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Understanding Temporality and Asynchronicity in the Brain

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In this paper we attempt to describe the processes in the brain that are involved with temporality, operating over a number of time scales. These involve things such as motor control, interval timing, and the consciously experienced passage of subjective time, something that can differ from the progression of Newtonian time that we can observe on a clock. We also elaborate on how the brain deals with the different timings of sensory pathways, as somehow, through the asynchronous and distributed nature of the brain, the concept of a unified self emerges.

1. Introduction

The brain is an exceedingly complex and interconnected dynamical system. Taken together with the body, living organisms such as us are capable of self-sustaining adaptive behavior, dealing robustly with the changing environment that they find themselves in. The spatio-temporal nature of our existence, along with our capacity for memory, allows us to draw temporal horizons that stretch backward in time as we remember our past, and forward in time as we project ourselves into future situations. Thus the concept of time is of fundamental importance to understanding our existence. But how do we understand the nature of time within ourselves? Specifically, what neural mechanisms might be involved in time critical functioning and moreover, constitute our subjective experience of time? What must be explained for is how the brain manages to have a momentary “now”, despite the different speeds of sensory pathways and despite the brain being a decentralized and highly interconnected network of asynchronous parallel processes.

In this paper we attempt to describe the salient features of the brain that are involved in asynchronicity and temporality, and in turn identify the standing questions that remain about their function. This is conducted for the purpose of developing new computational models of the brain that will further our understanding.

We firstly summarize a number of neural mechanisms that have been so far identified with different aspects of temporality within the brain. We conduct this with respect to how timing can be used to help resolve or integrate asynchronous processes; somehow the brain must deal with the different latencies inherent in different mental processes. We also differentiate between unconscious temporal processes and our conscious, subjective experience of time, something that deserves special attention. We define *subjective time* to be our first person experience of the passage of time, as opposed to the Newtonian time that is measureable by a clock. As an example, in critical situations, time appears to slow down and our subjective feeling of such an event differs from the physically measured duration of a clock.

2. Overview of the neuroscience

We consider there to be four main types of time related phenomena within the brain. Indeed, these are a matter of time scales but they also differ in mechanism; we can divide them into those involved in things such motor control, for interval timing, and for a higher level, subjective and conscious appreciation of the passage of time. In summary the four main types are:

- Circadian timing: a rhythm entrained to roughly 24 hours.
- Millisecond timing: responsible for motor control.
- Timing in the seconds range: interval timing, cognitive processes, decisions and conscious time processing.
- Subjective time: appearing in the conscious mind when we reflect on the passage of time in our lives, perhaps the most enigmatic type of time we know of.

2.1 Neural circuitry involved in timing

Sub-networks of neurons in the brain seem to have timing mechanisms that can operate without any central coordinator. The basal ganglia (BG), supplementary motor area, cerebellum, and prefrontal cortex are all known to be involved in the measurement of duration in the brain [Coull 2011]. It is suggested that time is represented in both sensory specific brain regions and in context independent networks of regions for internal timing over a range of scales. There is also a strong neuroanatomical overlap between brain regions involved in timing tasks and those involved in motor function – suggesting the possibility for new therapies for patients of motor disorders. For example, Parkinson’s disease is a well-known motor neuron disease that strongly affects the basal ganglia.

Dezhe et al. found that the basal ganglia neural circuitry encodes timing of events at short time scales [Dezhe 2009]. By training monkeys with simple tasks they were able to identify neurons that always fired at certain time intervals after an initiating signal (such as 100, 110, 150 ms), effectively acting as timestamps for events. This phenomenon was then replicated in a perceptron style neural network model. This type of low-level timing would be integrated into the larger network of cortical regions to support cognitive processes.

Could there be a unified, emergent timing signal in the brain? Coull et al. state that interval timing involves the activity of a large number of cortical regions, but that neurophysiological evidence supports the idea that the dorsal striatum could serve as a core timer in the brain [Coull 2011].

Reward expectation involves the integration of previous rewards over time, conditioned on the environment. For example, in an unpredictable environment, payoffs for the same option

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should be evaluated at shorter time scales and vice versa in a predictable environment. Bernacchia et al. found that the brain deals with this problem by generating a number of timescales at which neurons can operate upon memories [Bernacchia 2011]. The authors found that a reservoir neural network model was capable of generating such timings - in the millisecond to second range - consistent with that observed in the brain.

2.2 Temporal order judgement and temporal binding

Organisms must judge the relationship between motor output with sensory input for voluntary acts. This is especially true across sensory modalities, where the different speeds of processing pathways must be coordinated. This problem is known as temporal order judgement (TOJ) and Cai et al. have proposed a model of how this works [Cai 2012]. The model uses delay-tuned neurons that are tuned to 'motor event before sensory input' and 'motor act after sensory input'. The outputs of these ensembles are pooled at a higher level and synaptic scaling is used to come to a decision as to which event occurred. If taken across multiple sensory modalities, the brain can account for the different speeds of the pathways and calibrate itself to a unified sense of 'now'. This could be imagined as a temporal wavefront of neural activity within a dynamic system always in flux. Thus, there seems to be neuronal circuitry that responds to fine grained temporal events in an asynchronous way.

For such an approach to make sense there must be a limited temporal range in which sensory events are considered to be results of a volitional act. This window was found to be about 80 ms. The brain, in an elegant manner, waits for the slowest information to arrive before it can judge the temporal order of events. This window of delay means that our understanding of events is post-dictive. But this talks nothing of our conscious experience of events. Importantly, the work of B. Libet has shown that roughly 500 ms must pass before conscious awareness of an event appears within the brain [Libet 2004]. The 80 ms window seems to be involved in temporal judgments at the subconscious level and is just another aspect of the mind that leads us to query past distinctions between time in the conscious versus the unconscious mind, especially when talking of episodic memories.

2.3 Episodic memory

So far we have discussed time in relation to procedural memory processes residing in the unconscious mind. But what can be said about longer timescales, such as the construction of episodic memories and the 'time' that we encounter when we consciously reflect on events? Episodic memory is the memory that acts as a map of events, linking together memories and ideas through context, temporality and association. Together with semantic memory, the memory of meanings and facts, they form different aspects of what is known as declarative memory.

When we think about durations over longer time scales such as weeks, months or years, what temporal mechanisms are used here? Is there an active construction of a timeline through episodic memory pathways, or is there a temporal signature for each memory? The answers remain unclear, but what is certain is that the hippocampus plays an important role in the formation of new episodic memories; damage to this region can inhibit their creation, but does not effect the recall of old episodes from a subject's past.

2.4 Conscious subjective experience of duration as cognitive load

According to Eagleman, the conscious, subject experience of duration is the result of cognitive load [Eagleman 2009]. In other words, it is a function of the amount of energy that has to be used to encode an event. These remarks refer to the conscious reports of events and how long they 'felt' to the subject when they reflected upon the situation. Therefore, such accounts of the passing of time can change depending on the mental state of the individual. For example, critical situations cause an increase in activation in the amygdala, causing memories to be encoded at a faster rate. This increased cognitive load and larger number of memories are what contribute to the subjective feeling of time slowing down during such critical moments [Stetson 2007].

But how does this relate to the old adage 'time flies when you are having fun', or when time seems to crawl during boring situations? It seems that subjective time cannot be accounted for only by cognitive load. One key might be found in the work of Meck, whose experiments showed the connection between the brain's internal clocks and the rate at which memories are encoded, and how this can be modulated with various chemical stimulants or depressants [Meck 1996]. The possibility for such modulations across distributed timing circuitry in different brain regions might provide the basis for a more complex yet more accurate description of subjective time.

3. Conclusion and future work

In this paper we have overviewed many aspects of asynchronicity and temporality in the brain. A number of questions have been raised in the previous sections and it is easy to imagine many more that are yet to have strong, empirically based answers. Some of these are listed below:

- Is there a minimum frame-rate of the brain in which information is encoded?
- Unconsciousness seems to be more important in the brain than consciousness (however, it could be said that the exact definition and function of consciousness is still an open question). The important difference between the two seems to be the aspect of 'awareness', appearing in the brain and experienced by us 500 ms after the stimulus [Libet 2004]. Due to this, how can we better characterize consciousness in the brain?
- Salient information from the situations we find ourselves in arrives at different times through our senses, over a range of timescales. How is this information updated, integrated and organized over time so that we can cognize?
- What are the implications of information overload in the brain? We have a finite capacity to process sensory information – if congestion occurs, what mechanisms are there to deal with such temporal issues?
- If the brain operates in a parallel manner, how can we understand a single processing mind - a single self from parallel systems?

- During dreaming or imagining of direct and involved experiences, the brain is able to replay past events in a fraction of the time that the original event took [Davidson 2009]. How does our brain achieve this?

Consciousness of cognitive systems can only come from massively parallel systems. For future work we would like to come up with a plausible model and mechanism for asynchronicity and temporality in the brain, that can also be used for understanding the formation of episodic memories, not just motor timing etc. Such a system should possess latencies with a number of asynchronous processes and temporal evolution. An open environment such as the Internet could provide a suitable platform for testing self-sustainability and adaptive behavior. Importantly, the phenomenon of latency is not represented in today's artificial neural networks and we would like to find a new model to replace them.

Established digital communications networks, such as packet switching networks (PSN) hold interest properties with regard to latencies and congestion and the emerging field of Big Data, where massive amounts of data is processed with technologies such as MapReduce - a distributed processing technology in terms of map and reduction operations [Dean 2004] - could both provide inspiration for a new computational model of brain processes.

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