthy adults, and inferences cannot be drawn about how these results would generalize to older adults or more demographically diverse populations. Further research would benefit from extending this paradigm to older adults in particular, given the well-documented age-related changes in hippocampal-prefrontal connectivity and oscillatory coordination discussed earlier (Grady et al.,

2003; Reinhart & Nguyen, 2019). It would be particularly valuable to examine whether this context-dependency of PAC is further modulated by age-related changes in neural coordination, given that older adults may show different patterns of oscillatory coupling under varying levels of environmental richness.

Naturalistic paradigms inherently involve a richer and more complex set of experiential features than traditional laboratory tasks, which opens up important questions about which specific aspects of the encoding context drive neural effects (Sonkusare et al., 2019). Although basic sensory differences between conditions, such as screen luminance, sound characteristics, and viewing distance, are unlikely to directly drive the observed PAC effects given that PAC reflects higher-order neural coordination rather than low-level sensory processing (Canolty & Knight, 2010; Esghaei et al., 2022), future studies should nonetheless better control these features to strengthen causal interpretations. Future research could build on these findings by systematically manipulating specific features such as social presence or sensory richness to further clarify which aspects of naturalistic encoding drive changes in theta-gamma PAC.

4.8 CONCLUSION

The present thesis investigated how encoding context shapes the neural dynamics underlying episodic memory formation, using a naturalistic paradigm that compared real-world and 2D versions of the same narrative. The central finding, that theta-gamma PAC was stronger in the 2D condition despite comparable recall performance across groups, challenges the commonly held assumption that stronger neural coupling reflects more effective or efficient memory encoding. Instead, the present results suggest that PAC reflects the degree of internally driven neural coordination required by the task, which is greater when the encoding environment provides less external structure and sensory support. This reframing has meaningful theoretical

implications: it positions PAC not as a static marker of encoding success, but as a flexible mechanism that scales with the cognitive demands imposed by the encoding context.

The condition-specific relationship between PAC and recall further supports this interpretation. The finding that PAC predicted recall performance in the 2D condition but not in the Real-world condition demonstrates that the functional relevance of theta-gamma coupling depends on the nature of the encoding environment. This contributes to a growing body of evidence suggesting that neural measures of memory cannot be interpreted independently of the context in which they are measured, and adds an important empirical demonstration of this principle, using a within-narrative comparison that controls for content while varying ecological richness.

The finding that comparable recall was achieved across conditions despite differences in neural coordination is itself theoretically significant. It demonstrates that episodic memory formation is not tied to a single neural strategy, but can be supported through different degrees of oscillatory coordination depending on how information is structured and presented. This supports a more flexible and context-sensitive model of episodic memory, one that acknowledges the role of environmental richness in shaping the neural processes that support encoding.

More broadly, these findings carry important methodological implications for cognitive neuroscience. The observation that the same neural measure showed fundamentally different relationships with behaviour across encoding contexts demonstrates that findings derived from controlled laboratory paradigms cannot be assumed to generalize to naturalistic settings. This underscores the need for greater integration of ecologically valid designs in memory research, not simply as methodological refinement, but as a necessary step towards understanding how memory operates in the real world. Future work examining how these context-dependent neural

dynamics unfold across different populations, including older adults and individuals with varying levels of cognitive ability, will be essential for building a comprehensive and ecologically grounded account of human episodic memory.

REFERENCES

Addis, D. R., Wong, A. T., & Schacter, D. L. (2007). Remembering the past and imagining the future: Common and distinct neural substrates during event construction and elaboration. *Neuropsychologia*, *45*(7), 1363–1377. https://doi.org/10.1016/j.neuropsychologia.2006.10.016

Arnone, J. (2024, July 8). *Over the Moon*. Monologue Blogger. https://monologueblogger.com/over-the-moon/

Bian, Z., Li, Q., Wang, L., Lu, C., Yin, S., & Li, X. (2014). Relative power and coherence of EEG series are related to amnestic mild cognitive impairment in diabetes. *Frontiers in Aging Neuroscience*, *6*. https://doi.org/10.3389/fnagi.2014.00011

Buzsáki, G., & Draguhn, A. (2004). Neuronal Oscillations in Cortical Networks. *Science*, *304*(5679), 1926–1929. https://doi.org/10.1126/science.1099745

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging*, *17*(1), 85–100. https://doi.org/10.1037/0882-7974.17.1.85

Cabeza, R., Nyberg, L., & Park, D. C. (2016). *Cognitive neuroscience of aging: Linking cognitive and cerebral aging*. Oxford University Press.

Canolty, R. T., Edwards, E., Dalal, S. S., Soltani, M., Nagarajan, S. S., Kirsch, H. E., Berger, M. S., Barbaro, N. M., & Knight, R. T. (2006). High Gamma Power Is Phase-Locked to Theta Oscillations in Human Neocortex. *Science*, *313*(5793), 1626–1628. https://doi.org/10.1126/science.1128115

Canolty, R. T., & Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences*, *14*(11), 506–515. https://doi.org/10.1016/j.tics.2010.09.001

Chen, J., Leong, Y. C., Honey, C. J., Yong, C. H., Norman, K. A., & Hasson, U. (2017). Shared memories reveal shared structure in neural activity across individuals. *Nature Neuroscience*, *20*(1), 115–125. https://doi.org/10.1038/nn.4450

Cohen, M. X. (2014). *Analyzing Neural Time Series Data: Theory and Practice*. MIT Press.

Combrisson, E., Nest, T., Brovelli, A., Ince, R. A. A., Soto, J. L. P., Guillot, A., & Jerbi, K. (2020). Tensorpac: An open-source Python toolbox for tensor-based phase-amplitude coupling measurement in electrophysiological brain signals. *PLOS Computational Biology*, *16*(10), e1008302. https://doi.org/10.1371/journal.pcbi.1008302

Conway, M. A. (2005). Memory and the self. *Journal of Memory and Language*, *53*(4), 594–628. https://doi.org/10.1016/j.jml.2005.08.005

Daume, J., Kamiński, J., Schjetnan, A. G. P., Salimpour, Y., Khan, U., Kyzar, M., Reed, C. M., Anderson, W. S., Valiante, T. A., Mamelak, A. N., & Rutishauser, U. (2024). Control of working memory by phase–amplitude coupling of human hippocampal neurons. *Nature*, *629*(8011), 393–401. https://doi.org/10.1038/s41586-024-07309-z

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2008). Qué PASA? The Posterior–Anterior Shift in Aging. *Cerebral Cortex*, *18*(5), 1201–1209. https://doi.org/10.1093/cercor/bhm155

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

DuPre, E., Hanke, M., & Poline, J.-B. (2020). Nature abhors a paywall: How open science can realize the potential of naturalistic stimuli. *NeuroImage*, *216*, 116330. https://doi.org/10.1016/j.neuroimage.2019.116330

Dvorak, D., & Fenton, A. A. (2014). Toward a proper estimation of phase–amplitude coupling in neural oscillations. *Journal of Neuroscience Methods*, *225*, 42–56. https://doi.org/10.1016/j.jneumeth.2014.01.002

Esghaei, M., Treue, S., & Vidyasagar, T. R. (2022). Dynamic coupling of oscillatory neural activity and its roles in visual attention. *Trends in Neurosciences*, *45*(4), 323–335. https://doi.org/10.1016/j.tins.2022.01.003

Friese, U., Köster, M., Hassler, U., Martens, U., Trujillo-Barreto, N., & Gruber, T. (2013). Successful memory encoding is associated with increased cross-frequency coupling between frontal theta and posterior gamma oscillations in human scalp-recorded EEG. *NeuroImage*, *66*, 642–647. https://doi.org/10.1016/j.neuroimage.2012.11.002

Gkintoni, E., Sortwell, A., Vassilopoulos, S. P., & Nikolaou, G. (2026). Neuroplasticity-Informed Learning Under Cognitive Load: A Systematic Review of Functional Imaging, Brain Stimulation, and Educational Technology Applications. *Multimodal Technologies and Interaction*, *10*(1), 5. https://doi.org/10.3390/mti10010005

Grady, C. L., McIntosh, A. R., & Craik, F. I. M. (2003). Age-related differences in the functional connectivity of the hippocampus during memory encoding. *Hippocampus*, *13*(5), 572–586. https://doi.org/10.1002/hipo.10114

Grall, C., & Finn, E. S. (2022). Leveraging the power of media to drive cognition: A media-informed approach to naturalistic neuroscience. *Social Cognitive and Affective Neuroscience*, *17*(6), 598–608. https://doi.org/10.1093/scan/nsac019

Gramann, K., Ferris, D. P., Gwin, J., & Makeig, S. (2014, January). Imaging natural cognition in action. In *International Journal of Psychophysiology* (Vol. 91, Issue 1, pp. 22–29). https://doi.org/10.1016/j.ijpsycho.2013.09.003

Gramfort, A., Luessi, M., Larson, E., Engemann, D. A., Strohmeier, D., Brodbeck, C., Goj, R., Jas, M., Brooks, T., Parkkonen, L., & Hämäläinen, M. (2013). MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience*, *7*. https://doi.org/10.3389/fnins.2013.00267

Hasson, U., Furman, O., Clark, D., Dudai, Y., & Davachi, L. (2008). Enhanced Intersubject Correlations during Movie Viewing Correlate with Successful Episodic Encoding. *Neuron*, *57*(3), 452–462. https://doi.org/10.1016/j.neuron.2007.12.009

Heusser, A. C., Poeppel, D., Ezzyat, Y., & Davachi, L. (2016). Episodic sequence memory is supported by a theta-gamma phase code. *Nature Neuroscience*, *19*(10), 1374–1380. https://doi.org/10.1038/nn.4374

Jääskeläinen, I. P., Sams, M., Glerean, E., & Ahveninen, J. (2021). Movies and narratives as naturalistic stimuli in neuroimaging. *NeuroImage*, *224*, 117445. https://doi.org/10.1016/j.neuroimage.2020.117445

Jacques, S., & L, P. (2024). Individuals who rarely adopt observer perspectives report richer scene-based autobiographical memories. *Scientific Reports*, *14*(1), 19310. https://doi.org/10.1038/s41598-024-70179-y

Jensen, O., & Colgin, L. L. (2007). Cross-frequency coupling between neuronal oscillations. *Trends in Cognitive Sciences*, *11*(7), 267–269. https://doi.org/10.1016/j.tics.2007.05.003

Köster, M., Friese, U., Schöne, B., Trujillo-Barreto, N., & Gruber, T. (2014). Theta–gamma coupling during episodic retrieval in the human EEG. *Brain Research*, *1577*, 57–68. https://doi.org/10.1016/j.brainres.2014.06.028

Lega, B., Burke, J., Jacobs, J., & Kahana, M. J. (2016). Slow-Theta-to-Gamma Phase–Amplitude Coupling in Human Hippocampus Supports the Formation of New Episodic Memories. *Cerebral Cortex*, *26*(1), 268–278. https://doi.org/10.1093/cercor/bhu232

Lisman, J. E., & Jensen, O. (2013, March). The Theta-Gamma Neural Code. In *Neuron* (Vol. 77, Issue 6, pp. 1002–1016). https://doi.org/10.1016/j.neuron.2013.03.007

Luck, S. J. (2014). *An introduction to the event-related potential technique*. MIT press.

Marucci, M., Di Flumeri, G., Borghini, G., Sciaraffa, N., Scandola, M., Pavone, E. F., Babiloni, F., Betti, V., & Aricò, P. (2021). The impact of multisensory integration and perceptual load in virtual reality settings on performance, workload and presence. *Scientific Reports*, *11*(1), 4831. https://doi.org/10.1038/s41598-021-84196-8

Mathewson, K. E., Kuziek, J. P., Scanlon, J. E. M., & Robles, D. (2024). The moving wave: Applications of the mobile <scp>EEG</scp> approach to study human attention. *Psychophysiology*, *61*(9). https://doi.org/10.1111/psyp.14603

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x

Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., & Bäckman, L. (2012). Memory aging and brain maintenance. *Trends in Cognitive Sciences*, *16*(5), 292–305. https://doi.org/10.1016/j.tics.2012.04.005

Papaioannou, O., Crespo, L. P., Clark, K., Ogbuagu, N. N., Alliende, L. M., Silverstein, S. M., & Erickson, M. A. (2022). Is Cortical Theta-Gamma Phase-Amplitude Coupling Memory-Specific? *Brain Sciences*, *12*(9). https://doi.org/10.3390/brainsci12091131

Pion-Tonachini, L., Kreutz-Delgado, K., & Makeig, S. (2019). ICLabel: An automated electroencephalographic independent component classifier, dataset, and website. *NeuroImage*, *198*, 181–197. https://doi.org/10.1016/j.neuroimage.2019.05.026

Radford, A., Kim, J. W., Xu, T., Brockman, G., Mcleavey, C., & Sutskever, I. (2023). Robust Speech Recognition via Large-Scale Weak Supervision. *Proceedings of the 40th International Conference on Machine Learning*, 28492–28518. https://proceedings.mlr.press/v202/radford23a.html

Ranganath, C., & Ritchey, M. (2012). Two cortical systems for memory-guided behaviour. *Nature Reviews Neuroscience*, *13*(10), 713–726. https://doi.org/10.1038/nrn3338

Reinhart, R. M. G., & Nguyen, J. A. (2019). Working memory revived in older adults by synchronizing rhythmic brain circuits. *Nature Neuroscience*, *22*(5), 820–827. https://doi.org/10.1038/s41593-019-0371-x

Rubin, D. C. (2006). The Basic-Systems Model of Episodic Memory. *Perspectives on Psychological Science*, *1*(4), 277–311. https://doi.org/10.1111/j.1745-6916.2006.00017.x

Sasmita, K., & Swallow, K. M. (2022). Measuring event segmentation: An investigation into the stability of event boundary agreement across groups. *Behavior Research Methods*, *55*(1), 428–447. https://doi.org/10.3758/s13428-022-01832-5

Schacter, D. L., Addis, D. R., & Buckner, R. L. (2008). Episodic Simulation of Future Events. *Annals of the New York Academy of Sciences*, *1124*(1), 39–60. https://doi.org/10.1196/annals.1440.001

Sonkusare, S., Breakspear, M., & Guo, C. (2019). Naturalistic Stimuli in Neuroscience: Critically Acclaimed. *Trends in Cognitive Sciences*, *23*(8), 699–714. https://doi.org/10.1016/j.tics.2019.05.004

Tort, A. B. L., Komorowski, R., Eichenbaum, H., & Kopell, N. (2010). Measuring Phase-Amplitude Coupling Between Neuronal Oscillations of Different Frequencies. *Journal of Neurophysiology*, *104*(2), 1195–1210. https://doi.org/10.1152/jn.00106.2010

Tulving, E. (2002). Episodic Memory: From Mind to Brain. *Annual Review of Psychology*, *53*(1), 1–25. https://doi.org/10.1146/annurev.psych.53.100901.135114

Vilberg, K. L., & Rugg, M. D. (2008). Memory retrieval and the parietal cortex: A review of evidence from a dual-process perspective. *Neuropsychologia, Part Special Issue: What Is the Parietal Lobe Contribution to Human Memory?*, *46*(7), 1787–1799. https://doi.org/10.1016/j.neuropsychologia.2008.01.004

Voytek, B., Canolty, R. T., Shestyuk, A., Crone, N. E., Parvizi, J., & Knight, R. T. (2010). Shifts in gamma phase-amplitude coupling frequency from theta to alpha over posterior cortex during visual tasks. *Frontiers in Human Neuroscience*, *4*. https://doi.org/10.3389/fnhum.2010.00191

Weintraub, S., Dikmen, S. S., Heaton, R. K., Tulsky, D. S., Zelazo, P. D., Bauer, P. J., Carlozzi, N. E., Slotkin, J., Blitz, D., Wallner-Allen, K., Fox, N. A., Beaumont, J. L., Mungas, D., Nowinski, C. J., Richler, J., Deocampo, J. A., Anderson, J. E., Manly, J. J., Borosh, B., … Gershon, R. C. (2013). Cognition assessment using the NIH Toolbox. *Neurology*, *80*(11 Suppl 3), S54–S64. https://doi.org/10.1212/WNL.0b013e3182872ded

Widmann, A., Schröger, E., & Maess, B. (2015). Digital filter design for electrophysiological data – a practical approach. *Journal of Neuroscience Methods, Cutting-Edge EEG Methods*, *250*, 34–46. https://doi.org/10.1016/j.jneumeth.2014.08.002

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: A mind-brain perspective. *Psychological Bulletin*, *133*(2), 273–293. https://doi.org/10.1037/0033-2909.133.2.273

Zacks, J. M., & Swallow, K. M. (2007). Event Segmentation. *Current Directions in Psychological Science*, *16*(2), 80–84. https://doi.org/10.1111/j.1467-8721.2007.00480.x

Zheng, J., Yebra, M., Schjetnan, A. G. P., Patel, K., Katz, C. N., Kyzar, M., Mosher, C. P., Kalia, S. K., Chung, J. M., Reed, C. M., Valiante, T. A., Mamelak, A. N., Kreiman, G., & Rutishauser, U. (2024). Theta phase precession supports memory formation and retrieval of naturalistic experience in humans. *Nature Human Behaviour*. https://doi.org/10.1038/s41562-024-01983-9

APPENDIX A: "OVER THE MOON" PLAY SCRIPT

This appendix presents the full script of the vignette used during the encoding phase of the experiment. The narrative, titled "Over the Moon", was performed either live by actors or presented as a recorded video, depending on the experimental condition (Real-world vs. 2D). The script was designed to stimulate a naturalistic social interaction between two characters, Lucia and Arnold. The narrative was structured into five key events: Flower, Nail polish, Coat, and Pocket watch, which were used as segmentation points for subsequent memory assessment. Each event was associated with a specific object cue used during the retrieval phase to facilitate cued recall. The complete script is provided below:

Lucia and Arnold are sitting on a bench in a park.

Event 1: Flower

(Lucia's Monologue on Flowers and Connection)

LUCIA: As I was saying. It's self-imposed claustrophobia.
I can't get back outside myself.
Not sure if I ever was outside myself.

ARNOLD: What do you mean by "outside yourself"?

LUCIA: You don't follow me at all, do you?
That's not to say you're dumb, 'cause you're a really nice fella and all—it's just that the way you look at me is different.
Different in the way that you actually care to listen to my problems, but also different in the way that it doesn't seem to register… on your face… what I'm saying.

ARNOLD: I hear you.

LUCIA: Sure, I'm grateful to even be heard in this great big world of ours. Isn't that amazing? Like, how there are billions of us spread out over the Earth and most of us don't really know one another? I find that scary.
I sound like a real tulip, don't I?

ARNOLD: Not at all, you're just being real. *(Leans down, grabs a flower from the ground, and hands it to Lucia)*

LUCIA: Thank you!

They do talk, you know… flowers, all we have to do is listen.
I pay attention to things like that.
My mother used to try and take care of plants but they would always die on her after a while.
Till one day she went on holiday and left me in charge of all the plants.
Within a week, they were all standing straight up, stretching out towards the sun…
You know why?

ARNOLD: Because you talked to them?

LUCIA: No. I would sing to them. Sing to them softly.
In the mornings, after I watered them, I'd sing them sweet lullabies…
I felt an instant connection, I would even say bond, you know, like they were friends of mine, even family if you really want to know the truth…
Great people.
In a way, you remind me of them, 'cause you listen and don't respond much.
It's nice.
It's nice 'cause you have nice eyes and I like looking into your eyes.

ARNOLD: Thank you my dear.

Event 2: Nail Polish

(Lucia Paints Arnold's Nails)

LUCIA: *(puts down the flower)*
Anyone ever tell you you're quite a charmer?
You make me dizzy inside.
Last time I felt this was in first grade.
A kid named Thomas kissed me—knocked me out cold! For real.
I fell over on top of this big pink Doll House.
My first kiss.

ARNOLD: Sounds unforgettable. You're glowing!

LUCIA: What?! like my makeup?
I try to keep it simple.
But do I glow?

ARNOLD: You glow like the moon.

LUCIA: Really? Oh, thanks.

ARNOLD: Your complexion is perfection.

LUCIA: Really? No shit.
Thank you. That's very kind of you to say to me.

LUCIA: So, where ya from?

ARNOLD: Over the hills just yonder.

LUCIA: What's your favourite colour?

ARNOLD: Silver.

LUCIA: What do you do for a living?

ARNOLD: I manage the land.

LUCIA: Oh! You're a real estate guy.
I figured you'd be something like that.

I work at a nail salon.
I'm really great with nails, always been great with nails.

ARNOLD: Nails??

LUCIA: Wanted to be an artist originally, like a great painter, but settled on doing nails.
I get loads of compliments too, 'cause of the detail.
See, that's the thing about it—life is in the details.
Most people forget the details,
like when Steve Jobs and his team signed their names inside the original Apple computers, that's detail, right?
And when I paint tiny stars, or trees, or cats and dogs for my clients, that's detail and I get good tips for that kind of level of work.

ARNOLD: You're incredible.

LUCIA: I'm a nail technician.

ARNOLD: And that makes you incredible. Can you paint my nails?

LUCIA: *(She reaches into her bag and pulls out her nail polish kit.)*
Really?
Well, I guess I can if... *(She searches her bag.)*
Ah! You're in luck.
I usually carry a few colors of nail polish with me wherever I go.
It keeps me calm just knowing they're with me. Like a comfort thing.
If something goes wrong, I whip them out and I get to painting my nails, and I can breathe clearly again.
I get anxiety.
Do you care what color I use on you?

ARNOLD: Not at all. Anything would be fine.

LUCIA: Cool.

(Lucia begins painting Arnold's nails.)

LUCIA: Do you like it?

ARNOLD: Magnificent!

LUCIA: Do you like the moon I drew on your pinkie?

ARNOLD: Why….?

LUCIA: It's a reminder of our special night together.

ARNOLD: You're too kind!

LUCIA: Don't mention it. I mean, I can always go back to painting on canvas. I still have a few of those canvases lying around my apartment. It's not like I can't pick up the brush at any time. My hands still work.

Done. Do you like that?

ARNOLD: *(Holds up his hand and stares at his hands)* It's like a work of art.

LUCIA: Told ya.

ARNOLD: Truly fantastic. Thank you!

LUCIA: Glad you like it.

ARNOLD: I'll always treasure this moment. *(scratches his nail)*

LUCIA: It usually rubs completely off in a few weeks, depending on how active your hands are.

(Lucia puts her nail polish back in her bag.)

Event 3: Taking Off Shoes

(Lucia Takes Off Her Heels Due to Pain)

ARNOLD: Shall we walk further, Lucia?

LUCIA: *(Rubbing her feet and begins to take off her shoes.)*
These heels... my feet are killing me.
Absolute murder to wear on a first date. *(She sighs in relief as she takes them off.)*
Should've known better. *(She kicks the heels off and stretches her feet.)*
But I guess beauty is pain, right? *(She chuckles to herself.)*
My footsies are gonna blow up triple the size by morning. *(She massages her feet a bit.)*

ARNOLD: Shall I carry you home? *(He offers a hand to help her stand.)*

LUCIA: Home? You ain't seeing my home, lover boy. Not yet. Anyway.

ARNOLD: I didn't mean to offend you.

LUCIA: No offence taken. Believe me, I've had guys come on to me and say the most horrible things.

ARNOLD: I'm sorry.

LUCIA: Don't be.

(Awkward silence. Lucia painfully stands up.)

ARNOLD: Allow me.

(Arnold gives her a hand.)

LUCIA: Thanks.

Event 4: Taking Off Coat

(Arnold Gives His Coat to Lucia When She Feels Cold)

LUCIA: *(Shivering slightly as the night grows colder)*
I'm glad you're here. It's nice to have somebody to listen.

ARNOLD: *(Notices her discomfort, takes off his coat and drapes it over her shoulders.)*
Here, for you. I enjoy listening to you. Sometimes I get lost in my thoughts while I'm listening to you.

LUCIA: You got lost? Have you even been listening to me this whole time? *(Jokingly serious)*

ARNOLD: Yes I have. I swear I haven't done anything but listen to you.

LUCIA: *(Starts laughing)* Don't you worry. I'm just messing with ya. You know what?

ARNOLD: What?

LUCIA: *(Smiling warmly, feeling the warmth of the coat.)*
This is really fun. I'm enjoying this.

ARNOLD: Me too.

Event 5: Pocket Watch

(Arnold Checks the Time and Indicates It's Late)

LUCIA: *(Sighs, leaning against him for support as the night winds down.)*
You know, I honestly lost track of time. It's getting late.

ARNOLD: *(He takes out his pocket watch and glances at the time.)*
It's late.

LUCIA: *(She grabs the pocket watch and looks at it)* Yeah, getting' late.

ARNOLD: I won't see you ever again.

LUCIA: Oh. I didn't… that's okay.

ARNOLD: I wish to see you again, but it's not possible.

LUCIA: You're married! I knew it! Why didn't you just tell me from the get-go?

ARNOLD: No, no, that's not it at all.

LUCIA: Are you dying?

ARNOLD: …This is too hard for me to explain, Lucia… there are things in life that are unexplainable and it's most probably better that way…

LUCIA: You think I'm dumb and can't understand it? *(Sounds angry)*

ARNOLD: No. It's not about you. I wish I didn't have to leave, but I must go back… I never intended to meet you and spend this entire evening with you… you will stay in my heart forever, until my final breath, I will be thinking of you and only you and hope that when I cease to exist,

that you will be found once again, amongst the meadow and high hills, amongst the sunsets and moonlit skies, I will forever love you.

LUCIA: Maybe you can come back to my place.

ARNOLD: Lucia, I must go.

LUCIA: Go? *(takes the purse and shoes from the ground)*

ARNOLD: Remember the words I have spoken. Perhaps in another life, another place, another time we could have been together… promise me this, promise me that you won't forget me.

LUCIA: Okay.

ARNOLD: Please, promise me you'll always remember me.

LUCIA: I promise.

ARNOLD: Never let me go.

LUCIA: Where are you going?

ARNOLD: If it were so simple. Please, go now, make it back to the street where the light is so you are safe. I can go no further.

LUCIA: What's wrong with you? Why are you acting so strange?

ARNOLD: I'm sorry.
Lucia, my love, go now, it is midnight… go now.

LUCIA: (Silence)

(They both leave the scene and go behind)

END OF PLAY

APPENDIX A.1: EVENT CUES USED FOR MEMORY RECALL

Specific objects were embedded within each event and later presented as cues during the retrieval phase to prompt recall of the corresponding narrative segments.

Figure A. 1: Flower cue associated with Event 1

Figure A. 2: Nail polish cue associated with Event 2

Figure A. 3: Shoes cue associated with Event 3

Figure A. 4*: Coat cue associated with Event 4*

Figure A. 5: Pocket watch cue associated with Event 5

APPENDIX B: SYNTHETIC DEMONSTRATION OF PAC

This appendix presents a synthetic validation of the PAC analysis pipeline. Simulated theta (6 Hz) and gamma (80 Hz) signals were generated to demonstrate coupling patterns. The results show gamma bursts aligned with theta phase and corresponding peak in the comodulogram, confirming that the pipeline accurately detects PAC.

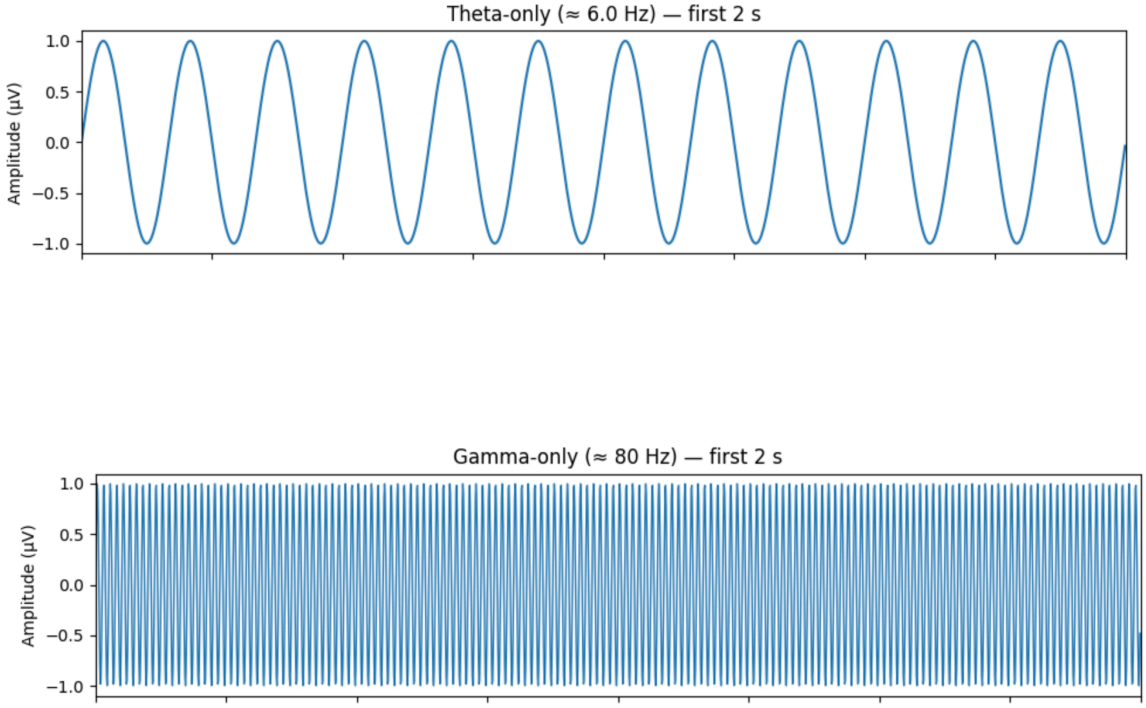

Figure B. 1: Synthetic theta and gamma signals

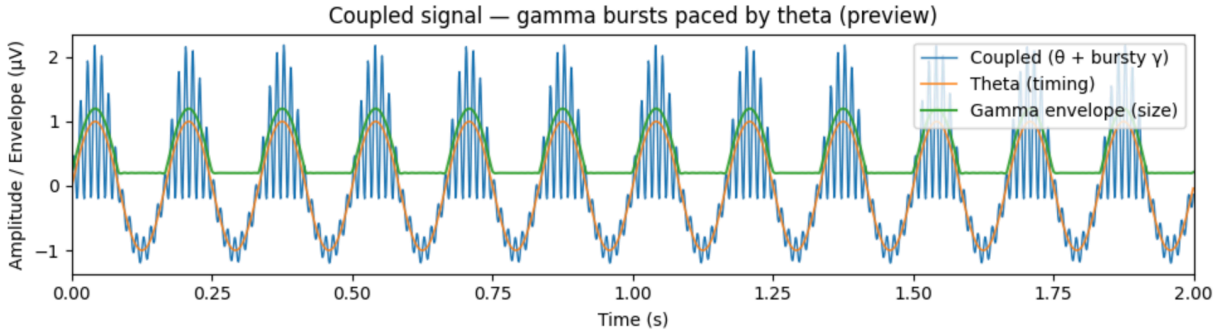

Figure B. 2: *Coupled signal demonstrating theta-modulated gamma bursts*

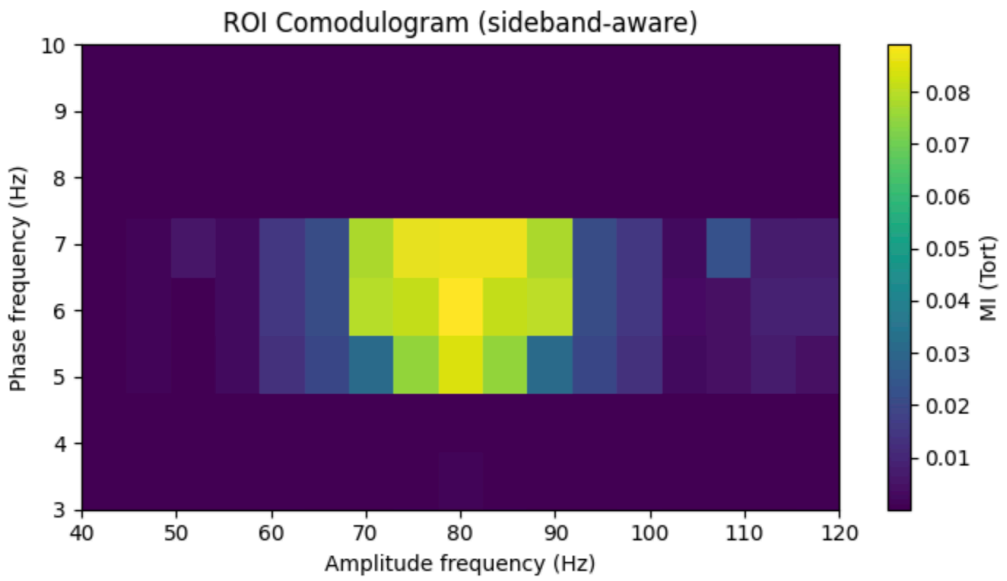

Figure B. 3: Comodulogram showing peak PAC at simulated frequencies

APPENDIX C: POWER ANALYSIS RESULTS

The appendix presents supplementary analyses of theta and gamma band power across Real-world and 2D conditions. Boxplots illustrate the distribution, central tendency, and variability of power values across participants in each condition. Importantly, these analyses were conducted to evaluate whether observed PAC effects could be explained by differences in signal power. The results indicated that variations in theta and gamma power do not account for the PAC patterns reported in the main analyses, supporting the interpretation that PAC reflects genuine cross-frequency interactions rather than artifacts driven by power differences.

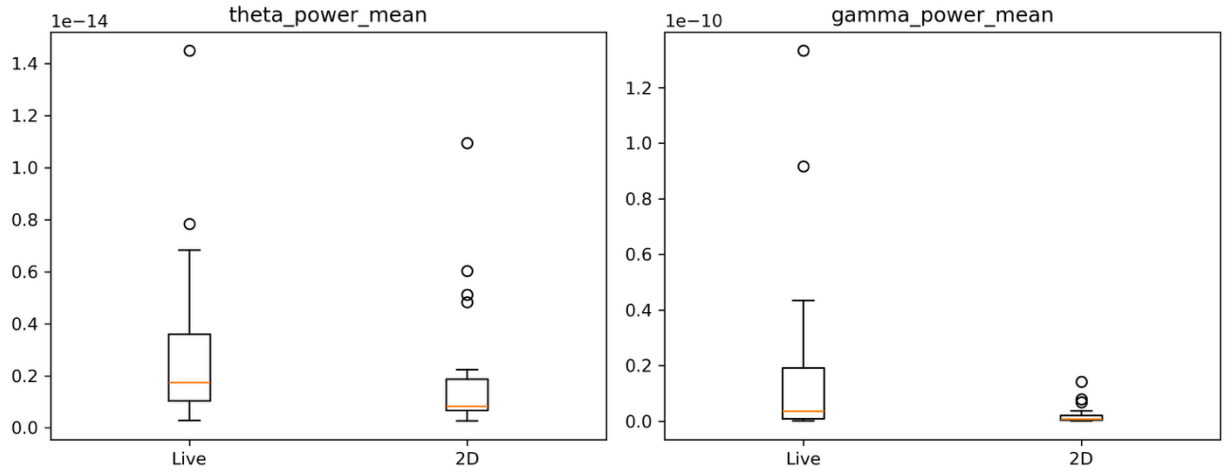

Figure C. 1: Theta and gamma power distributions across Real-world and 2D conditions

APPENDIX D: EXPERIMENTAL SETUP FOR REAL-WORLD AND 2D ENCODING CONDITIONS

This appendix illustrates the experimental setups used during the Real-world and 2D encoding conditions. In both conditions, participants were seated at a fixed distance from the stimulus while EEG data were recorded continuously using a 128-channel system. In the Real-world condition, participants viewed a real-time performance of the "Over the Moon" vignette staged within a controlled laboratory environment. Actors performed the scene directly in front of the participant, with the spatial arrangement designed to maintain a consistent viewing angle and minimize external distractions while preserving a naturalistic experience. In the 2D condition, participants viewed a recorded version of the same performance presented on the background wall using a projector. The visual perspective, framing, and timing of the recorded stimulus were matched as closely as possible to the Real-world condition to ensure comparability across conditions. Together, these setups enabled a controlled comparison between real-world and screen-based recording while maintaining consistency in stimulus content and viewing conditions.

Figure D. 1: Experimental setup for the Real-world encoding condition, showing participant EEG recording during a real-time performance of the vignette

Figure D. 2: Experimental setup for the 2D encoding condition. The vignette was presented on the background wall while EEG data were recorded. The participant perspective shown is a representative reconstruction for visualization purposes. The stimulus presentation environment reflects the actual experimental setup.

APPENDIX E: EVENT SEGMENTATION AND RECALL SCORING RUBRIC

This appendix outlines the event segmentation framework and scoring rubric used to evaluate participants' recall performance. The vignette was divided into 12 medium-grained events, representing meaningful narrative units that were neither overly coarse nor excessively fine-grained. This level of segmentation was selected to balance ecological validity with scoring precision, allowing for systematic and comparable assessments of episodic recall across participants. Participants' recall responses were evaluated based on the presence and accuracy of these predefined events. Each event was scored on a scale ranging from 0 to 1, with intermediate values reflecting partial recall accuracy. This approach enabled quantification of both complete and partial recollection of event-specific information.

APPENDIX E.1: EVENT DESCRIPTIONS

Event 1: Two actors walk into to the room and sit on the bench, and she was talking about herself and her feelings. Looks like they came back from a date.
Event 2: Male actor reaches to the base of the tree next to him to grab a flower (a red rose) to give it to the female actor and she starts talking about flowers.
Event 3: Female actor puts the flower on the side and gets a bit closer to him and starts complementing him and talking about her first kiss.
Event 4: She asked him about his job and things he likes, like his favourite colour or where he's from. Then she talks about her job.
Event 5: She reaches into her purse, takes out a bottle of nail polish, and starts painting his nails. And he liked it.
Event 6: She takes off her high heels (pink shoes) and she was in pain because of wearing those shoes. He offered to take her home and she said no.
Event 7: Male actor helped her to stand up. He takes off his coat (blue coat) and give it to her as they were talking.
Event 8: He takes out the pocket watch (silver pocket watch) out of his pocket and checks the time as she mentions it's getting late or she lost track of time. She takes a look at the time. He says he is never going to see her again.
Event 9: She takes off the coat and puts it on the bench. She gets mad or annoyed at him, and he tries to explain, but tells her that it's hard for him to explain this situation and hopes to see her again.
Event 10: She grabs her shoes and purse. He asks for her to never forget him. He is in a constant hurry to leave.
Event 11: Actors switch places in the scene. She gets annoyed again by him saying that he has to go but he says she needs to go. And she asks where he's going.
Event 12: He checks the time again and says sorry. He urges her to go and leave. She leaves the scene and he also takes his coat and leaves.

APPENDIX E.2: SCORING RUBRIC

Recall performance was quantified using an event-based scoring system in which each of the 12 predefined events was evaluated independently. For each event, participants received a score between 0 and 1 on the accuracy and completeness of their recall:

- 0 = No recall or incorrect recall
- 0.25 = Minimal recall (fragmentary or vague reference to the event)
- 0.5 = Partial recall (some correct elements, but incomplete)
- 0.75 = Mostly accurate recall (minor details missing or slightly incorrect)
- 1 = Complete and accurate recall of the event

The total recall score was computed by summing across all 12 events, yielding a maximum possible score of 12.

Table E. 1

Event-based scoring rubric used to evaluate recall performance across the 12 segmented narrative events.

	0	.25	.5	.75	1	Total
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
Score	/12					