Context & Episodic Memory Symposium

2024 · 20TH ANNIVERSARY

Philadelphia, Pennsylvania

May 30 - 31

Penn
University of Pennsylvania

Table of Contents

Locations

All spoken presentations will be delivered in the Ballroom. Breakfast will be served in the Ballroom Foyer. Lunch will be served in the Stenton room. Poster sessions will take place in the Courtyard. In case of inclement weather, poster sessions will be moved to the Stenton room.

Thursday Schedule

The first author is presenting unless marked with an asterisk (*).

8:20 Breakfast and registration *(Ballroom Foyer)*

8:50 **Michael Kahana:** Welcome and introductory remarks

Spoken Presentation Session 1

9:00 **Jiawen Huang, Eleanor Furness, Yifang Liu, Morell-Jovan Kenmoe, Ronak Elias, Hannah Tongxin Zeng & *Christopher Baldassano** *(Columbia University)*: Accurate predictions facilitate robust memory encoding independently from stimulus probability

9:20 **Kate Nussenbaum & Catherine A. Hartley** *(Princeton Neuroscience Institute and New York University)*: Reinforcement learning increasingly shapes memory specificity from childhood to adulthood

9:40 **David J. Halpern & Michael J. Kahana** *(University of Pennsylvania)*: Study-Phase Reinstatement: Encoding Spontaneous Thoughts as Memories

10:00 **BREAK**

Spoken Presentation Session 2

10:20 **James Antony, Angelo Lozano, Pahul Dhoat, Janice Chen & Kelly Bennion** *(California Polytechnic State University)*: Causal network properties predict memory organization for non-linear narratives

10:40 **Youssef Ezzyat & Abby Clements** *(Wesleyan University)*: Neural activity differentiates novel and learned event boundaries

11:00 **Nicole M. Long** (*University of Virginia*): Bottom-up or top-down? How to induce the retrieval state

11:20 **Rui Cao, Ian M. Bright & Marc W. Howard** (*Boston University*): Ramping cells in rodent mPFC encodes time to past and future events via real Laplace transform

11:40 **LUNCH**

12:50 **Keynote Address: Anthony Wagner** *(Stanford University)*: Mechanisms of Memory Variability in Human Aging

1:50 **GROUP PHOTO**

2:00 **BREAK**

2:20 - 3:50 ***Poster Session 1***

3:50 *Data Blitz*

1. **Frederick Callaway, Thomas L. Griffiths, Kenneth A. Norman & *Qiong Zhang** (*Rutgers University*): Optimal Metacognitive Control of Memory Recall
2. **Gabriel Kressin Palacios, Buddhika Bellana & Christopher J. Honey** (*Johns Hopkins University*): Blocking Persistent Mental Content
3. **Victoria Schelkun & Lila Davachi** (*Columbia University*): Hippocampal context maintenance and temporal pattern separation support episodic memory
4. **Eric R. Cole, Riley DeHaan, Lou Blanpain, John Sakon, Nealen Laxpati, Michael J. Kahana & Robert E. Gross** (*Georgia Tech and Emory University*): Stimulation-evoked connectivity predicts functional changes in the human temporal lobe
5. **Isabelle L. Moore, Devyn E. Smith & Nicole M. Long** *(University of Virginia)*: Effects of aging on memory brain state dynamics
6. **Xian Li, Nicole Kim Ni, Savannah Born, Ria J. Gualano, Iris Lee, Buddhika Bellana & Janice Chen** (*Johns Hopkins University*): Agency enhances individuality in memory for narratives
7. **Nelly Matorina, Yi Lin Wang, Javid Guliyev & Morgan Barense** (*University of Toronto*): Remote autobiographical memories have wider spatial scales and are more contextually rigid than recent memories
8. **Ameeruddin Ghouse & Raphael Kaplan** (*Universitat Jaume I*): The penumbra of social episodic content: Enhanced retention of irrelevant social information during episodic memory-guided decision-making
9. **Nathan F. Gillespie & Gregory E. Cox** (The *State University of New York at Albany*): Using Natural Language Processing to Understand Individual Differences: Integrating Quantitative and Qualitative Approaches to Memory and Perception

5:00 **END**

Friday Schedule

The first author is presenting unless marked with an asterisk (*).

8:20 Breakfast and late registration *(Ballroom Foyer)*

Spoken Presentation Session 1

9:00 **Gordon D. Logan, Gregory E. Cox, Simon D. Lilburn, Jana E. Ulrich** *(Vanderbilt University)*: No Position-Specific Interference from Prior Lists in Cued Recognition: A Challenge for Position Coding (and Other) Theories of Serial Memory

9:20 **Jeremy B. Caplan & Dominic Guitard** *(University of Alberta)*: Attentional subsetting theory: strength in small numbers

9:40 **Wei Tang, Morten H. Christiansen, Zhenghan Qi** *(Indiana University Bloomington)*: A hidden Markov framework for brain representations of temporal regularity

10:00 **BREAK**

Spoken Presentation Session 2

10:20 **Ashley Williams, Charan Ranganath & Randall O'Reilly** *(University of Pennsylvania)*: Prefrontal Modulation of the Hippocampus Supports Successful Switching Between Opposing Task Goals

10:40 **Sebastian Michelmann, Camilla K. Strauss, Werner K. Doyle, Daniel Friedman, Lucia Melloni, Patricia C. Dugan, Orrin Devinsky, Sasha Devore, Adeen Flinker, Uri Hasson & Kenneth A. Norman** *(New York University)*: Tracing the neural underpinnings of memory search across slowly unfurling states

11:00 **Qihong Lu, Ali Hummos & Kenneth A. Norman** *(Columbia University)*: Episodic memory supports the acquisition of structured task representations

11:20 **Samantha S. Cohen, Chi T. Ngo, Ingrid R. Olson &Nora S. Newcombe** *(Temple University)*: Pattern Completion and Pattern Separation during Early childhood

11:40 **LUNCH**

12:50 - 2:10 ***Poster Session 2***

2:10 *Data Blitz*

1. **Adam Broitman, Karl Healey & Michael Kahana** (*University of Pennsylvania*): EEG Spectral Features Capture Effects of Aging on Attention and Memory
2. **Rolando Masís-Obando, Chris Baldassano & Ken Norman** (*Princeton University and Johns Hopkins University*): How strong is your memory palace? Reliable room representations predict subsequent memory for placed objects
3. **Melisa Gumus & Michael L. Mack** (*University of Toronto*): Learning regularities and exceptions are supported by distinct hippocampal pathways as revealed by diffusion-weighted functional footprints
4. **Andrei Amatuni, Nicole L. Varga, Alex Gordienko, Omer Ashmaig, Neal W Morton & Alison R. Preston** (*University of Texas at Austin*): Probabilistic inference of latent causes develops through adolescence
5. **Wangjing Yu, Benjamin M. Silver, Kevin N. Ochsner & Lila Davachi** (*Columbia University*): Social and semantic relationships shape temporal memory in a virtual escape room game
6. **Ian M. Bright, Kohl Swift, Alex P. Vaz, Sara K. Inati, Marc W. Howard, and Kareem A. Zaghloul** (*National Institutes of Health, NINDS*): A Multi-scale Representation of Temporal Context in the Human Anterior Temporal Lobe
7. **Emily T. Cowan, Elizabeth A Horwath, Joseph E. Dunsmoor, Vishnu P. Murty** (*Temple University*): A computational model of replay-facilitated retroactive memory effects

3:10 **BREAK**

Spoken Presentation Session 3

3:30 **Aleix Alcacer Sales, Lubna Abdul Parveen, Marina Martinez Garcia, Daniel McNamee & *Raphael Kaplan** *(Universitat Jaume I)*: Relational Episodic Inference for Episodic Simulation

3:50 **Derek J. Huffman, Shuran Yang, Ainsley Bonin, Chandrachud Gowda & Nikhil Jaha** *(Colby College)*: Cognitive and neural representations of real-world spatial environments

4:10 **Emily R. Weichart, Layla Unger, Vladimir M. Sloutsky & Brandon M. Turner** *(Utah State University)*: Gaze as a direct input for encoding structure in models of human learning

4:30 **Gregory E. Cox, Supriya Samaroo & Nathan F. Gillespie** *(The State University of New York at Albany)*: Integration of Information Across Separate Events

5:00 **END**

Keynote Speaker: Dr. Andrew Wagner

Andrew Wagner (PhD '97, *Stanford University*) is a Lucie Stern Professor in the Department of Psychology and a deputy director of the Wu Tsai Neurosciences Institute at Stanford University. His basic science focuses on the psychology and neurobiology of learning, memory, and executive function in young and older adults. His translational research examines aging and Alzheimer's disease, the relationship between multitasking and cognition, and the implications of neuroscience for law. He is a fellow of the Society of Experimental Psychologists, American Association for the Advancement of Science, and the Association for Psychological Science

Keynote Address: Mechanisms of Memory Variability in Human Aging

Age-related episodic memory decline is characterized by striking heterogeneity across individuals. In cognitively unimpaired (CU) older adults, this variability reflects functional and structural changes in and connectivity between multiple brain regions that support memory formation and retrieval. In this talk, I will discuss findings from the Stanford Aging & Memory Study, which draws on imaging, biofluid, and behavioral assays in a cohort of CU older adults to understand within- and between-person variability in memory. The talk will focus on neocortical and hippocampal mechanisms of memory, including the representation of event features during experience, pattern completion and cortical reinstatement at retrieval, along with interactions between attention and memory. Moreover, the talk will consider how preclinical Alzheimer's disease pathology, assayed from blood plasma and CSF, reveal early disease-related and disease-independent neural and behavioral differences.

Thursday Talk Abstracts

Listed in order of presentation. The first author is presenting unless otherwise marked (*).

Jiawen Huang, Eleanor Furness, Yifang Liu, Morell-Jovan Kenmoe, Ronak Elias, Hannah Tongxin Zeng & *Christopher Baldassano *(Columbia University)*: Accurate predictions facilitate robust memory encoding independently from stimulus probability

We can use prior knowledge of temporal structure to make predictions about how an event will unfold, and this schematic knowledge has been shown to impact the way that event memories are encoded and later reconstructed. Existing paradigms for studying prediction, however, are largely unable to separate effects of prediction accuracy from effects of stimulus probability: likely outcomes are assumed to be predicted, while unlikely outcomes are assumed to cause prediction errors. Here we use a novel approach in which we can independently manipulate prediction success and stimulus probability, by using real-time eye-tracking when viewing moves in a board game. We found that both probability and prediction accuracy boost memory through two separate mechanisms, leading to different eye-movement strategies at retrieval. These results challenge the prevailing idea that only prediction errors can enhance event memories, and provide a more realistic paradigm for studying schemas, learning, and decision making.

Kate Nussenbaum & Catherine A. Hartley *(Princeton Neuroscience Institute and New York University)*: Reinforcement learning increasingly shapes memory specificity from childhood to adulthood

In some contexts, abstract stimulus representations can effectively promote the pursuit of reward, whereas in others, more detailed representations are needed to guide choice. Here, using a novel reinforcement-learning task, we asked how children, adolescents, and adults flexibly adjust the specificity of the representations used for learning and memory based on experienced reward statistics. Across two experiments (N = 224), we found that participants across age flexibly adjusted the specificity of their learning representations based on experienced rewards. The representations used for learning shaped mnemonic specificity; placing greater weight on detailed representations during value-guided learning enhanced subsequent memory for stimulus details, while placing greater weight on broader, categorical representations enhanced memory only for categorical information. Moreover, the relation between learning and memory strengthened with age; relative to adults, children demonstrated reduced coupling between the specificity of the representations used for value-based choice and the specificity of their subsequent memories.

David J. Halpern & Michael J. Kahana *(University of Pennsylvania)*: Study-Phase Reinstatement: Encoding Spontaneous Thoughts as Memories

Can the brain improve the retrievability of an experience after it has occurred? Systems consolidation theory proposes that cortical reactivation during extended post-encoding rest periods facilitates the formation of stable memory representations, a prediction supported by extensive neural evidence. Such reactivation may also occur on short time scales as spontaneous thoughts come to mind during encoding, offering a potential account of classic list memory phenomena but lacking in support from neural data. Leveraging the high temporal specificity of intracranial electroencephalography (iEEG), we investigate spontaneous reactivation of previously experienced items during brief sub-second intervals between individual encoding events. Across two free recall experiments, we show that reactivation during these periods predicts subsequent recall. In a third experiment, we show that the same methodology identifies memory-predictive post-encoding reactivation. Thus, spontaneous study-phase reinstatement reliably predicts memory behavior, linking psychological accounts to neural mechanisms and providing the first evidence for rapid consolidation processes.

James Antony, Angelo Lozano, Pahul Dhoat, Janice Chen & Kelly Bennion *(California Polytechnic State University)*: Causal network properties predict memory organization for non-linear narratives

While recounting a story, one could transition between events by recalling nearby events in time (temporal), similar events (semantic), or events produced by the current event (causal). To disentangle these factors, we had participant watch the non-linear narrative, Memento, under different task instructions and presentation orders. For each scene, we separately computed semantic and causal networks. Critically, the causal strategy matched recall transitions better than semantic or temporal strategies – even after asking participants to specifically recall the film in the presented order. Nevertheless, time still predicted recall transitions, suggesting it continues to modestly influence recall alongside more salient forms of structure. Additionally, semantic and causal network properties predicted scene memorability, including showing a stronger memory-boosting role for incoming causes of events than their outgoing effects. In sum, these effects highlight the importance of accounting for complex, causal networks in scaffolding knowledge building and organizing recall.

Youssef Ezzyat & Abby Clements *(Wesleyan University)*: Neural activity differentiates novel and learned event boundaries

People segment experiences at natural breakpoints called event boundaries, however it remains unclear how different forms of uncertainty affect the parsing of continuous experiences. We exposed participants to a continuous sequence of images that were grouped into temporal communities by an undirected graph. After learning, we asked participants to segment another sequence that included both Novel and Learned event boundaries. Greater segmentation at Novel boundaries was associated with enhanced parietal scalp EEG activity between 250-450 ms after stimulus onset. Multivariate classification of EEG activity showed that Novel and Learned boundaries evoked distinct patterns of neural

activity, particularly posterior theta power. Learning led to distinct neural representations for the temporal communities, while neural activity at Learned boundary nodes showed evidence for the adjacent community. The findings suggest the brain flexibly responds to event boundaries of distinct types, which could support dynamic modulation of neural activity in response to ongoing experience.

Nicole M. Long (*University of Virginia*): Bottom-up or top-down? How to induce the retrieval state

Memory brain states impact what we will (and won't) remember, but how memory states are induced remains an open question. Here I present two scalp EEG studies in which we manipulated both bottom-up and top-down factors. We used a cross-study decoding approach to measure how bottom-up stimulus repetition and top-down task demands modulate retrieval state engagement. We find that top-down demands to recognize past experiences induce the retrieval state regardless of stimulus repetition and that changing top-down demands across consecutive trials also induces the retrieval state. Together, these findings suggest that the retrieval state is engaged in response to explicit demands to direct attention internally.

Rui Cao, Ian M. Bright & Marc W. Howard (*Boston University*): Ramping cells in rodent mPFC encodes time to past and future events via real Laplace transform

To reproduce a particular interval, animals must remember the starting point in the past and anticipate the endpoint in the future. We analyzed previously published recordings from rodent mPFC (Henke et al., 2021) and identified two groups of cells. The "past-cells" peaked at the start point and relaxed exponentially back to baseline. The "future-cells" increased firing exponentially and peaked right before the end of the interval. Contrary to the previous assumption that timing information in the brain has few time scales for a given interval, we found strong evidence for a continuous distribution of the rate constants across both past-cells and future-cells. The real Laplace transformation of time predicts exponential firing from the event with a continuous distribution of rate constants across the population. Therefore, the firing pattern of the past-cells and future-cells can be identified with the Laplace transform of time to the past event and the future event.

Friday Talk Abstracts

Listed in order of presentation. The first author is presenting unless otherwise marked (*).

Gordon D. Logan, Gregory E. Cox, Simon D. Lilburn, Jana E. Ulrich *(Vanderbilt University)*: No Position-Specific Interference from Prior Lists in Cued Recognition: A Challenge for Position Coding (and Other) Theories of Serial Memory

Position-specific intrusions of items from prior lists are rare but important phenomena that distinguish broad classes of theory in serial memory. They are uniquely predicted by position coding theories, which assume items on all lists are associated with the same set of codes representing their positions. Activating a position code activates items associated with it in current and prior lists in proportion to their distance from the activated position. Thus, prior list intrusions are likely to come from the coded position. We tested this account with a position-cued recognition task, cuing a position to activate a position code, which should activate items in nearby positions in current and prior lists. Lures from nearby positions in both lists should be harder to reject, increasing RT and error rate. We found no evidence for such interference in 10 experiments, falsifying the position coding prediction. These results challenge all theories of serial memory.

Jeremy B. Caplan & Dominic Guitard *(University of Alberta)*: Attentional subsetting theory: strength in small numbers

Attentional subsetting theory posits that participants only attend to and process a small subset of item features in episodic memory tasks. The theory examines the dimensionality of the feature space; if large, working representations will tend to be sparse, with very little cross-talk interference across list items, and if small, they will not be sparse, resulting in considerable interference. This provides a continuum account of list-strength effects in recognition, which have otherwise been thought to be null, but are positive and large in the production effect and sometimes inverted in manipulations of stimulus duration, which we replicate in two pre-registered experiments. The theory explains additional features of production-effect data. Finally, the theory can be incorporated into any model with a vector representation of items, offering a nuanced understanding of key phenomena, including the list-strength effect and the production effect in recognition tasks.

Wei Tang, Morten H. Christiansen, Zhenghan Qi *(Indiana University Bloomington)*: A hidden Markov framework for brain representations of temporal regularity

We investigated the neural basis of chunking during statistical learning (SL). Behavioral evidence suggests that a common mechanism in learning and memory can serve to combine smaller units into larger ones to facilitate higher-level processing. And yet, the neural underpinnings of this mechanism remain unclear.

We propose a hidden Markov model (HMM) that operationalizes chunking with two core principles: (1) the hidden states represent serial order rather than specific visual features, and (2) the formation of temporal chunks leads to autocorrelated brain activity. Applying the HMM to functional neuroimaging data from subjects performing a visual SL task, we found a brain representation of triplet structure (1) for triplet sequences but not random sequences, (2) at the later stage but not earlier stage of learning, and (3) in the hippocampus but not in the early visual cortex. These results shed light on a chunking mechanism for SL in the hippocampus.

Ashley Williams, Charan Ranganath & Randall O'Reilly *(University of Pennsylvania)*: Prefrontal Modulation of the Hippocampus Supports Successful Switching Between Opposing Task Goals

The hippocampus is known to play a central role in memory processes with computational and theoretical models assigning a broad range of functions to the hippocampus. Many of these functions can be grouped under the umbrella of two opposing key processes: "integration" and "differentiation". However, there is literature to support that the prefrontal cortex (PFC) is also necessary to complete these processes and may be acting to modulate activity in the hippocampus. Specifically, we suggest that the PFC can inhibit the information that is "distracting" (i.e., overlapping feature information between similar items) so that differentiation can occur when performing a task that requires mnemonic discrimination. In this talk, I am proposing a simple, proof-of-concept hippocampal-PFC model that is capable of both differentiation and integration, depending on task goals.

Sebastian Michelmann, Camilla K. Strauss, Werner K. Doyle, Daniel Friedman, Lucia Melloni, Patricia C. Dugan, Orrin Devinsky, Sasha Devore, Adeen Flinker, Uri Hasson & Kenneth A. Norman *(New York University)*: Tracing the neural underpinnings of memory search across slowly unfurling states

Fast neural processes support episodic memory (e.g., Roux et al. elife 2022), yet slowly unfolding neural states underlie the perception of long narratives and their reinstatement (Baldassano, Neuron 2017). We bridge these timescales with human electrocorticography: Ten patients watched a movie and answered interview-questions, prompting them to scan their memory (typically: "after X, when is the next time Y happens"). We segmented their neural data into discrete states based on slow components capturing spatiotemporal patterns. Neural state-transitions predicted event segmentation (Zacks, 2007) of the movie in a separate norming sample (N= 195), preceding behavioral responses by ~1.3 seconds. During the interview, neural states from described moments in the movie were reinstated and silent memory-scanning was characterized by states unfurling in a forward direction. In cortex, state-transitions were accompanied by low-frequency power decreases that were preceded by power decreases in

hippocampus; connectivity analysis revealed information-flow from hippocampus to cortex underpinning state-transitions.

Qihong Lu, Ali Hummos & Kenneth A. Norman *(Columbia University)*: Episodic memory supports the acquisition of structured task representations

Generalization to new tasks requires learning of task representations that accurately reflect the similarity structure of the task space. Here, we argue that episodic memory (EM) plays an essential role in this process by stabilizing task representations, thereby supporting the accumulation of structured knowledge. We demonstrate this using a neural network model that infers task representations that minimize the current task's objective function; crucially, the model can retrieve previously encoded task representations from EM and use these to initialize the task inference process. With EM, the model succeeds in learning the underlying task structure; without EM, task representations drift and the network fails to learn the structure. We further show that EM errors can support structure learning by promoting the activation of similar task representations in tasks with similar sensory inputs. Overall, this model provides a novel account of how EM supports the acquisition of structured task representations.

Samantha S. Cohen, Chi T. Ngo, Ingrid R. Olson & Nora S. Newcombe *(Temple University)*: Pattern Completion and Pattern Separation during Early childhood

Here we examine the development of two fundamental memory processes: pattern completion, the ability to recollect an event as a unified holistic episode, and pattern separation, the ability to distinguish similar items from one another in children (4-7 years). We test holistic dependency in a scene-animal-object triads (a pattern completion task) and their ability to distinguish scenes, animals, and objects in this triad from similar lures (a pattern separation task). Performance on the two measures was unrelated, not only at the individual level, but in analyses of individual triads. Our results suggest that pattern completion and separation are distinguishable properties of episodic memory that develop in parallel.

Aleix Alcacer Sales, Lubna Abdul Parveen, Marina Martinez Garcia, Daniel McNamee & *Raphael Kaplan *(Universitat Jaume I)*: Relational Episodic Inference for Episodic Simulation

The neural computations guiding pattern completion of related similar episodes are typically investigated separately from episodic simulation. In the relatively few mechanistic models integrating episodic memory and planning, episodic memories are passively sampled during decision-making in a unitary fashion insensitive to their granular structure. This limited approach encounters difficulty when attempting to capture how humans make inferences about fictive scenarios for which individual episodic memories may be only partially relevant. We

develop a sample-based approximate inference approach called relational episodic inference. The relational episodic inference model captures how efficient episodic simulation is facilitated by the flexible integration of fragmentary elements of episodic memories. Under time constraints, our model displays more effective future inference than extant episodic reinforcement learning approaches. Notably, incorporating common reinforcement learning baselines as a reward function in the model enhances episodic simulation, where our recurrent network model can flexibly sample both within- and across-episodes.

Derek J. Huffman, Shuran Yang, Ainsley Bonin, Chandrachud Gowda & Nikhil Jaha *(Colby College)*: Cognitive and neural representations of real-world spatial environments

Studying memory for real-world spatial environments provides a method for determining the structure, precision, and temporal evolution of our memory. I will discuss our results that suggest that our memories for extremely familiar, large-scale spatial environments (the participants' college campus and hometown) appear to incorporate systematic distortions. Thus, our results suggest that even when we have years to form spatial memories, we still rely on specific cognitive heuristics rather than forming extremely precise, Euclidean, map-like knowledge. I will also discuss an experiment in which we used mobile EEG while participants were situated in a real-world environment (i.e., allowing full body rotations). We found that alpha-band oscillations play a role in coding the specific direction of a retrieved landmark in 3D space around the participant. In sum, I will discuss results and theories regarding the cognitive and neural representations that support memory for real-world spatial environments.

Emily R. Weichart, Layla Unger, Vladimir M. Sloutsky & Brandon M. Turner *(Utah State University)*: Gaze as a direct input for encoding structure in models of human learning

Humans selectively attend to task-relevant information in order to make accurate decisions. However, selective attention incurs consequences if the learning environment changes unexpectedly. The current work extends the generalized context model (GCM; Nosofsky, 1986) to account for both the intentional and consequential aspects of selective attention when predicting choice. In a novel direct input joint modeling approach, we used trial-level eye-tracking data from training and test to replace the attention parameters of GCM, which would otherwise be freely estimated from behavior. We demonstrate that only a model imbued with gaze correlates of memory precision for features encountered during learning can accurately predict key behaviors at test. Although humans engage selective attention with the intention of being accurate in the moment, our findings suggest that its consequences on memory constrain the information that is available for making decisions in the future.

Gregory E. Cox, Supriya Samaroo & Nathan F. Gillespie *(The State University of New York at Albany)*: Integration of Information Across Separate Events

Repetition enhances memory, though the mechanism by which it does so remains unclear. Repetition may form separate memory traces that each afford independent retrieval opportunities, or it may strengthen a single integrated trace. Using a novel paradigm that jointly leverages the speed and precision of recall, we find evidence for both mechanisms. When cued to recall the color of a repeated object, 41% of participants did so consistent with having independent memory traces for each repetition. Recall performance of the remaining participants could only be explained in terms of an integrated trace. For the majority of these individuals, the integrated trace coexisted with a weaker trace representing the first encounter with the object. These results reconcile mechanisms by which repetition enhances memory and suggest how repeated experience may lead to knowledge that integrates information across events without necessarily erasing memory for separate events.

Thursday Data Blitz Abstracts

Listed in order of presentation. The first author is presenting unless otherwise marked (*).

Frederick Callaway, Thomas L. Griffiths, Kenneth A. Norman, and *Qiong Zhang (*Rutgers University*): Optimal Metacognitive Control of Memory Recall

Most of us have experienced moments when we could not recall some piece of information but felt that it was just out of reach. Research in metamemory has established that such judgments are often accurate; but what adaptive purpose do they serve? Here, we present an optimal model of how metacognitive monitoring (feeling of knowing) could dynamically inform metacognitive control of memory (the direction of retrieval efforts). In two experiments, we find that, consistent with the optimal model, people report having a stronger memory for targets they are likely to recall and direct their search efforts accordingly, cutting off the search when it is unlikely to succeed and prioritizing the search for stronger memories. Our results suggest that metamemory is indeed adaptive and motivate the development of process-level theories that account for the dynamic interplay between monitoring and control.

Gabriel Kressin Palacios, Buddhika Bellana, Christopher J. Honey (*Johns Hopkins University*): Blocking Persistent Mental Content

Recent experiences persist in our minds over minutes without overt volition, shaping our thoughts, decisions and actions. This persistence can be beneficial, enabling us to find creative solutions, but it can also be detrimental, leading to repetitive unwanted thoughts. What are the temporal dynamics of the thoughts that persist following an experience, and how can we block these thoughts? We characterized the persistence of mental content by asking participants to generate word chains before and after reading an immersive story; some participants were instructed to suppress-story related thoughts. We found that volitionally suppressing story-related thoughts reduced the semantic influence of the story on participants' word chains, but it did not eliminate their subjective experience of unwanted lingering thoughts. In follow-up experiments, we have begun to characterize the precise timing of story-related thoughts, and the effectiveness of working memory and episodic interference manipulations in blocking this persisting content.

Victoria Schelkun & Lila Davachi (*Columbia University*): Hippocampal context maintenance and temporal pattern separation support episodic memory

Continuous experience is parsed into discrete episodes in memory that preserve associative memory between items and their shared context. Prior work has shown that momentary contextual shifts (i.e., event boundaries) are critical to guiding this process, but it remains unclear how the memory system balances integration and differentiation to promote episodic memory. While undergoing

high-resolution fMRI, participants engaged with an episodic encoding task in which sequences of images were presented within contextually bound events. We found widespread activation across the ventral stream and attentional regions in response to event boundaries. In contrast, the hippocampus shows stable activity within events that sharply decreases at event boundaries. Pattern similarity analyses further revealed that the dentate gyrus subfield differentiates within-event objects, which in turn supports temporal memory judgements. Our results suggest a mechanism by which episodic memory is conserved within events through pattern separation and subsequent integration into the relevant event context.

Eric R. Cole, Riley DeHaan, Lou Blanpain, John Sakon, Nealen Laxpati, Michael J. Kahana & Robert E. Gross (*Georgia Tech and Emory University*): Stimulation-evoked connectivity predicts functional changes in the human temporal lobe

Closed-loop stimulation of the temporal cortex has potential to ameliorate memory dysfunction, a key symptom in diseases such as traumatic brain injury, epilepsy, and Alzheimer's. We aim to improve this stimulation paradigm by characterizing its effects on neurophysiological biomarkers of memory throughout brain-wide networks. 46 epilepsy patients with implanted depth electrodes were electrically stimulated (0.5mA/200Hz) throughout temporal and prefrontal cortical areas. Our preliminary results suggest that cortical stimulation primarily decreases both theta power and high-frequency activity throughout the brain while also increasing spectral tilt, an established biomarker of encoding. Additionally, we use evoked potentials to quantify the connectivity between regions of the temporal lobe, showing that stimulation-evoked connectivity predicts functional connectivity as well as the spatial profiles of induced memory biomarker changes. These features could be used prospectively to guide selection of electrical stimulation parameters for studying human memory and repairing memory dysfunction.

Isabelle L. Moore, Devyn E. Smith & Nicole M. Long *(University of Virginia)*: Effects of aging on memory brain state dynamics

Healthy older adults typically show impaired episodic memory -- memory for when and where an event occurred -- but intact semantic memory -- knowledge for general information and facts. We hypothesize that these effects arise from an increased tendency to engage in a 'retrieval state,' a brain state in which attention is focused internally in an attempt to access prior knowledge. Engaging in a retrieval state can impair subsequent memory. We conducted multivariate pattern analyses of scalp electroencephalographic data while participants were explicitly directed to encode or retrieve object images. We find that whereas young and middle-aged adults show increased encoding state engagement over the course of the stimulus interval, older adults show inconsistent maintenance of an encoding state. These findings suggest that the temporal dynamics of memory brain states differ across the lifespan with possible implications for the ability to maintain versus flexibly shift between memory states.

Xian Li, Nicole Kim Ni, Savannah Born, Ria J. Gualano, Iris Lee, Buddhika Bellana & Janice Chen (*Johns Hopkins University*): Agency enhances individuality in memory for narratives

In daily life, we continually make choices that create a chain of events, shaping the narrative of our personal history and guiding our memory. However, laboratory experiments on memory using narratives typically do not allow participants to direct the story. We investigated how agency affected memory for narratives using an interactive story. Participants were either 'Free' (made influential choices), 'Yoked' (made choices but some were denied), or 'Passive' (made no choices), as they read the same stories. We found that event recall was predicted by semantic and causal connectedness to other events ("centrality") across all groups, but agency selectively reduced the semantic centrality effect on memory. Agency also increased individual variability in event-by-event memory and enhanced the tendency of recalling neighboring events. Overall, this study demonstrated that agentive control in narratives significantly alters memory, both systematically and individually, offering new insights into the organization of human memory in real-life scenarios.

Nelly Matorina, Yi Lin Wang, Javid Guliyev & Morgan Barense (*University of Toronto*): Remote autobiographical memories have wider spatial scales and are more contextually rigid than recent memories

Selected autobiographical memories remain episodic over time. Although other forms of episodic memory change in their context-dependency (Cox et al., 2014), little is known about how context-dependency changes in autobiographical memories. Here, 393 participants recalled two recent and remote memories and answered questions about memory contextualization. We found that remote memories were reported at a wider spatial scale, $p < .001$, suggesting that spatial scale widens over time. Participants also reported that remote memories were both more difficult to imagine and would be more changed in a new location, $ps < .001$, indicating a greater contextual rigidity. Critically, larger spatial scales were associated with both being more difficult to imagine and being more changed in a new location, $ps < .05$. We propose that as autobiographical memories age, they become decontextualized through a widening of their spatial scale, which makes the memories more difficult to imagine in a new location.

Ameeruddin Ghouse & Raphael Kaplan (*Universitat Jaume I*): The penumbra of social episodic content: Enhanced retention of irrelevant social information during episodic memory-guided decision-making

Episodic memory helps facilitate navigation of the prosocial world, but whether there is a bias towards encoding social content in episodic memory is unclear. We test whether retaining social event content is prioritized using an episodic memory-guided choice task. We have participants encode episode triplets linked to fictitious individuals comprising a location, activity, and a social group. Participants then indicate which individual is best suited for a role in a social scenario, where only the activity is indicative of optimal role assignment. After

role assignment, social episodic recall primacy is tested by comparing retrieval performance for activity-group(social) and activity-location(non-social) pairings. In separate replications and varying levels of retrieval difficulty, we observe enhanced memory for social versus non-social episodic content. Notably, participants' role assignment performance positively correlates with irrelevant social content recall accuracy. These data hint at a propensity for retaining social over non-social content in episodic memory.

Nathan F. Gillespie and Gregory E. Cox (*The State University of New York at Albany*): Using Natural Language Processing to Understand Individual Differences: Integrating Quantitative and Qualitative Approaches to Memory and Perception

Much of memory research focuses on quantitative outcome variables. Despite the utility of such metrics, they are often insufficient for understanding individual differences in how people encode and retrieve items. We address this gap by examining narrative answers to questions about strategies people used in similarity rating and recognition judgement tasks for a set of novel auditory stimuli. We applied topic modeling to 779 responses to three questions about: how people judged similarity between sounds; how people recognized previously heard sounds; and how people formed impressions of the sounds they heard. 20 topics characterized the similarity responses, 16 characterized the recognition judgements, and 30 characterized people's impressions. Principal components analysis identified latent themes within each topic set. Individual differences in topic prominence were related to recognition memory. Results will be discussed, with the goal of proposing a methodology for triangulating quantitative, qualitative, and computational methods in memory research.

Friday Data Blitz Abstracts

Listed in order of presentation. The first author is presenting unless otherwise marked (*).

Adam Broitman, Karl Healey & Michael Kahana (*University of Pennsylvania*): EEG Spectral Features Capture Effects of Aging on Attention and Memory

We investigated whether EEG subsequent memory effects, previously identified in young adult populations, similarly predict encoding success in older adults or reflect changes in task demands. We recorded scalp EEG in 156 young adults (aged 18-30) and 37 older adults (aged 60-85) as they memorized lists of words. Participants studied each word either freely (without encoding instructions) or while performing a secondary encoding task (judging the size or animacy of each item). Older adults exhibited distinct neural subsequent memory effects, characterized by reduced negativity in the theta and alpha frequency bands, particularly during dual-task encoding. Surprisingly, age-related neural differences were most pronounced at the end of the word list, despite similar recency effects in recall rates between the age groups. The results suggest that neural differences between the age groups may capture compensatory processes that mitigate the effects of aging by helping older individuals encode the final list items.

Rolando Masís-Obando, Chris Baldassano & Ken Norman (*Princeton University and Johns Hopkins University*): How strong is your memory palace? Reliable room representations predict subsequent memory for placed objects

Real-world experiences happen at physical spatial locations. Trying to remember them may happen by leveraging our general knowledge of the structure of the world to help retrieve episodic details. However, it is still not well understood how spatial contexts scaffold the recall of these experiences. We hypothesized that for a memory of a spatial context to be the scaffold for future memories, it needed to be reliable: stable over time to provide a consistent cue everytime it is retrieved and distinct from other spatial context memories to be free from interference. To test how the neural properties of a spatial context memory supports new memories, we developed a novel paradigm that allowed us to quantify the within-subject reliability of a spatial context memory ("room reliability"), before it became the location in which a new memory occurred, and then used it to predict the degree at which that new memory was remembered.

Melisa Gumus & Michael L. Mack (*University of Toronto*): Learning regularities and exceptions are supported by distinct hippocampal pathways as revealed by diffusion-weighted functional footprints

Learning is supported by the hippocampus (HPC) and its two central pathways: trisynaptic (TSP) and monosynaptic (MSP) pathways. It is theorized that MSP-related functions are key to encoding regularities whereas TSP-related functions

support rapid encoding of distinct items. To investigate the complementary involvement of MSP and TSP in learning, we had participants complete a rule-plus-exception category learning task during fMRI scanning. We leveraged diffusion-weighted imaging to identify pathway-specific endpoints (i.e., footprints) within entorhinal cortex and HPC subfields and their activations. Results showed that successful learning was associated with distinct pathway engagement: Learning category regularities was associated with higher MSP footprint activation, whereas learning category exceptions was tied to higher TSP footprint activation. These findings (1) provide novel evidence that learning category regularities and exceptions is distinctly supported by hippocampal pathways, and (2) suggest the "pathway footprint" may provide insights into the functional dynamics of hippocampal circuitry.

Andrei Amatuni, Nicole L. Varga, Alex Gordienko, Omer Ashmaig, Neal W Morton & Alison R. Preston (*University of Texas at Austin*): Probabilistic inference of latent causes develops through adolescence

Adaptive behavior requires extracting knowledge about the predictable structure of the world from numerous, noisy experiences. However, leading theoretical perspectives and recent empirical data indicate that children and adolescents struggle to infer knowledge beyond what they observe directly. Here, we extend prior work to quantify developmental differences in latent structure learning in a probabilistic task. Participants learned the probabilities of observing five friendly "monsters" in three distinct virtual environments and were then asked to infer the latent environment given only a sequence of monsters and no other cues. While all participants learned to successfully predict which monster would appear when navigating through an environment using direct observation, children and adolescents were less accurate when extending this knowledge during inference. We show that adults acquire full knowledge of the probability distributions underlying the entire task, whereas younger participants form more simplistic representations of latent causes that limit their reasoning ability.

Wangjing Yu, Benjamin M. Silver, Kevin N. Ochsner & Lila Davachi (*Columbia University*): Social and semantic relationships shape temporal memory in a virtual escape room game

Daily experiences involve interactions with other people, and some experiences are semantically related to other experiences. Here, we examined how relationships between people and between events shaped temporal memory in a virtual escape room game. Groups of friends participated in the game to collaboratively solve a series of puzzles. Importantly, clues obtained from some puzzles were used to solve other puzzles, forming semantic interconnections between events. We tested participants' subsequent temporal memory for key events in the game. Results revealed that while puzzles unfolded in the same order for all groups, sharing an experience increased temporal memory similarity across individuals. Further, temporal memory within a group was biased towards those who contributed more to solving puzzles. Examining the impact of event-event interconnections, we showed that after controlling for the actual temporal

distance between events, related events were remembered as being closer in time than the unrelated events, suggesting enhanced temporal integration.

Ian M. Bright, Kohl Swift, Alex P. Vaz, Sara K. Inati, Marc W. Howard, and Kareem A. Zaghloul (*National Institutes of Health, NINDS*): A Multi-scale Representation of Temporal Context in the Human Anterior Temporal Lobe

Cognitive neuroscientists propose that episodic memories are associated with a gradually changing state of temporal context. Temporal context produces a recency effect; similarity in brain activity decreases over time. Across experiments, the reported time scale of contextual change varies, ranging from seconds to tens of minutes. Further, the mechanisms that drive contextual change remain open. We recorded single units in the anterior temporal lobe of epilepsy patients during a paired associates task. We report a neural recency effect at multiple time-scales simultaneously; population activity changed within a trial, within a list, and within a session. Critically, these changes were consistent across repeated experiences, enabling the decoding of trial time and list position. Finally, we connect these results to coding at the individual unit level, with a focus on time cells and ramp/decay/temporal context cells. Taken together, these results expand and constrain our understanding of how the brain implements temporal context.

Emily T Cowan, Elizabeth A Horwath, Joseph E Dunsmoor, Vishnu P Murty (*Temple University*): A computational model of replay-facilitated retroactive memory effects

It is adaptive to prioritize retaining salient information in long-term memory. However, the value of information is often only evident through further experience. Research has shown exposure to salience cues (e.g., threat, reward) can facilitate delay-dependent retroactive memory enhancements for conceptually related, but previously neutral content. It's thought consolidation-related mechanisms, such as replay, may facilitate such benefits, yet this hypothesis remains untested. We adapted the Context Maintenance and Retrieval model (CMR) to examine if reactivating memories during replay facilitates the retroactive spread of salient signals. Simulating prior behavioral work, we presented two categories of stimuli in a neutral phase and a 'conditioning' phase, with one category modeled with a higher learning rate to simulate shock. We found that replay, modeled as cycles of iterative recall, facilitated retroactive memory benefits when the model included temporal context and stimulus category as source context. This work illustrates how the brain may adaptively tag and retain memories.

Listed in alphabetical order. The first author is presenting unless otherwise marked (*).

Aakash Sarkar & Marc Howard *(Boston University)*: Neurally inspired Deep networks with Laplace Neural Manifolds can show Temporal Receptive Windows

We study properties of SITHCon, a neurally-inspired deep CNN with continuous scale-invariant time cells at every layer. Each layer tracks what X when, but learnable weights between layers change the definition of `what'. We study the properties of RNNs to examine constraints required for them to be similarly timescale-invariant. A sequence of RNNs gradually incorporating these constraints perform successively better at generalizing to different scales but only become timescale-invariant when they are equivalent to SITHCon. When SITHCon classifies language-like sequences, with discrete transitions between symbols at multiple hierarchical levels, different layers encode the input sequence at different levels of granularity. We permuted the input sequence at scales corresponding to each hierarchical level. Earlier layers are affected at small scales but not larger ones, while higher layers are impacted at all timescales including long timescales. Networks with continuous time constants can exhibit a discrete hierarchy of temporal receptive windows.

Abigail M. D. Mundorf, Mitchell G. Uitvlugt & M. Karl Healey *(Michigan State University)*: Is organization decided at encoding? Effects of encoding and retrieval strategies

Although there is evidence temporal information is both encoded and retrieved automatically, temporal contiguity in recall is modulated by strategic control processes. It is unclear if these control processes operate primarily at encoding, by interfering with learning temporal information, or at retrieval, by organizing recall based on non-temporal associations. To address this question, we independently manipulated encoding and retrieval strategies. Prior to encoding the first list, subjects were told to focus on either temporal or semantic associations and ignore the other (initial strategy). Before recalling the final list, half of subjects were instructed to switch strategies, while the other half kept the same strategy (test strategy). Temporal contiguity was observed in all conditions. A semantic test strategy greatly reduced temporal contiguity, while there was only a small effect of initial strategy. Variations in temporal contiguity may be primarily due to differences in intentional memory search at retrieval, rather than encoding.

Adam F. Osth, Samuel Williams & Lyulei Zhang *(The University of Melbourne)*: A global similarity model of choice and response times of semantic and perceptual false memories in the Deese-Roediger-McDermott paradigm

What is arguably the most common method of eliciting false memories in the laboratory is the Deese-Roediger-McDermott paradigm (Deese, 1959; Roediger & McDermott, 1995), where participants study a set of items that are all similar to a non-presented item (e.g., the critical lure). A common finding is that false alarm rates to the critical lures are much higher than to other non-presented items and are in some cases even comparable to hit rates, even when the critical lure is perceptually similar to the studied items. Despite decades of work on this paradigm, there are only a handful of computational models that can describe this phenomenon, and the existing models that do only address semantic false memory. An even larger gap is that there is very little work that addresses response times (RTs) in this paradigm. We present a global similarity model in which probe decisions are based on the global similarity of semantic and perceptual cues to the contents of memory. The global similarity is used to drive a pair of linear ballistic accumulators, which can make predictions about the RT distributions for "old" and "new" responses. The model not only provided a strong account of hits and false alarm rates to critical, related, and unrelated lures, but also provided an excellent account of the corresponding RT distributions, and was also able to account for individual differences.

Aditya M. Rao, Alexander M. Papanastassiou, Aaron S. Geller, Michael R. Sperling, Chengyuan Wu, Bradley C. Lega & Michael J. Kahana *(University of Pennsylvania)*: Synchronous theta networks characterize successful memory retrieval

Previous studies have found that brain-wide theta synchrony underlies improved encoding of free recall items, but the theta synchrony effect underlying memory retrieval is not well understood. Here, we analyzed free recall data from 390 neurosurgical patients implanted with intracranial electrodes. For each electrode pair, we compare theta (3–8 Hz) phase locking during the periods before correct recall, and during matched periods of silence, to construct a theta synchrony map specific to memory retrieval function. We report a whole-brain theta synchrony effect, as well as network hubs distributed throughout the medial and lateral temporal and frontal lobes. Theta synchrony changes during successful retrieval are stronger in slow theta than fast theta, and a region's global synchrony correlates positively with its modulation of power during successful retrieval. Moreover, retrieval-evoked synchrony is stronger than encoding-evoked synchrony, and patterns of memory-specific synchrony are reliably but weakly correlated between encoding and retrieval.

Ami Falk & Per B. Sederberg *(University of Virginia):* Detecting Heterogeneous Cognitive Strategies in Episodic Memory Tasks

Previous analyses of continuous recognition tasks indicate that disparate cognitive process parameter values produce similar performance for individuals at both low and high task performance levels, but a theory-driven account of this phenomenon has yet to be developed. We hypothesize that the heterogeneity in parameter values across ability levels is evidence that different people rely on distinct cognitive strategies to accomplish episodic memory tasks. This begs two

questions: what are the strategies that most people use, and what kinds of people tend to use the same strategies? To answer these questions, we develop a novel Bayesian mixture-of-regressions model that clusters together participants that use similar cognitive strategies. We demonstrate the results of this model on both recall and recognition tasks.

Anup Das, Erfan Zabeh, Bard Ermentrout, Joshua Jacobs *(Columbia University):* Planar, Spiral, and Concentric Traveling Waves Distinguish Cognitive States in Human Memory

A fundamental challenge in neuroscience is explaining how widespread brain regions flexibly interact to support behaviors. We hypothesize that a mechanism of neural coordination is brain oscillations that propagate as traveling waves across the cortex in distinctive patterns that control when and where different regions interact. To test this hypothesis, we used direct recordings from humans performing multiple memory experiments and a novel analytical framework that measures the directional propagation of oscillations. We found that traveling waves propagated along the cortex in not only plane waves as seen previously, but also in spirals, sources and sinks, and more complex patterns. These traveling wave patterns correlated with various aspects of behavior, with specific propagation patterns reflecting broad cognitive processes, and the identities of specific remembered items. Together, these findings show that complex spatiotemporal patterns of traveling waves underlie human cognition and are relevant practically for neural decoding and brain–computer interfacing.

Paula P. Brooks, *Augustin C. Hennings, Brigitte A. Guzman, Kenneth A. Norman & Maureen Ritchey *(Princeton University):* Eye movements reveal the dynamics of memory reactivation supporting successful memory suppression

The ability to prevent the retrieval of unwanted memories is adaptive and may be protective against psychiatric disorders. The non-monotonic plasticity hypothesis (NMPH) predicts that forgetting occurs when memories enter a moderate state of activation during voluntary memory suppression. Here, we combined eye-tracking with a think/no-think paradigm to measure the strength of memory reactivation during retrieval suppression attempts. Memory items consisted of scene-object pairs in which each object was presented on either the left or the right. After learning, participants saw background scenes and were instructed to either retrieve or suppress the associated object in memory. Gaze position served as a proxy for memory reinstatement. Across two experiments (N=21; 34) unsuccessful forgetting of no-think items was associated with a gaze repulsion effect. In contrast, successful forgetting was associated with an initial gaze attraction to the object location followed by a subsequent repulsion to the opposite side, consistent with a moderate level of activation. These results provide novel evidence in support of the NMPH and highlight how gaze reinstatement can covertly measure memory strength during retrieval suppression.

Austin Greene & Per Sederberg *(University of Virginia):* A general and light spatial associative learning task for wide-scale application

Associative learning and spatial memory show marked change during development and aging. Designing a lightweight, widely applicable, scalable, and repeatable task would allow for quick and effective evaluation of associative learning ability. Here, we design, test, and validate against standard memory paradigms an item-to-location associative memory task that requires memory reconstruction as a robust assay of memory that still allows for automatic response processing, unlike recall tasks. After studying a list of objects presented at pseudo-random locations, participants must reject studied items and place novel items from a matching category where the original item was presented. This task thus assesses both item-to-location binding and one-shot category learning. We expect item memory and location memory to be dissociable, providing an effective assay of episodic memory ability. We will present an initial model of the observed behaviors, with the ultimate goal of quantifying changes in spatial and categorical memory across the lifespan.

Blake L. Elliott & Vishnu P. Murty *(Temple University):* Hippocampal novelty signals dynamically predict goal relevant VTA activation

Novelty is an important learning signal that invigorates goal-oriented behavior via afferent hippocampal (HPC) regulation of the mesolimbic dopamine (DA) system. Specifically, animal research shows that HPC novelty signals lead to increased sustained mesolimbic engagement, which magnifies phasic VTA responses to goal-relevant targets. However, the extent of these interactions during human behavior remains unclear. We employed a novel analysis of fMRI data from human subjects (n=91) performing a target-detection task intermixed with familiar and novel pictures. Hierarchical linear regressions examined goal-relevant VTA activation and HPC-VTA regulation during novelty. HPC activation to novel events dynamically predicted subsequent goal-relevant activation in the VTA ($\beta = 0.042$, $p<0.05$). Notably, this relationship did not hold true for striatal novelty signals ($\beta = 0.017$, $p=0.25$). These findings support models of goal-oriented behavior in which HPC regulatory systems in response to novelty invigorate VTA responsivity. Future work will explore prefrontal-VTA-HPC interactions and their impact on goal-directed behavior.

Brian Winston, Janice Chen & Frederick Barrett *(Johns Hopkins University):* Effects of Psilocybin at Encoding on Recall of Naturalistic Stimuli

The psychedelic drug psilocybin profoundly alters perception and cognition; however, its precise effects on episodic memory have not yet been characterized. In two separate double-blind, crossover studies, we administered 10mg/70kg psilocybin and placebo to subjects and recorded BOLD response during either music listening (study 1) or movie watching (study 2) at peak drug effects. In study 1 (n=18), psilocybin shifted multi-voxel pattern responses to music systematically across subjects in high-order cortical regions such as PCC, but not

in lower-level sensory regions. These results suggest that psilocybin may alter long-timescale integration rather than sensation of stimulus information, with potential consequences for long-term memory. After drug effects subsided in study 2, subjects were cued with screenshots from each movie and asked to recall the movie in detail. We hypothesize that systematic changes in neural responses to movies in regions related to episodic memory will correspond with altered movie interpretations as assessed via recall. From a preliminary analysis (n=3 in each drug condition, 3 movies) recall data is highly detailed, and subjects were more likely to recall narrative events with greater causal (mean r=0.27) and semantic (r=0.16) centrality.

Buddhika Bellana, Shihara Fernando, William Fisher, Gabriel Kressin Palacios & Christopher Honey *(York University, Glendon Campus):* A distinctive role of deep processing on the persistence of recent experiences in spontaneous thought.

Human thought is history-dependent – our recent experiences constrain our ongoing thoughts. While central to many computational models of memory, little work has examined factors that modulate the drift rate of 'mental context'. Why do some experiences elicit more persistent mental context than others? In recent work, using narratives and free word association, we argued that 'deep processing' (i.e., attending to semantic/situational features of an event rather than superficial perceptual ones) causes elements of the target experience to persist in mind for minutes after presentation. However, when reading a narrative, it is difficult to disentangle processing depth from overall task engagement. To address this, we adapted our paradigm to Wordle: a task that is highly engaging and word-based, but does not elicit deep situational processing. Interestingly, Wordle appeared markedly less likely to persist in spontaneous thought – consistent with a distinctive role of deep processing in generating persistent mental contexts.

Charlotte A. Cornell, Kenneth A. Norman, Thomas L. Griffiths, & Qiong Zhang *(Rutgers University–New Brunswick):* Improving Memory Search Through Model-Based Cue Selection

We often use cues from our environment when we get stuck searching our memories, but prior research has failed to show benefits of cuing with other, randomly selected list items during memory search. What accounts for this discrepancy? We proposed that cues' content critically determines their effectiveness and sought to select the right cues by building a computational model of how cues affect memory search. Participants (N = 195 young adults from the United States) recalled significantly more items when receiving our model's best (vs. worst) cue. Our model provides an account of why some cues better aid recall: Effective cues activate contexts most similar to the remaining items' contexts, facilitating recall in an unsearched area of memory. We discuss our contributions in relation to prominent theories about the effect of external cues.

Chenyu Wang, Rui Cao & Marc Howard *(Boston University):* Time cells for future actions in monkey PFC

We re-analyzed the published recordings from monkey PFC (Watanabe, et al. 2023, Nat Comm). In this experiment, monkeys wait for a period of time and then reach to a particular location. We found that planned future actions are coded by PFC neurons that fire sequentially during the delay. These sequentially-firing neurons for planned future actions share many properties with classic time cells: More cells fire later with wider time fields. These "time cells for future actions" are stimulus-specific; different time cells prefer different reaching directions. These results show that planned future actions are coded with the same kind of conjunctive what A when representation observed in memory experiments. These findings are not inconsistent with the hypothesis that memory for the time of past events and anticipation of the time of planned future events share a common neural code.

Chong Zhao & Edward K. Vogel *(University of Chicago):* Attention Control Differences Predict Both Source and Recognition Memory Performance

Attentional control abilities predict various cognitive abilities, such as gF and source memory performance. Specifically, its predictive power in source memory echoed the findings that source memory was more impaired than recognition memory under split-attention conditions. Here, we directly tested if attentional control differences predict visual recognition memory performances. In Exp 1, we showed that attention control predicted both source and recognition memory performances when participants needed to study 100 images for 3500ms per image. To further examine the role of attentional control in memory encoding, we surprisingly found that attentional control stopped predicting recognition memory when images were predicted rapidly (250ms ISI + 250ms stimulus, Exp 2), but predicted recognition memory when the total time of encoding were long enough in Exp 3 (3250ms ISI + 250ms stimulus). Therefore, we concluded that attentional control predicted source and recognition memory performance, except when rapid presentation rate overflowed attentional control capacities.

Christopher S. Hall, Zahra G. Esfahani, Marc W. Howard & Per B. Sederberg *(University of Virginia):* Towards a Neurally Viable Computational Model of Continuous Recognition

Computational temporal context models have provided a good account of behavioral data in many human episodic recall and recognition tasks, but have not yet specified a neural mechanism by which a temporal context could be retrieved. To address this, our model simulates a population of time cells and inhibitory neurons that track a spatiotemporal context modeled after cells found in the hippocampus. The network learns via Hebbian plasticity and showcases bump attractor dynamics during retrieval. The model is able to recover a previous context and is robust against different stimulus presentation rates due to the selection of time cell receptive fields. We also find a contiguity effect in that

retrieved contexts are more similar to their temporal neighbors than distal contexts. Here we study this model in a continuous recognition paradigm. Specifically, we examine the model's predictions of the effect of lag on retrieval time and recognition performance.

Cody Dong & Kenneth Norman *(Princeton University):* Strategic Control of Episodic Memory Retrieval During Story Reading

Past work has shown that people are biased towards automatically predicting upcoming words when listening to stories. Can people learn to overcome this bias and cease memory-based predictions when it is adaptive to do so? In this experiment, participants read stories twice where we manipulate the overall predictability by presenting the same story with a different ending (in the low predictability condition) or the same ending (high predictability). We predicted that participants in the low predictability condition would, upon presentation of only the beginning part, be less likely to retrieve the rest of the story, leading to worse subsequent memory compared to participants in the high predictability condition. In keeping with our prediction, we found that participants in the low predictability condition had worse memory on a subsequent cued recall test, suggesting that people modulate memory retrieval based on the predictability of the environment.

Daniella Rafla, David Halpern, Brandon Katerman & Michael Kahana *(University of Pennsylvania):* Organizational Dynamics of Memory Across Days

How does the organization of memory change over several repeated experiences? Previous studies of multi-trial free recall investigated changes in patterns of retrieval for the same list within a single learning session. We analyze data from a free recall experiment previously reported by Katerman et. al (2022). In each of five sessions, subjects studied a list of 576 words, with the words appearing in a new random order in each session. Prior to encoding, subjects performed a 10-minute recall task in which they attempted to recall as many words as they could from the previous session, which occurred at least one and often several days earlier. We found preserved contiguity effects reflecting previous recall order instead of encoding order. This effect increased across subsequent sessions, attesting to the strength of the associative processes taking place during retrieval. Intrigued by this behavioral finding, we inquire into the neural activity underlying retrieval. We ask whether neural activity preceding onset of recall predicts whether the recalled word will be retained after days of intervening cognitive activity. Preliminary results suggest that increased high frequency activity (HFA) in the moments leading up to recall predicts subsequent recall of the vocalized word.

David F. Gregory, Büşra Tanrıverdi, Bailey C. Spangler, Emily T. Cowan & Vishnu P. Murty *(Temple University):* Arousal and neural circuity of temporal distance during horror movie watching

How we perceive and use temporal memory impacts our lives and our ability to survive. For example, to identify predictors of upcoming threats or the causal relationships between actions and harm necessitates the ability to understand not only what events came first, but also at what timescales these events occurred. As such, distance as a factor of perception may be influenced and guided by current arousal states which are impacted during encoding. Previous work from our group and others has shown that threat increases temporal order memory, but less research has examined its influence on estimations of temporal distance. Here, we investigated the influence of arousal and valence on a variety of short movie clips depicting threatening and neutral events extracted from horror movies. We tested a retroactive estimation of elapsed time (i.e., distance estimation) between two pairs of image stills drawn from the same clip. Neural findings (n=47) are currently being analyzed for fMRI application of the task. We hope to replicate our behavioral finding (n=168) that threat altered distance estimations for aversive (M = 1.96) compared to neutral clips (M = 2.01), $t(167) = -2.3707$, $p = 0.0189$, such that perceived elapsed time was compressed for the aversive clips. We also found on a clip-by-clip basis, arousal was a significant predictor of distance estimations, $\chi 2(1) = -2.3707$, $p = 0.01889$, such that greater self-reports of arousal predicted compressed estimations of elapsed time. This research comprises behavioral and neural investigation that threat-related arousal during encoding affects how we perceive time and remember events in a multifaceted functional interchange of brain and behavior.

Devyn E. Smith & Nicole M. Long *(University of Virginia):* Multivariate decoding of memory retrieval feedback signals

It remains unclear how goals influence the neural mechanisms engaged following successful retrieval. We have previously found that theta power (4-8Hz) decreases following successful retrieval, which may reflect a positive feedback signal. Alternatively, these signals may reflect goal attainment; in a typical recognition experiment, the subjects' goal to identify old items is confounded with successful retrieval. To adjudicate between these hypotheses, we conducted two recognition memory experiments (E1, E2) in which we manipulated test-phase instructions. Subjects' goal was to either successfully retrieve study items (E1) or detect new items (E2). We recorded scalp electroencephalography to separately measure memory vs. feedback related theta signals. If feedback signals reflect successful retrieval, the same post-response signals should dissociate hits vs. correct rejections (CRs) regardless of memory goals. We find decreased theta power following hits vs. CRs in both experiments. These preliminary findings are consistent with the hypothesis that successful retrieval is intrinsically rewarding.

Paul Scotti, *Elita Lee, Ross Kempner, Elizabeth McDevitt & Kenneth A. Norman *(Princeton University):* Learning with caricatures facilitates discrimination of similar stimuli

Failure to discriminate similar experiences can cause memory interference. One way to resolve this is through differentiation of the corresponding representations in the hippocampus. Previously, Wanjia et al. (2021) found that

differentiation happened at the moment of successful behavioral discrimination. Here, using the same learning paradigm, we examined whether first learning caricatured (easier-to-discriminate) versions of similar stimuli benefits discrimination. Participants learned face-object associations across successive study-test rounds; every face belonged to either a caricatured or uncaricatured (harder-to-discriminate) face pair. Once both face-object pairs of a caricatured pair were learned (suggesting that the faces differentiated), the faces were shown in their uncaricatured form in the subsequent round. In the final round, which only tested uncaricatured pairmates, we found that performance was better for the pairs initially studied using caricatured faces versus uncaricatured faces ($t(50)=1.88$, $p=.03$). This suggests using caricatures to highlight visual differences may help trigger differentiation of similar stimuli.

Geoff Ward, Cathleen Cortis Mack, Charlotte Doherty, Nathanael Knight & Vanessa Loaiza *(University of Essex and University of Sheffield):* Effects of repetition, rehearsal, and a filled delay on free and serial recall

Four experiments examined the similarity and differences between free recall and serial recall by manipulating repetitions and rehearsals in immediate and delayed free and serial recall. Three experiments used a modified Brown-Peterson task in which the repetitions and rehearsals of to-be-remembered word sequences were manipulated prior to a variable delay. Experiments 1 -3 replicated and extended the findings of Hellyer (1962) showing recall accuracy of 3- or 6-word sequences decreased with increasing retention intervals and increased with increasing numbers of rehearsals/repetitions in both serial and free recall. A fourth experiment will also be presented in which sequences of 2-12 words were tested immediately or following a filled delay using serial and free recall. This experiment provides a conceptual replication and extension of Glanzer and Cunitz (1966) to immediate and delayed free and serial recall with the aim of exploring the theoretical integration of the two tasks.

Haydn G. Herrema & Michael J. Kahana *(University of Pennsylvania)*: Phonetic Features of Free Recall

In free recall studies, researchers have conducted considerable work characterizing the effects of temporal contiguity, semantic similarity, and spatial proximity on human memory. We further hypothesize that phonetic features of the studied words factor into encoding and retrieval. We define a novel "phonetic clustering score" to measure the extent to which participants rely on phonetic similarity to guide recall. Utilizing free recall data from intracranial EEG experiments, we learn that, while evident for some participants, phonetic similarity does not appear to act as a law of memory. However, we do find that phonetic features modulate inter-response times, with faster transitions occurring between phonetically similar items. Moreover, we show that false memories display a marked phonetic signature, as participants recall incorrect words that sound like encoded items. Finally, we conduct neural similarity analyses to investigate how phonetic similarity, participants' use of phonetic features, and spectral power of neural activity interact during encoding and retrieval.

Hemali Angne, Charlotte A. Cornell & Qiong Zhang *(Rutgers University–New Brunswick)*: Why Two Heads Together are Worse Than Apart: A Context-Based Account of Collaborative Inhibition in Memory Search

Counterintuitively, groups of people recalling information together remember less than the same number of individuals recalling alone (collaborative inhibition effect). To understand this effect in a free recall task, we build a model of collaborative recall, extended from the Context Maintenance and Retrieval (CMR) model which captures individuals recalling information alone (Polyn, Norman, & Kahana, 2009). We propose that in collaborative recall, one uses not only their previous recall as an internal retrieval cue, but also someone else's recall as an external retrieval cue. Attending to this cue updates the listener's context to be more similar to the context of someone else's recall. Over a dataset of individual and collaborative recall (Gates, Suchow, & Griffiths, 2022), our model captures collaborative inhibition across group sizes from 2 to 16, and recall patterns of recency and semantic clustering. Our model shows contexts of collaborating individuals converging more than that of individuals recalling alone.

James Mochizuki-Freeman, Md Rysul Kabir & Zoran Tiganj *(Indiana University Bloomington)*: Incorporating a cognitive model for evidence accumulation into deep reinforcement learning agents

Recent neuroscience studies suggest that the hippocampus encodes a low-dimensional ordered representation of evidence through sequential neural activity. Cognitive modelers have proposed a mechanism by which such sequential activity could emerge through the modulation of the decay rate of neurons with exponentially decaying firing profiles (also called temporal context cells). Through a linear transformation, this representation gives rise to neurons tuned to a specific magnitude of evidence, resembling neurons recorded in the hippocampus. Here we integrated this cognitive model inside reinforcement learning agents and trained the agents to perform an evidence accumulation task inspired by the behavioral experiments on animals. Compared to commonly used recurrent networks, we found that agents based on the cognitive model can learn faster and produce neural activity closer to the biological neurons.

Jennifer Fiedler, Kelly Giovanello, & Christopher N. Wahlheim *(University of North Carolina at Chapel Hill)*: Repeating Contexts Enhances Episodic Memory Updating by Promoting Remindings and Integrative Encoding.

Updating episodic memories is necessary when we encounter information that is similar to past experiences. Research suggests that the contexts associated with related experiences play a key role in updating. Two competing theories attempt to explain this relationship. Interference theory predicts that differentiating contexts associated with the encoding of similar events promotes updating. Integration theory predicts that reinstating contexts promotes updating by engaging a reminding process that enables the integration of existing memories

and new similar events. To evaluate these theories, we varied the context (i.e., scene picture) presented with word pairs containing shared cues with changed responses across lists (A-B, A-D). Our findings support the integration theory by showing that cued recall of original and changed pairs was enhanced when context was reinstated. This is consistent with the idea that remindings can support memory updating when the context of existing memories matches with that of new learning.

Jiang Mao, Mengting Fang & Alan Stocker *(University of Pennsylvania):* The cost of stimulus encoding and maintenance in perceptual working memory

Evidence accumulation reflects key characteristics of perceptual working memory. In addition to classical primacy and recency effects, our prior study found that a temporal break in the middle of an otherwise regular sequence of stimulus samples resulted in an increased weighting of the first post-break sample in subjects' subsequent recall of the overall sample mean. Here we show that perceptual evidence accumulation can be formulated as an active process that optimizes the trade-off between recall performance and cognitive effort in both memory encoding and maintenance. We conducted visual estimation experiments with varying durations and positions of the break in the sample sequences. Our model effectively captures the temporal dynamics of the accumulation process in conditions with or without breaks of various durations and positions, which cannot be explained by other models (e.g., bump attractor network). Our results suggest that perceptual working memory is an actively controlled, resource-rational process.

Jie Sun, Adam. F. Osth & Daniel Feuerriegel *(The University of Melbourne):* The Late Positive Event-Related Potential Component is Time-Locked to the Decision in Recognition Memory Tasks

The Frontal Negativity (FN400) and Late Positive Component (LPC) are widely interpreted as event-related potential (ERP) correlates of familiarity and recollection. However, the interpretation of LPC effects is complicated by inconsistent results regarding the timing of the effect and its relationship with decision confidence. To clarify these issues, using a large EEG dataset (n=132), we performed ERP deconvolution to disentangle contributions to LPC effects that were time-locked to either the stimulus or the vocal old/new response. We found that the left-lateralised parietal LPC effect was time-locked to the recognition memory decision, in contrast to the classical definition of the LPC as a stimulus-locked ERP component. We also isolated a response-locked, midline parietal ERP correlate of confidence that influenced measures of LPC amplitudes. Our analysis framework provides more accurate ways to measure LPC effects than existing work, which will help better define relationships between the LPC, recollection and confidence.

Jordan Gunn & Sean Polyn *(Vanderbilt University):* Some Problems for the Retrieved Context Account of Repetition and Spacing Effects

Retrieved-context theory (RCT) explains spacing and repetition effects in free recall in terms of contextual variability and study-phase retrieval [@lohnas2014retrieved]. Here, though, we present evidence of gaps in this account. We applied likelihood-based fitting [@morton2016predictive] to a computational model embodying RCT [CMR; @polyn2009context] using previously collected datasets [@lohnas2014retrieved; @kahana2005spacing]. Across datasets, CMR poorly generalized between task conditions that included or excluded item repetitions in study lists and underpredicted the mnemonic benefit of spaced repetition. Participants also exhibited a deficient repetition contiguity effect after recalling an item presented repeatedly in a list. They transitioned more often to neighbors of the item's initial, rather than successive, presentation position. CMR could not account for this pattern, even after adding mechanisms to either suppress memory for items' successive presentations or enhance memory for neighbors of items' initial presentations. These results help clarify the challenges presented by spacing and repetition effects for theories of memory.

Joseph Kahana & Michael Kahana *(The Haverford School):* Neural Decoding of Anticipation

You know its coming: the start of a race, the beginning of a quiz, the onset of a memory task. The onscreen countdown is mirrored by one in your head. But how does the brain time the anticipation period? Neuronal recordings have revealed time cells that fire at specific temporal delays, and ramping cells that increase or decrease their firing across an interval. Here we asked whether spectral components of EEG activity similarly represent temporal information. To answer this question, we analyzed intracranial recordings of patients (N = 396) watching ten-second countdown videos preceding the onset of a memory ask. Using the wavelet transform, we decomposed these brain signals into frequencies ranging from 3-280 Hz. We first asked how theta [3 Hz], alpha [12 Hz] and gamma [110 Hz] power varied across the countdown period across frontal (N = 337), temporal (N = 352), and hippocampal (N = 173) electrode pairs. Throughout the interval, theta frequencies went up, gamma frequencies went down, and alpha frequencies exhibited spikes corresponding to the ten countdown ticks. Inspired by these results, we used penalized regression models to predict time as a function of spectral power for subjects who had data from at east 80 countdown periods. Both lasso and ridge regression reliably predicted time within the interval, with correlations of 0.12 ($t(50) = 9.18$, $p < 0.001$) and 0.11 ($t(50) = 8.04$, $p < 0.001$), respectively. These results, however, could have arisen from the brain's transient response to the onset of the countdown video. To rule out this explanation, we repeated our analysis, excluding the first two seconds of the interval, and found similarly reliable correlations 0.11 ($t(50) = 8.86$, $p < 0.001$) and 0.10 ($t(50) = 7.67$, $p < 0.001$), respectively). These results demonstrate that spectral components of EEG activity can reliably decode temporal information during anticipation.

Joseph Sommer, Pernille Hemmer, Daniel R. Cavagnaro & Michel Regenwetter *(Rutgers University):* Order-Constrained Models of Memory

Hypotheses in free recall experiments often predict a greater average recall for one type of stimuli compared to another. A frequent assumption – often implicit in statistical tests of these hypotheses – is that item recall is normally distributed. However, this assumption can be problematic in the domain of memory. Additionally, common statistical testing methods for testing theories can be blunt instruments. Researchers may be interested in more nuanced hypotheses that are cumbersome to test with traditional methods. For example, ideal theories might even make granular predictions about the memorability of each studied item, including that certain individual items are equally memorable. Here, we propose order-constrained models for recall data as a fruitful method of analysis that allows researchers to formulate, and test, nuanced and fine-grained hypotheses about recall. We illustrate the benefits of order-constrained modeling by re-analyzing data from a pre-registered experiment on the memorability of supernatural, bizarre, and natural concepts.

Listed in alphabetical order. The first author is presenting unless otherwise marked (*).

David Zarrin, Uma Mohan, Oceane Fruchet, Kelsey Sundby, Weizhen Xie, Julio Chapeton, Sara Inati & Kareem Zaghloul *(National Institutes of Health)*: The Effect of Real-time Ripple Oscillation Interference on Human Memory Retrieval

Coupled high-frequency ripple oscillations between the medial temporal lobe (MTL) and association cortices have been associated with successful episodic memory retrieval in awake humans. While closed-loop ripple disruption in rodents has been shown to impair spatial memory, the causal role of ripples in human memory retrieval remains unknown. We implemented a closed-loop system for monitoring and decoding coupled ripples in real-time in humans. We delivered targeted electrical stimulation to the MTL or association cortices when high rates of coupled ripples (MTL-cortical or cortical-cortical) were detected before retrieval during a visual paired associate learning task. Our results demonstrate real-time ripple detection with an average ripple duration of 32 ms. We verified a higher coupled ripple rate at stimulation in ripple-triggered vs randomized control stimulations ($p<0.0001$). Memory performance and ripple patterns in the MTL and association cortices were compared between the targeted stimulation and control conditions.

Min Kyung Hong, Jordan Gunn, Sean M. Polyn & *Katherine S. Aboud *(Vanderbilt University)*: The Role of Temporal and Semantic Factors in Encoding and Recall of Expository Text

The contiguity effect, the tendency for successively recalled items to come from neighboring positions in the study list, has been a near-ubiquitous finding in free recall studies. Expertise and recall proficiency amplify this effect, hinting at the automatic nature of memory encoding. Although extensively examined in single word lists and stories, the role of the contiguity effect in understanding expository texts is less explored. In our current study, we examined the link between temporal context and recall performance. We used lag-conditional response probability, serial position curves, and temporal clustering scores to measure recall patterns. While we observed the contiguity effect, our preliminary results also indicated the absence of the pronounced recency effect. Follow-up analysis indicates that semantic information and other word properties also guide recall organization, and may compete with temporal contiguity as the dominant organizational factor. This suggests that the organization of expository information in memory is directed not only by temporal contiguity but also relational features of the text.

Kelsey K. Sundby, V. Sreekumar, K. Zaghloul & S. Lopez-Guzman, *(National Institutes of Health, NINDS)*: Testing the role of the subthalamic nucleus in memory-guided decisions

The appropriate response to decisions often varies across contexts. Thus, context-dependent decisions may require memory, to retrieve the context specific response, and top-down control, to withhold the response until sufficient evidence accumulates. The subthalamic nucleus (STN) is thought to mediate response inhibition for high conflict or ambiguous motor-based decisions yet less is known about its role in memory-guided decisions. We recorded intraoperative STN electrophysiology in Parkinson's patients receiving deep brain stimulation as they performed a novel memory decision task with both context-dependent and context-free decisions. Patients were slower and less accurate for context-dependent decisions and exhibited increased STN spiking, a putative neural correlate of conflict. Using a drift diffusion model, preliminary analyses suggest that increased STN spiking results in slower evidence accumulation. These data extend prior work by implicating the STN in memory-guided decisions and raise important questions as to how memory interacts with the STN to guide decisions..

Linda J. Hoffman, Blake L. Elliott, Vishnu P. Murty & Ingrid R. Olson *(Temple University)*: Charting the Hippobellum: Dissection of Cerebellar-Hippocampal Connectivity

Only recently has the cerebellum's role in higher order cognitive processes including learning, memory, and navigation gained traction in the field of cognitive neuroscience. Because of this, cerebellar projections to areas that are canonically known to underpin learning and memory, namely the hippocampus, are still unknown. Yet, studies of epilepsy have shown that hyperactivity in the hippocampus result in cerebellar degeneration, suggesting the "hippobellum" represents a functional circuit. Here, we performed tractography between the cerebellum and hippocampus using the Human Connectome Project dataset (n=101). We identified bidirectional cerebello-hippocampal connections, with fibers exiting the cerebellum via the superior cerebellar peduncle, and re-entering via the middle cerebellar peduncle. Moreover, we found two different polysynaptic tracts from the cerebellum to the hippocampus—one via the ventral tegmental area, and one via the mediodorsal thalamus. The first tract may play a role in reward-based learning, while the second may subserve spatial learning.

Lucy L.W. Owen & Jeremy R. Manning *(Brown University):* High-level cognition is supported by information-rich but compressible brain activity patterns

Brain activity patterns are highly flexible and often complex, but also highly structured. Here we examined how fundamental properties of brain activity patterns relate to ongoing cognitive processes. To this end, we applied dimensionality reduction algorithms and pattern classifiers to functional neuroimaging data collected as participants listened to a story, temporally scrambled versions of the story, or underwent a resting state scanning session. These experimental conditions were intended to require different depths of processing and inspire different levels of cognitive engagement. We considered two primary aspects of the data. First, we treated the maximum achievable

decoding accuracy across participants as an indicator of the "informativeness" of the recorded patterns. Second, we treated the number of features (components) required to achieve a threshold decoding accuracy as a proxy for the "compressibility" of the neural patterns (where fewer components indicate greater compression). Overall, we found that the peak decoding accuracy (achievable without restricting the numbers of features) was highest in the intact (unscrambled) story listening condition. However, the number of features required to achieve comparable classification accuracy was also lowest in the intact story listening condition. Taken together, our work suggests that our brain networks flexibly reconfigure according to ongoing task demands, and that the activity patterns associated with higher-order cognition and high engagement are both more informative and more compressible than the activity patterns associated with lower-order tasks and lower levels of engagement.

Luke Pemberton, Byron Price, Aakash Sarkar & Marc Howard *(Boston University):* Compressed conjunctive temporal representation of what and when in primary visual cortex

Many studies have shown the brain represents time with a continuous spectrum of time constants in brain regions associated with episodic memory, spatial navigation, working memory, and conditioning in a range of species. To study how visual cortex represents time, we analyzed neuropixels recordings from the Allen Institute Visual-Coding dataset while mice viewed static gratings and natural scenes images. Neurons in primary and higher order visual areas were sensitive to image identity but also fired in a consistent sequence across image types. These sequences extended through subsequent image presentations and showed decreasing resolution for time points further in the past: a fading temporal memory. Temporal receptive field width increased linearly with peak time similar to time cells indicating a compressed temporal representation. This study adds more evidence that time is a general organizing principle of the brain.

Lynn Lohnas *(Syracuse University):* Bridging retrieved context models across serial recall and free recall

It is important to characterize how participants use endogenous cues to guide episodic retrieval. In free recall endogenous cues play a large role, and retrieved context models have emerged as a leading explanation (Lohnas & Healey, 2021). Retrieved context models can also account for several critical findings in serial recall (Logan, 2021; Logan & Cox, 2023). Empirically, free recall and serial recall share similarities in serial position and transition phenomena (e.g., Bhatarah et al., 2008). Yet differences in assumptions of retrieved context models across recall tasks, as well as some serial recall effects, have posed challenges to these models. I present a retrieved context model which can overcome some of these challenges, by using a common set of assumptions across free recall and serial recall. The model's success reveals the commonalities and differences between these two classic recall paradigms, and also underscores contributions of context to both recall tasks.

Mason McClay, Jiayang Li, Chrissy Sandman & David Clewett *(University of California, Los Angeles):* Using a novel web app to examine dynamic emotional states and their relation to depression and trauma symptoms

Emotional flexibility, or the capacity to adapt emotional responses to one's surroundings, is believed to be impaired in conditions such as depression and post-traumatic stress disorder (PTSD). Traditional methods for assessing emotional flexibility do not evaluate emotion changes in real-time. In a study with 350 participants, we examined how emotional responses to music relate to depression and trauma symptoms using a novel tool, the Mobile Emotion Compass, designed to monitor real-time emotional shifts. Participants also completed an autobiographical memory segmentation task, where they segmented positive and negative autobiographical memories into distinct events. We found a relationship between the depression and PTSD severity and reduced emotional state transitions. Further, lower emotional transitions scores were related to impaired structure in autobiographical memory. These findings demonstrate the Mobile Emotion Compass's capacity to track emotional flexibility, and a relation between the capacity to transition across emotional states and memory organization.

Maya Geva-Sagiv, Kamin Kim, Chaodan Luo, Evangelista, C. Rocelle, Jack J. Lin, Ignacio Saez, Randy O'Reilly & Charan Ranganath *(University of California, Davis):* Hippocampal-prefrontal interactions underlying memory processes during goal-search in humans

The hippocampus and its functional interactions with cortical areas are thought to support flexible behaviors, guided by previous experience. Mazes provide a controlled environment to study behaviors oriented toward reaching a previously memorized location. Current theoretical models predict that hippocampal-prefrontal interactions would be key to route-planning and navigational-decisions. The difficulty of recording electrophysiological activity directly from deep structures in the human brain has limited detailed characterization of these interactions in humans to date. Here, we present a novel maze paradigm, implemented as an animated video game, tailored to test brain activity during continuous memory-guided movement in a virtual maze. Upon informed consent, patients with pharmacoresistant epilepsy, implanted with intracranial electrodes for clinical monitoring, participated in electrophysiological-recordings while performing the task (8/7 sessions/patients). Intracranial recordings during this task will be used to relate the dynamics of hippocampal and prefrontal oscillatory-activity during critical navigation moments to subsequent efficient usage of prior experiences.

Md Rysul Kabir, James Mochizuki-Freeman & Zoran Tiganj *(Indiana University):* Making Deep Neural Networks scale-invariant using cognitive models

The ability to estimate temporal durations is critical for both animals and artificial agents. Scale invariance observed in behavior and supported by neural data is a key principle that goes beyond interval timing and governs animal perception. Here we investigate how different architectures of artificial agents compare to animal behavioral and neural data. We found that agents based on a cognitive model of scale-invariant memory perform well across multiple temporal scales and exhibit neural activity that resembles the neural activity in animal brains. This result provides an example of integrating models from cognitive science into deep neural networks to advance our understanding of biological and artificial systems.

Michelle A. Dollois, Randall K. Jamieson & Chris M. Fiacconi *(University of Guelph):* Modelling the underlying mechanisms of sequential dependencies in recognition memory

It is well established that extraneous information, unrelated to prior exposure, impacts recognition memory judgments. One source of irrelevant, but influential, information is the previous trial during a recognition test. Though limited, research has consistently found sequential dependencies at test, such that judgments (i.e., "old" or "new") tend to repeat across consecutive trials. Our lab has expanded this finding to consider whether trial content also carries across trials to sway responding. More specifically, we have found that similar items occurring sequentially at test increase the probability of an "old" response. To better understand these sequential dependencies and whether they may occur through the same mechanism, we here attempt to model these effects using a MINVERA 2 framework. We present several potential mechanisms through which sequential dependencies during recognition memory may occur, granting insight into whether responses and content cross trials through the same means.

Muhammad B. Khan, , Yang S. Liu & Jeremy B. Caplan *(University of Alberta):* Judgements of spacing without reminding

Hintzman and colleagues' classic experiment found that participants were better at judging the spacing between two items that were similar (or the same) than different. This motivated recursive reminding theory, which presumes an item can remind us of a similar previous item, leading to encoding of an order-rich association between the two items. We wondered if similar findings might nonetheless be found when reminding is not feasible: in short lists with fast presentation rates. We found continuous-valued similarity impaired relative-recency judgements of consonant lists (4 or 8 letters, 750 ms/item) but in a new experiment, had no effect on spacing judgements (7-letter lists). A second experiment found an advantage for judgements of spacing of exact repetitions of the same item, which replicated in a third experiment at an even faster rate (250 ms/item). We describe several theoretical mechanisms that could explain these results without recursive reminding.

Nathaniel R. Greene, Moshe Naveh-Benjamin & Michael J. Kahana *(University of Pennsylvania):* New Perspectives on Age-Related Declines in Episodic Memory Specificity

Failures to remember the specific details of our prior experiences can have profound consequences on our daily functioning. These failures are more pronounced in older adulthood, where, relative to younger adulthood, episodic memories are "fuzzier" or more imprecise in nature. Despite decades of research on the topic of age-related declines in memory specificity, spanning numerous fields of study, we still lack a complete understanding of the mechanisms underlying these declines. Here, I present recent empirical and mathematical modeling investigations attempting to unearth latent encoding and retrieval mechanisms underlying the loss of specific details in episodic memory in general, and in older adulthood in particular. Results suggest a dynamic interplay between different encoding and retrieval processes drives age-related impairments in the ability to remember the specifics of past experiences. Findings are discussed in the context of multi-component theories of age-related memory impairment.

Neal W Morton & Sean M. Polyn *(University of Wisconsin-Milwaukee):* Memory search dynamics reflect retrieval of semantic context

Behavioral and neural studies suggest that episodic memories contain information about both the semantic content of events and the temporal context in which they occur. However, it remains unclear how specifically content and context are represented in episodic memories. We recently proposed a distributed context maintenance and retrieval (DCMR) model, wherein distributed semantic features and temporal features are incorporated into a single representation of context. Here, we used a free-recall dataset to test a novel prediction of DCMR that retrieved context should include semantic information not only about the just-recalled item, but also the item presented prior to it in the list. Consistent with this prediction, we found that participants were more likely to recall items that were semantically related to the prior item in the list compared to the following item. Our results provide novel evidence that item memories include information about the semantic context in which they appeared.

Neomi Mizrachi & Ehud Ahissar *(Weizmann Institute of Science):* Gaze scan-paths are part of recall strategy in context dependent memory

Motor-sensory dynamics is an essential component of visual perception. During an episode, scanning patterns of the eyes are part of the acquisition process. To reckon eye movements' role in context dependent memory, we designed a recall task in virtual reality environments. Two groups were asked to explore a room with 15 virtual objects; 20 minutes later they were asked to retrieve objects' names in a similar (SIM group) or different (DIFF group) environment. Under similar context (SIM group), recall gaze scan-paths were spatio-temporally similar to encoding scan-paths, such that the same locations were visited at the same relative times. Recall accompanied the gaze trajectory; SIM group participants retrieved objects' names according to the order of their gaze fixations at encoding

and not by random or semantic connections. These results suggest that gaze scan-paths dynamics is part of recall of past perceptions and plays a significant role in context dependent memory.

Nick Ichien & Sudeep Bhatia *(University of Pennsylvania):* Relations in semantic memory search

We present two studies that examine how people retrieve structured representations from memory. In Study 1, participants completed a relational fluency task, in which they were asked to produce word pairs that instantiated a given relation (e.g., antonymy). In Study 2, participants completed a free association task, in which they were asked to generate word pairs that come to mind, given some word-pair prompt (e.g., old:young). Markov modeling of retrieval patterns showed strong semantic clustering in both studies, with successively retrieved word pairs being more associated with each other. However, the effect of relational structure was mixed: Participants did use relations as cues when explicitly instructed to do so in Study 1, but similarity in relational structure did not influence successive retrievals in either study. This suggests that people can use relational knowledge in a top-down manner, and this is distinct from the semantic similarity-based processes that guide free association.

Nikolaus Salvatore & Qiong Zhang *(Rutgers University):* Parallels between Neural Machine Translation and Human Memory Search: A Cognitive Modeling Approach

In this work, we propose a neural network model for free recall that draws direct parallels between neural machine translation (NMT) and cognitive models of memory search, specifically the Context Maintenance and Retrieval (CMR) model. We hypothesize that NMT advancements such as attention mechanisms (Luong et al., 2015) closely resemble how humans reactivate prior contexts ("mental time travel"; Tulving, 1985). To demonstrate these parallels, we train a seq2seq model as a cognitive model of memory search, and evaluate behavior against available human free recall data. We find that at intermediate levels of training, the model can capture several phenomena observed in human free recall experiments (Kahana et al., 2022); and after optimization, the model demonstrates the same optimal behavior as previously derived by the CMR model (Zhang, et. al., 2023). Performing an ablation study, we demonstrate that behavioral differences between models with and without attention aligns with impaired behavior observed in hippocampal amnesia patients (Palombo, et. al., 2019).

Pierce C. Johnson, Greg E. Cox & Ronald Friedman *(The State University of New York at Albany):* Statistical Learning: The Formation of Musical Preferences

Memory for information is influenced by its usefulness; information that helps one react to changes in the environment—or even predict when changes will

happen—is more useful than information that does not. Theorists claim this utility results in the formation of aesthetic preferences, such as in music. This study addressed two questions: how do we process different kinds of information to form predictions; and are there differences in preference for these kinds of information? Participants listened to contingently paired novel melodies intermixed in a stream with filler melodies. A memory task probed subjects' memory for the order of contingently paired melodies, and subjects rated their preference for each melody. The preliminary results indicate people have memory for paired items, and may prefer when their predictions are confirmed. Specifically, they may come to prefer music that confirms learned expectations. These results show the role of predictive utility in shaping preferences.

Rebecca Waugh, Ami Falk & Per Sederberg *(University of Virginia)*: Whole brain connectomics in episodic memory: neural correlates of the Continuous Associative Binding task

Although the medial temporal lobe (MTL) is implicated in episodic memory, memory encoding and retrieval processes involve the whole brain. Neural connectivity profiles associated with task-performance can be similar across task- and resting state (RS). To understand the brain-wide connectomics of episodic memory, we collected fMRI data in 29 healthy younger subjects who completed the continuous associative binding (CAB) task, along with an RS scan. In the CAB task, participants indicate the novelty of object pairs that are either repeated intact or recombined, requiring that participants track item and associative information, likely requiring MTL involvement. We created a model based on functional connectivity (FC) using machine learning to predict task performance based on CAB and RS. While analyses are ongoing, we expect that connections between MTL and prefrontal cortex will be highly weighted and that similar region-to-region connections will be important for both RS and task-based FC-based models.

Riley DeHaan & David Halpern *(University of Pennsylvania)*: Predicting the Effects of Brain Stimulation from Observational Data

Improving memory through neuroscientific interventions requires understanding of the neural activity that causes behavior. While decades of work link memory performance to neural activity, it remains unclear whether these conclusions from observational data reflect causes of successful memory encoding. Here we analyze intracranial electroencephalography recordings of 140 subjects performing a delayed free recall task. We compare models accounting for confounders of causal neural effects, including item and serial position effects, to unadjusted models. We find that accounting for these variables results in different conclusions about the relevant neural activity. Hypothesizing that this de-confounded model may better reflect an endogenous state of memory performance rather than the features of the presented stimuli, we predicted such a model should in turn better predict the effects of brain stimulation. We validate our model using a separate dataset of 20 subjects who received randomized electrical brain stimulation while performing the free recall task.

Ryan A. Colyer, Jerome D. Hoover & Alice F. Healy *(University of Pennsylvania, University of Massachusetts Amherst, and University of Colorado Boulder)*: Large Language Model Simulation of Human Responses to Bat-and-Ball Problems

We investigated how an open source large language model (LLM) AI responded to bat-and-ball style problems, following the procedures used with humans by Hoover and Healy (2019). We queried confidence in their own responses and opinions about the answers of others, for both the standard and control versions of the bat-and-ball problems. The standard problem included an error-inducing phrase, whereas the control did not. LLM participants were generated using matched age and gender to previous human participants, done by providing age and gender as prompt context before matched problems. In both the LLM and humans, higher confidence and opinion were given for the control versus the standard problem, and for each, higher confidence was given than opinion. We also found corresponding LLM and human response accuracy patterns across matched age groups. These LLM simulations of bat-and-ball problems showed nuanced behavioral dynamics that could be useful for pilot study explorations.

Ryan P. Kirkpatrick, Molly Baumhauer, Sara K. Inati & Kareem A. Zaghloul *(National Institutes of Health, NINDS):* Investigating the latent representations of encoded and retrieved memories in the anterior temporal lobe

Study of the neural correlates of episodic memory retrieval has found evidence suggesting that the neural activity present at the encoding of a memory is similar but not identical to the activity present at the successful retrieval of the memory. It is an open question as to the nature of the transformation of the neural activity from encoding to retrieval and how the neural population represents this information. Previous researchers have applied dimensionality reduction techniques to neural recordings taken from various species to theoretically decode this information. We recorded from subdural and microelectrodes implanted in the anterior temporal lobe of patients under observation for the localization of epileptic seizures. Then we applied principal components analysis to the recordings taken while the patients completed a paired associates task to uncover the latent trajectories of the neural response and how these trajectories change between encoding and retrieval.

Sameer Sabharwal-Siddiqi, Mathew Grilli, Sean Thayer, Andrew Yonelinas, Arne D Ekstrom *(University of Arizona):* Hippocampus is Important for Representational Precision of Public Event Memories Regardless of Their Age

Although the necessity of the hippocampus to episodic memory is well-established, its necessity to semantic memory remains more contentious. Impaired semantic memory following hippocampal lesions suggests that hippocampus is important for new semantic learning and maintenance of recently

acquired semantic memories (retrograde semantic amnesia). However, previous studies have reported mixed findings regarding maintenance of remote semantic memory in hippocampal amnesiacs. Importantly, the precision of their semantic memories has not been tested. In this study, we tested hippocampal amnesiacs (n=7) and age-matched controls (n=14) on their ability to precisely recall the dates of famous public-events that occurred either before or after participants' birth date. We show that deficits in dating accuracy are greatest for recent lifetime events, consistent with the notion that recent event memory may be influenced by anterograde/retrograde gradients and may be more intertwined with episodic memory. We also show more subtle differences in the precision of retrieved events for both early and pre-lifetime events, which likely correspond with remote semantic memories. Together, these findings suggest that the hippocampus is important for representational precision of semantic memories regardless of their age.

Jordan B. Gunn & *Sean M. Polyn *(Vanderbilt University):* An instance-based retrieved-context theory of memory search in free recall

Modern computational models of human memory either follow an instance-based tradition, where an independent trace is formed for each memory, or a composite tradition, where a common set of associative structures (e.g., synaptic weights) are used to store memories. Recent developments in machine learning suggest deep similarities between these traditions, with Modern Hopfield Networks replacing synaptic weights with instances similar to MINERVA2. We construct an instance-based version of retrieved-context theory for free-recall performance, which to date has been implemented as composite neural network models. We demonstrate that instance-based and composite implementations perform equivalently, can be parameterized similarly, and that the failures or challenges of one model are shared by the other. We demonstrate that these similarities extend to the simulation of repetition and spacing effects, despite the seemingly distinct approaches the two models take in this domain. We propose a theoretical unification that will benefit practitioners of both traditions.

Soroush Mirjalili & Audrey Duarte *(University of Texas at Austin):* More than sum of its parts: investigating episodic memory as a multidimensional cognitive process

Why do we remember some events yet forget others? Understanding this question is important not only for basic science but also for potential interventions that improve learning in real time and real-world settings such as the workplace or classroom. As such, our ability to successfully predict memory performance from neural activity remains weak. Critically, episodic memory is believed to be a multidimensional process in which various cognitive functions contribute to memory formation. However, no study has investigated the involvement of multiple cognitive functions during episodic encoding simultaneously. Using EEG recorded during external tasks, we investigated the within and trial-to-trial fluctuations in the levels of engagement of sustained attention, selective attention, and perception processes during episodic encoding.

We inspected whether this multidimensional perspective of memory can improve our ability to successfully predict, from encoding-related brain activity, which events will be later remembered vs. forgotten and the underlying reasons why.

Tamara Gedankien, Jennifer Kriegel, Joshua Jacobs & Bradley Lega *(Columbia University):* Cholinergic modulation of human hippocampal oscillations during encoding and retrieval

Cholinergic dysfunction is a hallmark of Alzheimer's disease and other types of memory disorders. Yet, we don't fully understand the neural mechanisms implicating the cholinergic system in memory. Previously, we showed that administering scopolamine, a cholinergic blocker, to humans during a free recall task impaired memory encoding and simultaneously disrupted the amplitude and timing of theta oscillations in the hippocampus. Here, we expand this paradigm to an associative recognition task. We describe how scopolamine impairs both theta and gamma amplitude and coherence during encoding, as well as how it modulates the reinstatement of spectral patterns during retrieval. Together, our results suggest that cholinergic blockade impairs memory by disrupting theta and gamma dynamics which normally facilitate synaptic plasticity within the hippocampus. These findings provide insights into the neural basis underlying memory formation in humans, which may aid in the development of new treatments for memory loss.

Antonios Georgiou, *Tankut Can, Mikhail Katkov, Misha Tsodyks *(Institute for Advanced Study, Princeton University):* Large-Scale Study of Human Memory for Narratives using Large Language Models

We use large language models (LLMs) both to design naturalistic narrative stimuli for large-scale recall and recognition memory experiments, as well as to analyze the results. We performed online memory experiments with a large number of participants and collected recognition and recall data for narratives of different lengths. We found that both recall and recognition performance scale linearly with narrative length. We repeated the experiments with scrambled versions of the stories, and found that although recall performance declined significantly, recognition remained largely unaffected. Recalls in this condition seem to follow the original narrative order rather than the actual scrambled presentation, pointing to a contextual reconstruction of the story in memory. Finally, using LLM text embeddings, we construct a simple measure for each clause based on semantic similarity to the whole narrative, that shows a strong correlation with recall probability.

Taylor Chamberlain, Jiawen Huang, Akshay Manglik, Hannah Tarder-Stoll, Robert J. Ajemian, Qiong Zhang, Kenneth A. Norman, Christopher Baldassano *(Columbia University):* Conjunctive encoding representations in expert and novice users of the "Method of Loci" mnemonic technique

One often needs to associate items (e.g. keys) with their corresponding contexts (e.g. under doormat). How does the brain represent this item-context combination in memory? One possibility is that the combination is formed by linking the individual representations of the item and context. However, recent neuroimaging work suggests an alternative possibility: that binding an item to context involves the creation of a new combined representation, using a nonlinear conjunctive code [1,2]. Here, we test these hypotheses using fMRI data from participants utilizing the Method of Loci memorization technique, wherein words are associated with locations in an imaginary "memory palace." In a preliminary analysis of novice (n=25) and expert (n=5) users of the technique, we find evidence for the creation of conjunctive codes during encoding that are reinstated during memory retrieval. These codes are instantiated primarily in DMN regions and reflect semantic information about the item-context interactions imagined by each individual.

[1] Baldassano et al., 2017 [2] Erez et al., 2016

Uma Mohan, John Wittig, Oceane Fruchet, Sara Inati & Kareem Zaghloul *(National Institutes of Health, NINDS):* Modeling and predicting neural responses to multisite direct electrical brain stimulation in humans

Direct electrical brain stimulation combined with intracranial electrophysiological recordings hold the potential to modulate and test the functional role of neural activity in the awake human brain; however, the effects of stimulation on neural activity are poorly understood. To better understand and precisely control the responses to stimulation in individual patients, we applied a control-theoretic framework to model the effects of stimulation on neural dynamics across the brain. We collected human electrocorticographic recordings from 8 neurosurgical epilepsy patients while systematically delivering cortical stimulation at different frequencies, amplitudes, durations, and locations while patients were at rest. Using a dynamic linear state-space model framework, we fit input-output models to timecourses of neural activity, represented by high frequency activity, while patients received stimulation. We first accurately predicted dynamic responses in brainwide neural activity following stimulation at individual locations across brain regions. We further show patient-specific models can be used to predict responses to novel stimulation locations. Lastly, we analyzed changes in large-scale neural activity in response to multisite stimulation and compare these responses to those predicted from patient-specific state-space models built while patients were stimulated at individual locations. The ability to characterize and model neural responses to novel locations as well as patterns of multisite stimulation could allow clinicians and researchers to design stimulation protocols for precise modulation of neural activity.

Xinming Xu & Jeremy R. Manning *(Dartmouth College):* Modeling the knowledge asymmetry of the past and the future

We know more about our past than our future, since we have memories of our past, but not our future. However, it remains unclear what might be the origin of

this knowledge asymmetry, given that we have access to only the current state of the world and most laws in physics are time-symmetric. That is, we should be able to extrapolate to the past and the future equally well. Inspired by probably the only physical law that is not time symmetric: the second law of thermodynamics, we designed a set of simple simulations to explore how the flow of time is related to uncertainty about the past and future (conditioned on the present). In our simulations, we modeled a small set of molecules that gradually become mixed over time. We explored how the entropy of the system changed over time, conditioned on different initial conditions. We then asked: given the current state of the system, what were the conditional entropies of past or future states of the system? We modeled a variety of scenarios whereby the state of the system was fully known, or only partially known. We found that, in each case, the conditional entropy of the past is always lower than the conditional entropy of the future. Our simulations help provide some insight into when and why we know more about the past than the future, conditioned on our knowledge and observations available to us in the present.