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The Spacetime of Memory

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The artist's eye is often quicker than the scientist's at parsing the world. When I first saw Dalí's famous painting in art history books, I thought it to be a very creative piece of art – nothing more, nothing less. You know the one I am talking about. It's that painting about the size of a sheet of paper, yet with a whole dedicated central wall at the MoMA. It's most recognizable as the painting with melting watches, draping an impersonal dead tree and geometric shapes, embedded in a timeless place, with the golden cliffs of Catalonia in the background. Standing in front of it at the museum, something struck me anew — the title. *The Persistence of Memory*. Somehow, connecting the surrealist imagery with the idea of *memory*, in that timeless, spaceless land, made perfect sense. Time – as we feel it – is gooey, just like those watches. More to the point, the way we remember our life hardly matches how events metronomically unfolded in our days. Think about how a routine week of work might blur; yet a handful of days in a new country swells in our recollections. Analogously, we remember some places better than others. I remember every single centimeter of my room, but I have a vague reconstruction of my friend's lab. Memory warps space and time. How might we understand this warp? The aim of this essay is to pull together theories and evidence from the cognitive sciences, to human electrophysiology and computational neuroscience, and to work towards a unified theory of how everyday memories are stored.

CONTINUOUS LIFE, DISCRETE MEMORIES

One of the most fascinating conundrums of cognitive science — and, honestly, of our human nature — is a fundamental discrepancy between how we live life, and how we remember it. We live our life as a continuous stream: each second spills into the next, each step extends the space we have walked. *Panta rhei*—or everything flows—Heraclitus would say. And *yet*, our memory recall is discrete. Think about it. If I asked you "How was your evening last night?," your mind would not remember every instant; it would surface a few *episodes* that stand in for the whole — perhaps you on your couch with your partner, or you poring over your paper. How does this life "chunking" happen? We segment life continuously and automatically. You just did: most likely there is an episode *before* you sat down to read this essay, and another one *after* you began. Parsing helps us manage complexity[228]. For example, when entering a new room, our attention might first latch on to the people we see, then the objects, then the walls. Carving the scene into parts makes it comprehensible. Time is no different. If you ask people to watch a scene and press a button when one perceived ”event” ends and another begins, their judgments largely agree[191]. These *event boundaries* tend to occur with shifts: a change in place, a new goal, or a salient change in what is perceived[40]. Our predictive minds flag these shifts when their expectations are in conflict with incoming sensory input—a core tenet of the Event Segmentation Theory[119]. Space and time, therefore, both contribute to crafting boundaries that confer an episode its identity.

Why does event segmentation matter? Because event structure creates a scaffold for memory. Here I focus on *episodic memory*, or the recollection of everyday experience[205]. Let's go back to the button pressing during a scene task. Experimental evidence has shown that people who segment more consistently later remember the movie better. In contrast, older participants with mild cognitive impairment segment less reliably, which predicted poorer memory[229].

Boundaries also mold sequence memory. Items that fall within the same event are more likely to be "bound" together, making their order easier to memorize. If, instead, items appear on different sides of a boundary, order memory weakens. You might already be familiar with this trick since childhood, when you were taught to sing your ABCs to remember which letter comes first, and which follows. If you instead had made up a different melody for every four letters of the alphabet, this probably would have made your memorization significantly harder. Boundaries even stretch our perception of time[61]: when events straddle a boundary, they are remembered as farther apart—a stretching effect that echoes Dalí's gooey clocks.

Perhaps the most important thing about boundaries is that they have a privileged status in episodic memory. At boundaries, when space, time, or goals shift, the mind's attention is enhanced, allowing the brain to process information more fully. Numerous experiments have probed the capabilities of remembering boundary versus non-boundary moments, and the evidence overwhelmingly suggests that boundary moments are recalled better[196]. This mechanism might be one way the brain chooses which moments of our lives are meaningful to remember. If we'd try to store every instant of our lives, we would—quite literally—run out of memory. Therefore, the brain smartly selects which "frames" of our days are worth preserving, thus compressing experience into a manageable format.

Artists have long intuited this. I suspect that most of Hollywood has not studied neuroscience.

And yet, movie directors have applied neuroscience for a long time! To a certain degree, cinema segments its stream of events for us, and by artfully deciding when to place a cut, or a camera move, it creates an experience that, if well done, will coalesce into our memory. Next time you watch a film, focus on the director's artistic choices, and you might realize how your memory is being quietly shaped.

The Brain's Compasses and Clocks

In the spirit of making this essay more memorable, let me place a boundary right here, and shift gears. If memories are shaped by boundaries, where do these shifts in space and time live in the brain? A famous clinical case of Henry Molaison—better known as "patient H.M."— offered neuroscientists an important clue. As a treatment for his epilepsy, in 1953 patient H.M. underwent a bilateral temporal lobectomy, which surgically removed key brain structures, among which the *hippocampus*—Greek for "seahorse", because of its curious curly shape—and most of the neighboring *amygdala*. This operation would forever transform H.M.'s memory in an astonishing way. On the one hand, he could not form—or more scientifically, *encode*—new episodic memories. He lived the rest of his life very much in the present. On the other hand, memories encoded long before his surgery were largely spared, though not always richly anchored to space and time. Henry Molaison's amnesia is one that the neuroscientific community will never forget. From it, we have learned that the hippocampus is essential for memory encoding, and that formed memories do not live in the hippocampus itself, but rather move to other brain regions —such as the cerebral cortex, deeply connected with the hippocampus— for long-term storage.

Thus, the hippocampus and its neighboring regions became one of the most studied brain parts in neuroscience. You can well imagine that having human beings that allow scientists to tinker with their brains is quite a rare treat. Therefore, most of what we know about cellular and network neuroscience comes from rodents. Neurons communicate with each other electrically through *action potentials*, or rapid spikes of electrical activity (henceforth spikes, and over the last century, scientists have devised ingenious ways to record them. You might be wondering: "How can you possibly ask a mouse what it remembers?" Evolutionarily, memory is a transmission mechanism gleaned from past experience to guide current and future behaviors[29]. In rodents, memory-based spatial navigation is used as a powerful proxy to study memory, on the idea that navigating the world and navigating a remembered episode rely on the same brain machinery[29].

If you head out for a hike in the White Mountains, what would you need? You'd need to know where you are now, a map with a coordinate system, and a compass to point you in the right direction. Astonishingly, you have all of that between your ears.

One of modern neuroscience's most spectacular findings is the discovery that some hippocampal neurons fire reliably at specific locations in an environment. It's really that impressive: when implanting an electrode in a rodent's hippocampus, while letting it move through an environment, neurons will spike vigorously for one place in space, but fall quiet elsewhere. These are named *place cells*[148]. Zooming out, place cells tile the whole environment, activating in sequence as animals move. *Grid cells*, residing in the entorhinal cortex (adjacent to the hippocampus offer a coordinate system by beautifully tiling the whole environment with an hexagonal pattern across space[83]. Within the same circuit, a plethora of other cells, seemingly specialized for different aspects of navigation, were discovered, such as cells informing about the head's direction (your very own compass[198], the animal's speed[115], or its proximity to the environment's borders[149]. Together, these discoveries carved out how *space* is encoded in the brain—a mechanism profound enough to earn the 2014 Nobel Prize in Physiology or Medicine.

Within the same decade, researchers observed sequential firing of hippocampal cells even when the animal was not moving, suggesting their activity is not modulated by space, but rather correlated with passage of time, tiling subsequent moments with sequential firings. These aptly became known as *time cells*[57].

With *space* and *time* figured out, together with neurons that reliably fire at specific objects, it was tempting to declare the binding problem of the 3 Ws—the what, where and when—solved, and with it, episodic memory understood.

However, it is quite peculiar and intriguing that both the brain's clocks and maps converge on the same brain regions, with what appear to be strikingly similar mechanisms of sequential tiling. Is this a coincidence, or is there a deeper connection between the two?

If I successfully convinced you that memories are formed from experience being fragmented into discrete pieces, what system sets event boundaries? It appears vastly inconvenient to have two independent systems—one for space, one for time—without a unifying mechanism for segmenting events. Space and time systems supply *context* (where did it happen, and when?), but they fail to provide a unified mechanism for event segmentation. Perhaps it is worth taking a closer look to human neurophysiology, and ask a more everyday, mundane question. What happens in the brain at the very moment an event boundary occurs?

Brain Boundaries

The human brain has for a long time been a white whale in neuroscience. On the one hand, the human brain is more complex than most animal brains, with its 86 billion neurons—one thousand times more than a mouse's—and some 100 trillion connections. On the other hand, the tools and technologies that scientists can employ to study it are far more limited, rightfully and ethically so. Thus, analyzing the human brain's activity in an ecological setting is a particularly arduous task. Noninvasive methods let us measure whole-brain patterns during naturalistic tasks, sacrificing spatial and temporal accuracy in favor of brain coverage. The upside of working with human subjects is, naturally, that we can easily communicate with the subjects in our experiments.

Researchers have leveraged functional magnetic resonance imaging—which infers neural activity from blood oxygenation changes—to approximately study everyday cognition in the scanner. When participants were shown a movie and asked to segment the stream of information into episodes, scans revealed increased neural activity right after the boundaries in brain regions associated with memory, especially in the hippocampus. Notably, boundary-locked increased activity also occurred during passive viewing of the movie[227]. These findings suggest that memory networks at large, and the hippocampus in particular, are sensitive to event boundaries.

In rare experiments, clinical necessities let us peek into the human brain with *invasive* methods. Typically, in these cases, patients undergo brain surgery for pathological reasons—for example, they suffer from drug-resistant epilepsy, or they need deep brain stimulation for Parkinson's. While electrodes are in place inside the brain to record neural activity (for minutes in the case of Parkinson's, for days in the case of epilepsy), research groups might partner with clinicians to capitalize on this extraordinary opportunity, and conduct experiments with the patients, to then analyze their neural and behavioral data. My lab is one of such groups, and I am exceedingly excited to let you in on the discoveries that our lab has made.

A couple years shy of me joining for my PhD, my lab had sought out to study what happens at event boundaries at the single-cell level. They asked participants to view a series of video clips, containing two types of cuts: hard boundaries (juxtaposing two events with different, unrelated contexts; for example, a dog in the first event, and people playing cards in the second), and soft boundaries (visual cuts within the same context; for example, a person making a coffee in the first event, then loading the dishwasher in the second). What they found were *boundary cells*, which precisely fire at each boundary during passive viewing, and *event cells* that fired selectively at the hard boundaries, signaling a transition to a completely different event[239]. This hierarchy mirrors everyday experience: you can enumerate the sequential steps of a recipe (soft boundaries), and later leave the kitchen and go for a walk (hard boundary).

Might these cells contribute to memory? After having watched a series of video clips with hard and soft boundaries inserted, participants' memory was tested with a scene recognition task, whereby they were presented with a frame and had to indicate whether they had previously seen it in the movies. When analyzing memory correctness, trials encoded with greater spiking of boundary cells in the hippocampus were more likely to be remembered later. In other words, the activity of boundary cells is *predictive* of memory formation.

This work unearthed the neural mechanisms that bookmark life's chapters. To glean meaning from our past, we also need to weave lived episodes into the *order* they occurred. A child only learns that fire burns by remembering that the pain *followed* their reach for the flame. Order memory underwrites causal learning. Thus, now that we know how individual events are chunked, how does the brain keep track of their order?

Getting Life in Order

It was a Thursday afternoon, and I had sunk in that post-prandial torpor that hits especially hard on gloomy autumnal Bostonian days. I had been in the lab for a couple of months, set to investigate how temporal order is represented in human episodic memory. My collaborator had gotten a head start collecting electrophysiological data from the first subjects who kindly agreed to participate in our experiment. The task: watch 30-second long movies composed of a sequence of four events, all separated by visual cuts created by camera switches. The memory test afterwards: given frames of two different events, which one came first?

I had just finished this subject's spike sorting—or the operation of assigning each spike to a putative neuron. Imagine being seated in the audience of Boston Symphony Hall as the orchestra is playing Tchaikovsky's daunting Symphony No. 5. You can parse out the various instruments, perhaps your auditory system helps you perceive sounds incoming from the left or the right of the hall, but individuating the sound being produced by a single violinist from the whole might be quite challenging.

Similarly in the brain, when an electrode is recording signals, it is akin to our ears in the audience, capturing a summatory effect of all the voltages being produced by nearby neurons. If you wanted to determine which violinist played a specific note, you can in principle imagine that if you had information about how each violinist moved their bows, how much pressure they typically apply to their strings, and so on, you might be able to attribute the note to who played it. This is the principle behind spike sorting where, through the help of a clustering algorithm and manual inspection, we are able to assign which spike a neuron comes from by looking at their waveforms. Thus, having recorded the brain's symphony through electrodes implanted deep into the brain, and having labeled all the musicians of our neural orchestra, I could finally ask the burning question: does the brain keep track of the order of events?

We started by studying firing rates—or how many spikes occur in a given time window—aligned to event boundaries. For each neuron, I computed the responses time-locked to the first, second and third event boundary in each movie sequence of four events. Lo and behold, we again found the boundary cells from the lab's previous work. But now, with this experimental setup, we could ask whether neurons responded the same way at each boundary order. In other words, might there be neurons that respond differently to event boundaries of order 1, versus 2, or 3?

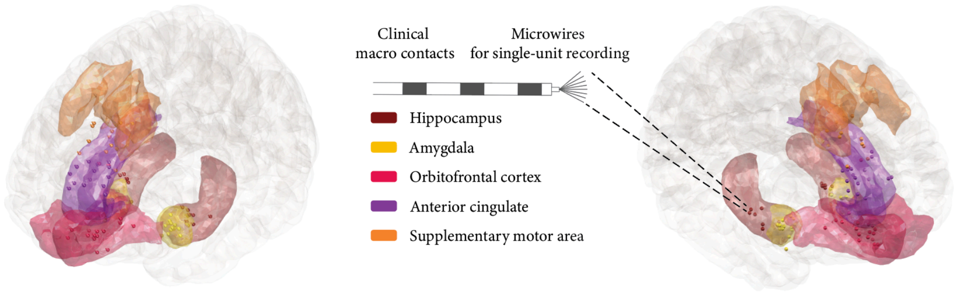

Figure A.1: Brain templates with highlighted brain regions we recorded from. Of note: in crimson, the hippocampus, in yellow the amygdala, and in bright red the frontal cortex. Neurons were recorded with depth electrodes (cartoon in the middle), and their terminal points (micro-wires we recorded our signals from) are projected as dots on the glass brains.

As my computer finished crunching numbers, I could not resist the temptation to start digging through the output figures, which showed the traces of firing rates for each neuron across the three boundaries of each video sequence. The torpor had dissipated, giving way to a jolt of excitement. Some neurons indeed fired at every boundary. But some did *not*. These neurons, in fact, *selectively* "cared" about a specific event order. Some spiked only after the first boundary; others, after the second; others yet, after the third. This blew our minds. It hinted at circuitry sophisticated enough to track *event order* via groups of neurons—which we named *order selective cells*, or OSCs—that label an event's ordinal position in a sequence[238].

Two crucial features make OSCs particularly intriguing. First, content invariance. These neurons responded to event order across different movies. Thus, their firing is not tied to a particular visual feature. In the top lines of each panel in Figure A.2, each row represents spikes in response to a different video. If you have seen these graphs before, called raster plots, they typically show different repeats of the same visual stimulus across rows. This is not the case in our experiment, where we applied a fundamental law of life: YOLO—you live only once. Thus, for a more faithful emulation of life stream in an experimental setup, we only showed each video once. Hence, I hope you can appreciate how impressive it is that OSCs consistently fire at different event orders, abstracting from the exact content of the event they are experiencing.

Second, independence from metric time. Event length varies dramatically: "event 1" might arrive 3 seconds into one movie, and 7 seconds into the next. If the neuron simply tracked elapsed time, then it would not fire in both cases. Instead, OSCs' activity locks into *which* boundary this is in the sequence—not when it occurred.

Galvanized by the preliminary data, we expanded recordings to 20 patients (for a total of 965 neurons, and found order selective cells consistently across brains (number of OSC = 68, 7.5% of recorded neurons. As you may have expected, most resided in memory-related regions—especially in the hippocampus and amygdala—with a smaller number in the frontal cortex as well.

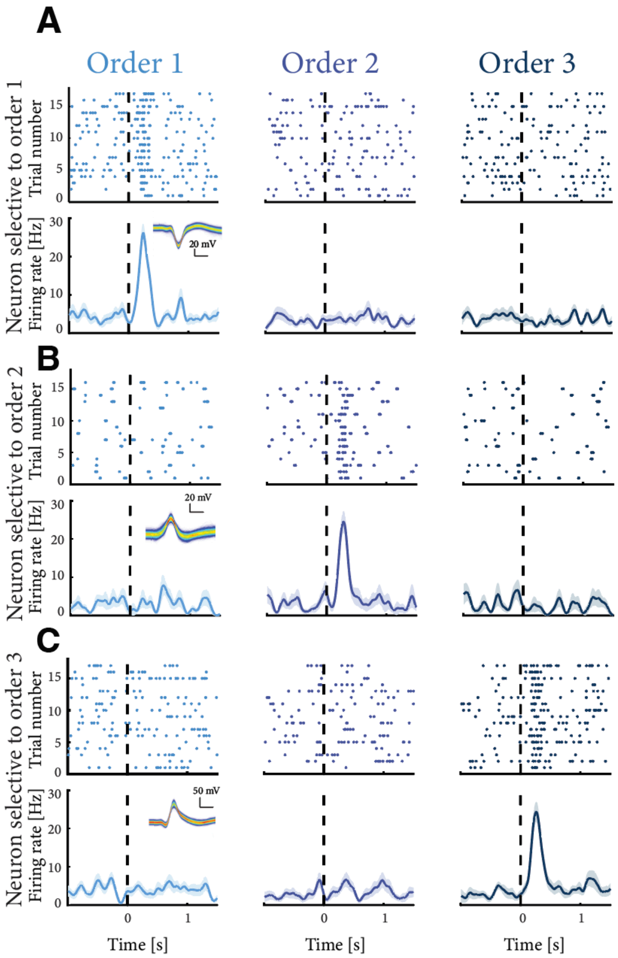

Figure A.2: Neural traces of order selective cells. Panels A, B and C represent the spikes (dots, top rows) and corresponding firing rates (smooth curves, bottom rows) of three different neurons. The dashed black lines are the event boundaries, and each column represents a different order. Panel A exemplifies an order selective cell responsive to order 1. Panel B shows an order selective cell responsive to order 2. Panel C reports an order selective neuron of order 3. Figure adapted from [238].

Finding order selective cells is interesting in its own right. But do they carry enough information to be useful? Imagine trying to guess which movement of Tchaikovsky's Symphony No. 5 is playing by just paying attention to which musicians are active. That is essentially what we did with OSCs. We asked: can we predict which event position the brain is experiencing at a given timepoint, just by looking at which neurons are firing?

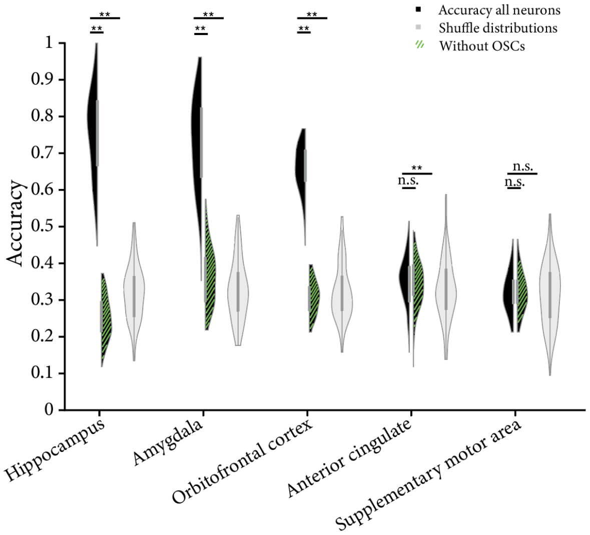

Figure A.3: Decoding accuracies for each brain region. When using all the neurons of a brain region (solid black), the accuracies are remarkably high in the regions of hippocampus, amygdala and—to a lesser extent—frontal cortex. These accuracies are significantly higher than chance level (gray). When removing order selective cells from the pool of neurons (black with striped green), the accuracy falls to chance level. Figure adapted from[238].

We used a machine learning classifier—think of it as a pattern recognition algorithm that learns to predict event order from neural activity patterns. When fed with the firing rates of all the neurons of a brain regions during the event boundary at order 1, boundary 2 and boundary 3, we asked: can the model learn to tell them apart?

The answer was overwhelmingly positive in the regions of the hippocampus, the amygdala, and the frontal cortex, where we could decode order with high accuracy (see Figure A.3). But here is a crucial test: when removing OSCs from the pool of neurons fed to the model, decoding accuracy fell to chance level. Thus, order selective cells are not just correlated with order, rather they carry the order signal that downstream neurons—or perhaps one day a computer—could use for further computations, such as memory consolidation.

So far, we have focused on individual neurons. But neurons do not work in isolation—they operate through populations. When we examined how groups of neurons especially in the hippocampus behave together over time, something quite beautiful emerged.

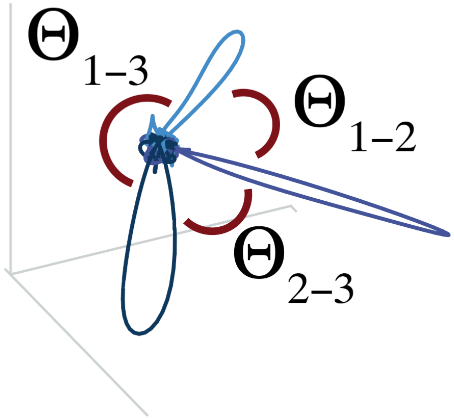

Figure A.4: Principal component trajectories in the neural state space. Light blue corresponds to the trajectory order 1, darker blue the trajectory of order 2, and darkest blue the trajectory of order 3. The three blues are entangled in a yarn ball, and at the moment of event boundary, then stretch out petals in different directions of the neural space. Figure adapted from[238].

Think of each neuron as a dimension in space. With hundreds of neurons constellating each brain region, we are dealing with space too high-dimensional to visualize directly, and we risk that important fundamental patterns remain nebulous. So we used Principal Component Analysis, or PCA—a mathematical method that finds the directions along which neural activity varies the most, essentially compressing our high-dimensional data into a viewable form, better suited to unearth important patterns. This let us visualize the trajectories that neural populations trace through what we call the *neural state space* as events unfold.

We found that events with different order of event boundaries follow distinct paths. Order 1 events trace one trajectory, order 2 another, and order 3 yet another, creating a petal-like pattern of Figure A.4, where each petal represents a different position in the sequence. Notably, this pattern held across the different movie stimuli. In other words, the brain is not encoding a specific event 1, or a specific event 2—it is encoding the “firstness”, or “secondness” or “thirdness” of an event.

Event boundaries, in essence, sculpt the brain’s neural dynamics, carving out distinct regions of neural space for each ordinal position in a sequence.

Binding Rhythms

People often say phrases like: "we are on the same wavelength", or "our brains are in sync". Do brains really have waves? Quite remarkably, they do. If we go back to our thought experiment of being at Symphony Hall, and rather than pinpointing singular musicians, focus on the overall patterns that reach our ears, we would notice patterns in what we are listening to. The brain is no different. If you were to poke an electrode into the depths of our neural tissue, you would notice a symphony of rhythmic patterns—or brainwaves—created by neural oscillations at various frequencies. Of particular relevance is the *theta rhythm* (a slow brainwave with frequencies ranging 5 to 10 Hertz), a prominent oscillation in the hippocampus which has been extensively studied in the context of memory[29].

In our data, we had the opportunity to look at theta oscillations picked up by the same electrodes from which we recorded spiking activity. Interestingly, when measuring the *power* of theta—or how strong the oscillation is—over the course of our movie sequences, we found that in the majority of cases it does not remain constant. In fact, it often increased or decreased monotonically across the trial, hinting that the brain might use this ramping signal to track progression through an episode.

So why do theta oscillations matter for order? When place cells activate in sequence as an animal moves through space, their firing is organized within theta cycles[55]. Think of each theta cycle as temporal brackets—neurons that fire together within one cycle are bound together as a unit, while neurons in different cycles remain distinct. This temporal scaffolding allows the brain to preserve sequential relationships: this place came before that place, which came before the next.

The exact timing at which individual neurons fire relative to the phase of the theta waveform matters. During memory encoding and spatial navigation, activated neurons fire at a slightly faster rate than the underlying theta rhythm. This creates a mismatch. Because of this speed difference, neurons progressively fire earlier and earlier within each theta cycle—a backward shift called *phase precession*[150].

Why does phase precession matter? Phase precession compresses sequences that unfold over longer timescales (seconds or more) into millisecond-scale within each theta cycle. This compression is crucial: synaptic plasticity—the mechanism by which memories are physically stored—operates on a millisecond timescale. Thus, theta oscillations essentially "replay" experiences at a speed the brain's learning machinery can capture[29].

We naturally were curious to study if the order selective cells we found also had a relationship with the underlying theta oscillations. After all, the order selective cells are picking out moments within a sequence of events, and having a candidate mechanism to bind such moments is warranted. We thus computed the strength of the phase precession for OSCs at the boundaries of the three events. Interestingly, these cells demonstrated a high phase precession only at their preferred order, and exhibited no phase precession at other orders.

Is phase precession linked to memory? In other words, is the strength of phase precession when viewing the sequence of events in a video related to the participant's ability to later recall the order of the events they had seen? For this, we turned to the time discrimination memory task our subjects completed after having watched the videos. As a reminder, participants were shown 2 frames from two adjacent events of a movie, and were then asked which came first. We sorted the trials among ones that were correctly remembered, and ones which were not. When examining the phase precession occurring at the time the participants were first watching the movies, we noticed that the movie clips later correctly remembered in order had a stronger precession, while the ones incorrectly remembered had a significantly weaker precession. This is perhaps one of the most impressive results, as it connects encoding-phase neural activity to successful memory formation. Phase precession strength during encoding allows us to predict correct order memory formation.

The Spacetime of Memory

There is a famous Buddhist parable in the *Tittha Sutta* (ca. 500 BCE) about a group of blind men who have never seen an elephant before. When presented with one, they each touched a part of it, and drew conclusions based on their previous knowledge. The blind man who touched the animal's trunk thought that this being was a thick snake. The one who reached for the elephant's leg concluded that it was a pillar like a tree trunk. The blind man touching the elephant's side said it was a wall, while the one touching the tail described it as a rope. And so on.

As I reflect upon what I have learned through my graduate school years, I come to wonder if we neuroscientists studying neural correlates of memory are like those blind men. Having place cells, and time cells, and boundary and order selective cells feels...at times redundant, at times unordered. Rather than finding unifying principles, we are adding new entries to the list of parts of our memory system.

Concepts of space and time are some of the most pervasive of our lives. And in our spoken logic, we are comfortable interchanging them[28]. When asked, I often say: "I live 15 minutes away from my lab", when in reality the more objective measure would be to say that my house is 1.3 kilometers away from my work place. And yet, because of the way they have been investigated in neuroscience, these entities currently still live very much separate. Space and time are dimensionless physics concepts, which we have operationalized by introducing measuring tools, that track distance and passage of time, respectively. And such measuring tools have been brought into neuroscience as well[28,30]. When observing cells sequentially firing in the hippocampus, these were called place cells when the rodent was moving around, and its displacement was highly correlated with the recorded neural activity. They were named time cells when the rodent was fixed in space on a wheel, and the sequential neural firing highly correlated with the passage of time.

This space and time scission reflects Newtonian thinking. In the *Philosophiae Naturalis Principia Mathematica*, Sir Isaac Newton wrote about how space and time are two absolute and independent entities, where "[time] flows equably without regard to anything external", as does space[144]. Thus, in neuroscience two lines of work, one for space, one for time, proceeded independently. But neurons deep in the hippocampus do not have access to measuring tools. Nor can they distinguish what is causing them to fire—in other words, they cannot tell if the upstream network is soliciting them to create action potentials due to passage of time or traveling in space[30]. Space and time in physics are connected through the law of velocity, and we know from prior experiments that the activity of place cells is dependent on the animal's speed, illustrating that a measure of space is influenced by time[75]. Given that anatomically many of these place and time cells are largely harbored by the same brain structures, it makes one ponder if we are looking at tusks and the tail of the same elephant.

1905 was an earthquake year for physicists—and really, for the world. Albert Einstein had just published a paper which would change the way we think about reality, by bestowing us with his theory of Special Relativity[58]. With it, Einstein provided a new system through which to see reality, by dismantling the very core of Newton's classic mechanics—time and space are not independent. According to the new theory, three dimensional space and time are fused together in a four-dimensional continuum, called *spacetime*. Time cannot be separated from space, as the passage of time depends on an object's velocity relative to the observer. Simply put, time is relative, as the saying goes.

And most of us have experienced the non-linearity of time: a week with your loved one flies by, while a boring lecture weighs like a geological era. Life is a sequential chain of events, placed in order by the arrow of time. The "speed" at which these events occur warps our time perception. As human brains have become more complex throughout evolution, it is reasonable to assume that they may have internalized many of the external cues that animals need to estimate the velocity at which events occur. Attention—according to some scientists—might play such a role by picking up environmental or internal changes, and detect mismatches between one's internal model of how the world works and the incoming sensory input (as posited by the aforementioned Event Segmentation Theory)[30,228]. This, in turn, might elicit activity from boundary cells, which fragment our lived life in events at an appropriate speed[239]. And thus, the hippocampal role (and the one of its associated circuits) is to generate sequences of cells firing in a specific order, to string all the fragmented events in a line, and to mark at which event—out of all the ones we have lived—we are currently at. The order selective cells we discovered seem to be an excellent candidate for exactly this purpose, indexing which event order one is living. The beginning of an event occurred *jointly* at a specific place, in a specific time, and thus has a unique coordinate in the spacetime tapestry of our life continuum.

Our brains single out these unique salient moments of our spacetime, increasing their probability of being correctly memorized. Provided that we cannot encode to remember every instant of our lives, the hippocampus and associated circuits might be the funnel tool that *compresses* our huge database of lived life into a subset of important frames that we cherish. This perhaps is why when on vacation in a new country, the arousal and attentive state are piqued, saving many more spacetime frames to our memory, while very few bits of memory may be allocated to a blurry week of uninteresting work.

I argue that indexing spacetime is perhaps one of our most impressive powers, as it allows us to defy a crucial law of nature. *We can reverse the arrow of time*. A baby can only grow older each day; a newborn star's destiny is to one day die. Our watches and calendars only proceed in one direction. *And yet!* In our brains we can bend this fundamental law. Assigning an address to our stored experiences could perhaps be the mechanism to then shuffle back in our minds and reaccess memories. Memories are a pillar of who we are, how we were molded by the world and what we have learned.

All we really have agency upon (if you believe in free will) is the present moment. We are impermanent. Every moment is fleeting. However, by really focusing on the present, we do build up a whole constellation of experiences we have the possibility to go back to, and reminisce. Humanity has long dreamt of building time machines, maybe to go back to happy moments, or to be once more with loved ones who moved on. Perhaps for today, we can take comfort in the fact that the most advanced time machine yet sits between our two ears.