

Grand Unified Theory of Mind and Brain

Part I Space-Time Approach to Dynamic Connectomes of *C. elegans* and Human Brains by MePMoS

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Abstract

In a total of six articles, **Grand Unified Theory of Mind of Brain: Part I – VI**, distinct and radical space-time approaches to the human mind and brain are presented step by step.

- Part I.** Space-Time approaches to Dynamic Connectomes of *C. elegans* and Human Brains
- Part II.** Neural Holographic Tomography (NHT) and Holographic Ring Attractor Lattice (HAL)
- Part III.** Holographic Visual Perception of 3D Space and Shape
- Part IV.** Navigation and Episodic Memory by Hippocampal Network
- Part V.** Grand Unification of Five Senses and Memories
- Part VI.** The Origin of Language, Consciousness, and Intelligence

Through these articles, it is shown that multiple brainwaves coordinate brain-wide neural activities in the frequency-time domain. Globally, allocentric 3D space is reconstructed by the phases of the low-frequency bands (< 20 Hz: Theta, Alpha, and Beta) via top-down signal processing. On the other hand, local stimulations of the five senses are encoded by the high-frequency gamma bands (> 30 Hz) via bottom-up parallel processing.

This **Part I** argues that the fundamental principles of physics, causality and locality, must be imposed at every synaptic connection. Under such strict constraint that coincides with Hebbian Plasticity, the brains of any animal must follow the top-down principle of **MePMoS** (**M**emory-**P**rediction-**M**otion-**S**sensing) in this order. By applying this new concept, the complete space-time dynamic connectomes of the neural networks for two phylogenetically distant animals, *C. elegans* and humans, are constructed for the first time.

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Abbreviations

Abbreviation	Definition
AIP	Anterior Intraparietal area
AIT	Anterior Inferior Temporal cortex
CA	Cornu Ammonis
CIP	Caudal Intraparietal area
CNS	Central Nervous System
CPG	Central Pattern Generator
CRT	Choice Reaction Time
DFT	Discrete Fourier Transformation
DG	Dentate Gyrus
ECoG	Electrocorticography
EEG	Electroencephalography
GUT	Grand Unified Theory
HAL	Holographic Ring Attractor Lattice
HC	Hippocampus
HCN	Hippocampal Network
iEEG	Invasive Electroencephalography
LEC	Lateral Entorhinal Cortex
LFP	Local Field Potential
LGN	Lateral Geniculate Nucleus
LIP	Lateral Intraparietal cortex
LTD	Long-term Depression
LTP	Long-term Potentiation
MEC	Medial Entorhinal Cortex
MEG	Magnetoencephalography
MePMoS	Memory-Prediction-Motion-Sensing
MIP	Medial Intraparietal cortex
MST	Medial Superior Temporal area
MT	Middle-Temporal Area
NHT	Neural Holographic Tomography
PFC	Prefrontal Cortex
PIT	Posterior Inferior Temporal cortex
PN	Pulvinar Nuclei
RF	Receptive Field
RSC	Retrosplenial Cortex
RT	Reaction Time
SAC	Somatosensory Association Cortex (Brodmann Areas 5 and 7)
SC	Superior Colliculus
SRT	Simple Reaction Time
STDP	Spike Timing-Dependent Plasticity
SWR	Sharp Wave and Ripples
TRN	Thalamic Reticular Nucleus
VTC	Ventral Temporal Cortex

1 Introduction: Perception of Space by Time

1.1 The Origin and Purpose of the Brain

Our daily life is enlightened by a wide range of visual stimulations; as soon as we wake up in the morning, we open our eyes and begin to walk around freely. Such prompt actions rely on a bombardment of continuous stimulation like visual sensations, which must be compared immediately with the past experiences and memories in our brains. Through this real-time neural signal processing, we perceive and reconstruct an external space that is three-dimensional and allocentric, regardless of the constant movements of our eyes/head/body. These processes seem so natural and effortless that we do not often notice our motion. It is especially so for involuntary, unconscious saccadic eye movements.

Similarly, when we navigate a much larger space like our hometown, we seamlessly integrate sensory signals with our motion as we travel to target landmarks such as a school, office, or coffee shop. Through this process, allocentric 3D space appears to be well maintained in our mind, like a GPS map, while we continue track of our position, direction, and speed in real-time while we navigate.

Furthermore, as we perceive and navigate through 3D space, we can identify and recognize countless objects (as landmarks) with 3D shapes and semantic information, including human faces, cars, as well as written language; moreover, we are able to do so naturally and effortlessly from any distance and angle, within a fraction of a second.

This series of six articles is an ambitious endeavor to elucidate the true physical origin of such flawless perception of 3D space and shapes, especially based on vision:

- 1) How can we perceive and reconstruct 3D allocentric external space?
- 2) How can we navigate within it promptly and reliably regardless of our own eye/head/body motion?
- 3) How can we extract and recognize complex 3D semantic shapes regardless of their location/shape/orientation?
- 4) What is the exact biological mechanism to memorize and repeat the above?

To accomplish this goal, we shall begin with two critical questions in **Part I**: (1) What is the brain's primary purpose? (2) And what is space according to physics? To answer the first question, we should restate that, from the evolutionary perspective, the brain was originally developed for animals to navigate their given space for survival. It is due to the simple fact that we, animals, cannot obtain food without motion – unlike plants, which can perform photosynthesis. Therefore, the regulated physical movements in 3D space for survival must have been the driving force for animals to develop and refine the function of neural networks (Llinás 2002).

There are three primary purposes of motion being key to survival. First, we must eat food that is sparsely distributed (by predating on prey). Second, we must make sure not to be eaten (by escaping from predators). Third, we need to conduct mating behavior (to pass on our genes). Efficacy is critical for all three purposes. Therefore, reliable and prompt motions with respect to these goals must be the immediate and ultimate purpose of neural networks. Unveiling the underlining mechanism is the central theme of this paper.

1.2 Principle of Navigation and Vision

Let us consider typical animals such as ants or mice, whose daily lives rely on traveling back and forth between food locations and their nests. First, they must identify and memorize the distinct

landmarks and semantic information associated with these locations. Then, they ought to memorize a navigation map by stamping these landmarks on the allocentric frame (i.e., the absolute outer world). While they are traveling back and forth between the landmarks, they must keep track of their location and direction in real-time, by integrating their physical movements and the sensory signals they receive – such as vision and hearing – within the egocentric frame (Klatzky 1998). This conversion from the egocentric frame to the allocentric frame must be prompt and accurate so that they do not lose their way.

This exercise reveals the two critical functions of the brain. First, it must recognize and remember the semantic shape of landmarks. Second, it must construct and maintain a 3D map in the allocentric frame, which is marked by the landmarks. The first step, recognition and memory of semantic shape, requires careful consideration. Conventional wisdom follows a bottom-up approach, where a retinotopic image forms a local receptive field (RF), which grows gradually through the visual pathway to the total size of the landmark. Unfortunately, this approach by itself has a fatal flaw: the problem of induction, whereby object recognition must be immediate and accurate despite the image on the retina infinitely varying in size and orientation. Here, one needs to consider frame translations under seven degrees of freedom: 3D linear translation, scaling, and rotation in 3D. If we could only memorize one fixed size or orientation of the landmark located at the center of the 3D frame, in order to recognize the observed shape at any location/size/orientation, seven-dimensional translations must be conducted to overlay the memorized shape and incoming visual pattern at the end of the visual pathway. It is a daunting task. As a matter of fact, In **Part III**, we will show that a significant fraction of the visual cortex is assigned to precisely conduct the 7D translations.

What about the memory and maintenance of the 3D allocentric map? The map in our mind must maintain an absolute coordinate system that is attached to external space, or the so-called allocentric frame. Yes, we ought to have some sort of a GPS (Global Positioning System) in mind. However, it is nontrivial because, by definition, all the sensory stimulations enter the sensory neurons within the egocentric frame. Therefore, prompt 3D translation from the egocentric to allocentric frame is indispensable for reconstructing and navigating the given space, regardless of our motion. The existence of such an allocentric frame in the brain has been extensively studied and demonstrated by the discoveries of place cells and grid cells in rodents' Hippocampal system (Moser, Kropff, & Moser 2008), at least, under the 2D Cartesian coordinate system. Nevertheless, the exact mechanism of the egocentric-to-allocentric frame transfer in 3D is still unknown. This will be addressed in **Part IV**.

1.3 What is Space?

Now is a good time to step back and recall what space is according to physics. Physics is the science that deals with dynamical motion/change of objects within a given space-time, so it should also be the foundation of the origin and mechanism of the brain. In classical physics, a traditional view is to consider a kind of “empty space” within the 3D Cartesian coordinate system of (x, y, z) before landmarks are placed. Although this approach is undoubtedly a convenient way to describe space, it is not necessary; a given 3D space could be expressed by the directional vectors based on the polar coordinate system of [Azimuth, Altitude, Distance] as well, for example.

Furthermore, the simple assumption that “empty space is sitting there” must be carefully evaluated. If there is nothing in space, we cannot define space. At least two points (i.e., landmarks) are required for 1D space, three points for 2D, and four points for 3D. Such distributions of the multiple landmarks are fundamentally required to define space. From this point of view, space could be expressed perfectly well by the multiple directional vectors connecting each landmark, without any emptiness surrounding the landmarks (Bouchekioua, Blaisdell, et al. 2021; Bouchekioua, Kosaki, et al. 2021).

This view of vectorial connections corresponds to the concept of path integration in the neuroscience (Etienne & Jeffery 2004). Our daily navigation seamlessly utilizes strategies of both a GPS-like 3D map and path integration, but how the integration process takes place is still unknown. We intend to address this issue and provide a unified solution step by step in **Part II**, **III**, and **IV**. [Please note that the exact definition of path integration is different in particle physics.]

Next, we shall move on to the critical argument by Einstein (1945), that is, how we measure the distance between points A and B that determines the scale of the space. He concluded that it must be measured by the traveling time of well-behaved motion with a constant speed. A perfect example is an electromagnetic wave (i.e., light) traveling from point A to B with a constant speed of light, $c = 3 \times 10^8$ m/s. For this reason, space must be essentially represented by traveling time; thus, space-time is an integrated concept. This expression of space by the traveling time of constant-speed motion is going to be the central dogma of the proposed holographic model of the brain in this paper.

1.4 How to Measure Distance

Let us consider the measurement of a one-foot-long bar in front of us. According to Einstein, to obtain the length, electromagnetic waves must travel from one end A to the other end B. Only then, the observed traveling time gives us the length. However, measuring the length by traveling light is impractical, because the speed of light is so fast that it only takes 1 ns per foot (~0.3 m). Assuming that we have no access to an artificial clock that measures with nanosecond precision, one could imagine four possible practical approaches to measure this distance in our daily life:

- 1) Extending one's fingers and utilizing the span between the thumb and pinky (~0.2 m) as a unit of length.
- 2) Moving the index finger at a constant speed from A to B and measuring the required time duration.
- 3) Focusing the eyes on A, then moving the eyes to focus on B by a saccade with a constant speed and measuring the elapsed time.
- 4) Focusing the eyes on A and utilizing a retinotopic image to sense B, then processing the image without a saccade by means of a traveling neural signal, such as a brainwave.

Throughout the six articles, we will discuss these four cases in different Parts, as listed below.

- 1) is the most primitive way and related to the nerve ring of the diffuse net (in Hydra, Jellyfish, etc.): **Part II**.
- 2) is related to the navigation of a flat space by a body motion, in general, utilizing the Hippocampal network (by rodents, primates, etc.): **Part IV**.
- 3) is known as overt attention (by our foveal vision): **Part III**.
- 4) is the most advanced and efficient way, known as covert attention (utilizing our visual image processing): **Part III**.

These four approaches are listed here in the order of evolution. The most advanced form, (4) covert attention, is purely based on the processing of a stored retinotopic image. In this case, the image of the one-foot bar is copied onto the retina → LGN → V1 and so on. In the primary visual cortex, V1, or a later stage of the visual pathway, to perceive the length between the images of A and B, some neural signal must propagate from A to B with a constant speed, according to Einstein's view. Throughout this paper, we postulate that a brainwave must propagate from A to B so that we can estimate the distance by the time difference between A and B in terms of the phase difference. This is the essence of our new holographic model, and we will explore this concept in detail (**Part II**). We will show that this approach can also explain the neural origin of perception of allocentric (to be exact, body-centric) three-dimensional space and semantic shapes (**Part III**).

1.5 Necessity of Converting Space to Time – A Lesson from Artificial Imaging Devices

To further explore the physics constraint by Einstein that space must be represented by time, let's consider a typical artificial imaging device such as a CCD or CMOS camera. Today's camera consists of a two-dimensional array of capacitors (with $> 1000 \times 1000 = 1\text{M}$ pixels) that store a 2D image of distributed light intensities as electric charges, pixel by pixel. Then, these charges are transported by an external gating mechanism, pixel by pixel, sequentially. A clock speed is an order of 10 – 100 MHz in today's analog to digital conversion (for > 30 frames per second of image digitization). These electric charges are transferred from the $\sim 1\text{M}$ pixels into a computer, which in turn processes the sequence of spatial information in the time domain. As a result, 2D video images can be reconstructed. In other words, inside the computer, there is no real "space" as space through image processing. Instead, space must be converted and represented by the time duration required for this conversion, such that a longer distance corresponds to a longer time delay proportionally. The time sequence is precisely coordinated by the CPU clock so that space is faithfully represented by the appropriate coordinate system.

If this is a general principle of perception of space, as it should be, our visual signal processing must apply the same principle and concept as well. Our retina is like a CCD/CMOS image sensor, and our visual cortex must be like an image-processing computer. That is, in our visual cortex, retinotopic 2D space must be converted to and represented by the proper time sequence. If this is true, the time difference is likely to be controlled by the well-defined phase shift of a certain brainwave.

One could rephrase the above fact more generally. Let us consider the observation of two points, A and B, in the retina \rightarrow LGN \rightarrow V1, and so on. Points A and B are recorded as two distant points on the retinotopic maps along the visual pathways. Therefore, there must be two corresponding distant neurons A_N and B_N , flashing at the corresponding locations. There are only three possibilities for when these neurons fire:

- 1) A_N and B_N fire at the same time;
- 2) A_N and B_N fire at random (uncorrelated) times;
- 3) A_N and B_N fire at the exact time sequence corresponding to the distance between A and B.

Among these three possibilities, (1) does not allow the perception of distance between A and B, because A_N and B_N are "space-like" and cannot communicate with each other. (2) does not allow the perception of a well-defined distance between A and B either, because the flashing times of A_N and B_N are uncorrelated. Their spike rates might be able to express the distance, but it is implausible. Therefore, only case (3) can produce a precise sensation of the distance between A and B.

Let us restate this fact more carefully to explore our vision. When we observe an external object by eye, its image is stored by the retina, and then transported to LGN \rightarrow V1. But if the retinotopic image stored in V1 is represented by flashing neurons, unless these neurons follow well-defined time sequences, the image is still "invisible." We can extend this argument to V1 \rightarrow V4, as well as the rest of the ventral pathway, and the dorsal pathway. Today's conventional wisdom is that the receptive field (RF) becomes larger and larger from V1 to V4. Eventually, at the Ventral Temporal Cortex (VTC), the RF would become large enough for us to recognize complex semantic shapes, such as human faces. This concept has a fundamental flaw: even if the RF becomes large enough at VTC to cover an entire human face unless the neurons at VTC in the RF follow a particular time sequence to represent its shape, the RF is still "invisible." Therefore, we ought to investigate how the time sequence of neurons within the RF at VTC contributes to the reconstruction of the shape of the human face. The basic principle of space to time conversion in the brain is given in **Part II**, and a complete account for shape recognition will be given in **Part III**.

Likewise, the dorsal pathway's endpoint, Frontal Eye Field (FEF), is known to maintain retinotopy. However, the retinotopic image at FEF is still "invisible" unless it is converted to the proper time sequence. This problem of "invisible retinotopy" is our primary motivation to consider the frequency-time domain for visual perception of space (by the dorsal pathway) and shape (by the ventral pathway) by means of brainwaves. In **Part III**, we conclude that visual perception (i.e., conscious awareness of external space) is fundamentally our internal creation, similar to what occurs in a dream or when painting an image on a virtual 3D canvas. Visual sensory inputs are only utilized to confirm the "dream" or the "painting."

1.6 Summary – Necessity of Space-to-Time Conversion

The primary purpose of the brain is navigation in space. Therefore, the brain must have evolved to perceive external allocentric space promptly and faithfully. However, due to the stringent constraint of causality and locality required in the brain, space must be converted to time. This conclusion is so firm that an entirely new approach, a new textbook, seems necessary to describe visual perception of 3D space and shapes.

In the following **Section 2**, we further investigate the necessity of the space-to-time conversion from the fundamental physics principle: Causality and Locality, which brings up the new concept of **MePMoS (Memory-Prediction-Motion-Sensing)**. In **Section 3**, we will apply the **MePMoS** to build up a complete space-time diagram of the entire brain of one of the simplest animals, *C. elegans*. Finally, in **Section 4**, we will construct a whole space-time dynamic connectome for the human brain with an emphasis on visual perception of external space.

Then, in the following paper, **Part II**, we review the evolutionary challenge to develop vision and navigation systems that insects overcame. After that, we will introduce another innovative concept of **Neural Holographic Tomography (NHT)** as the general principle of our perception of 3D space and shape. Then, as a universal memory unit to realize **NHT**, we will introduce the **Holographic Ring Attractor Lattice (HAL)**.

2 Causality and Locality – Principle of MePMoS

2.1 Causality and Locality in Particle and Neural Interactions

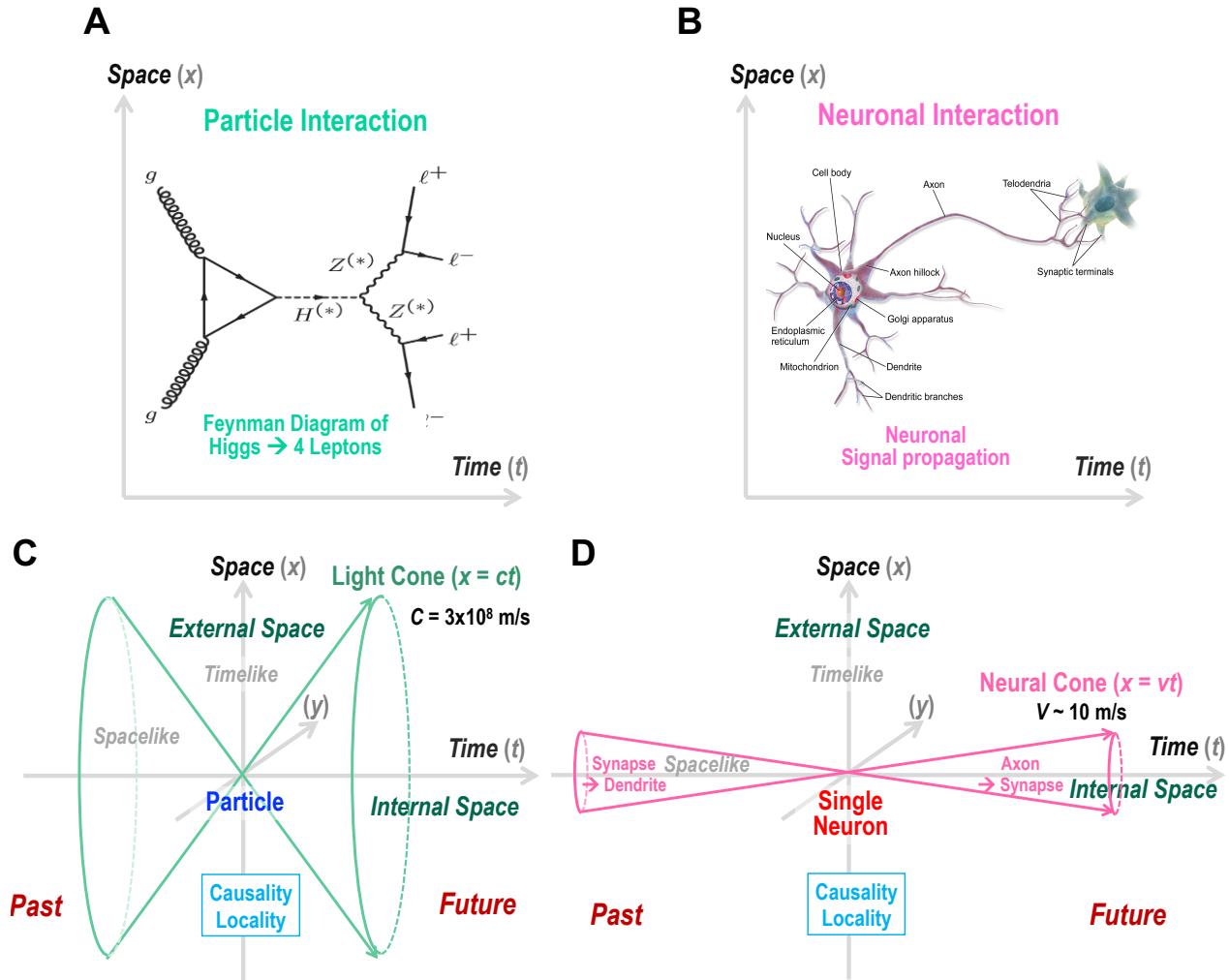


Figure 1. Feynman Diagram and Light Cone. (A) shows a typical diagram of Higgs' decay into four leptons (Bredenstein et al. 2006). (B) offers an illustration of the typical connection between two neurons via the axon and the dendrite. (C) Postulated by Einstein's relativity, any communication from the past to the future is bound by the light cone (green, called space-like). Information can be shared between two distant points within the light cone. (D) Likewise, any interaction between neurons must occur within a similar “cone-shaped inner space,” established by chemical connections of the synapse (red).

Let us investigate more details of space-to-time conversion in nature. The most fundamental process in physics is the interaction of elementary particles, such as electrons and quarks. Within a framework of four-dimensional space-time, Richard Feynman invented an intuitive and pictorial description of such a process, named a Feynman diagram (1948,1949). For example, **Figure 1-A** shows the Feynman diagram of a Higgs decaying into four leptons by gluon-gluon fusion (Bredenstein

et al., 2006). Here, the time-axis is assigned horizontally from the left to the right, whereas 3D space is convoluted into one dimension and expressed by the vertical axis, due to the limitation of the figure being expressed in 2D only. Throughout this article, we shall adopt the same graphical convention as we visualize neuronal interactions in 4D space-time, through which they will be expressed in 2D diagrams. In **Figure 1-B**, a typical interaction between two neurons via a synapse is illustrated. The apparent similarity between these two figures, **A** and **B**, indicates that neural interactions must indeed be based on the same physical principle that underlies the particles' interaction.

The basic principles of physics behind the Feynman diagram are referred to as causality and locality. As illustrated in **Figure 1-C**, the particle on which interactions are observed is given at the center. Causality imposes that information flows into this point from the past (depicted on the left) only and influences the future (on the right). Likewise, locality enforces the interactions only happen at the exact location of the particle itself. Combining both causality and locality, Einstein introduced the concept of the light cone for electromagnetic interaction and propagation; as shown in this figure, the electromagnetic interaction must reside within the light cones bound by the speed of light (3×10^8 m/s) (Einstein, 1945). These cones illustrate the boundaries of the communication between two points: the region inside the cones is called “time-like”, where causal communication can be established; conversely, the region outside of the cones is called “space-like”, where communication cannot be established, due to the finite speed of light.

2.2 Relativity of Neural Networks – Origin of Hebbian Plasticity

If the fundamental laws of physics are universal in the interactions of particles and neurons, the same constraints of causality and locality should be applied to the interactions among neurons, as shown by the red shallow dual cone shape in **Figure 1-D**. One should note that, since the typical speed of neural signals – in the range of 1-100 m/s – is extremely slow, causality and locality impose exceptionally stringent constraints for neural signals, which is analogous to the concept of “relativistic regime” in Einstein’s relativity. The extremely limited speed of neural signals has a dramatic consequence, as described rigorously in later sections.

Let us further explore causality and locality. It would be reasonable to imagine that environmental stimuli are processed by sensory pathways (e.g., the visual pathway, etc.), which somehow generate an inner world in the brain that must be a faithful representation of the outer world. This is the generally accepted view for the perception of space that follows the process of Stimulation → Sensing → Processing → Perception, in this order. However, this traditional view has a critical flaw: it is inconsistent with causality and locality; that is, space cannot be processed as it is, unless it is converted to time. This means that our brain would not be able to perceive space, which would be a fatal issue.

Why is it so fatal? Let’s explore the signal processing mechanism in the brain by strictly imposing causality and locality. **Figure 2-A** shows a “Feynman diagram”, or space-time diagram, of a brain again, in a conventional view. Here, the external environment (i.e., the outer world) feeds sensory stimulation from the past into the brain. Then, the brain processes it and decides where to move the body. Therefore, this process follows causality from the past to the future. What about locality? As shown in **Figure 2-B**, strictly speaking, when a stimulus enters a sensory neuron, any quantum mechanical fluctuation as wave-like behavior is going to collapse. For example, a single photoreceptor in a retina absorbs a photon and creates an electric signal. This mechanism – the collapse of the wave function – imposes the critical constraint for the classic interaction, as locality and causality must be strictly satisfied.

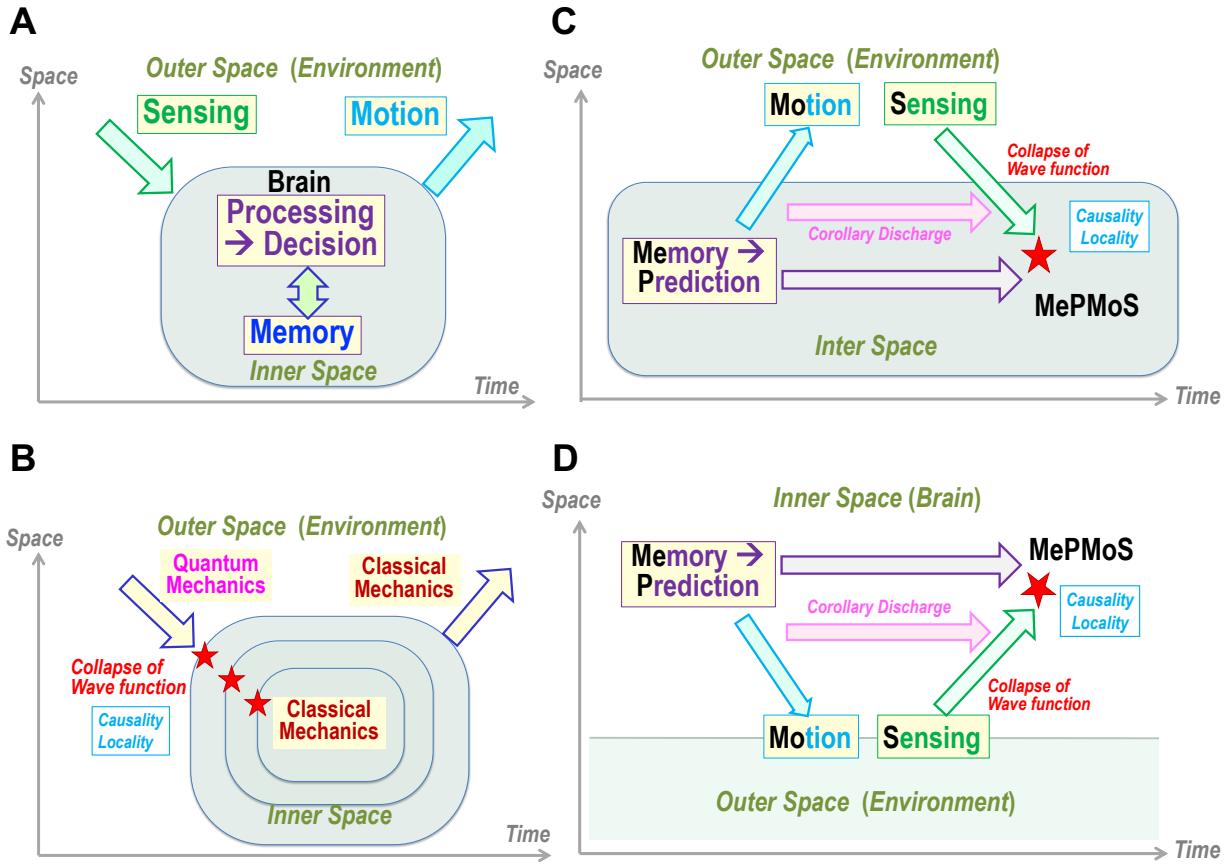


Figure 2. **(A)** Space-Time (Feynman) diagram of signal processing by the brain. It follows the time order of Sensing → Processing → Prediction → Motion. **(B)** Detailed space-time diagram expressing the constraint of causality and locality at the neuronal/synaptic level. In this diagram, spatial information cannot be derived, due to causality and locality. **(C)** Principle of MePMoS (Memory → Prediction → Motion → Sensing). It should be directly compared with the conventional view, given in (A). Unlike (A), this diagram satisfies causality and locality. **(D)** Upside-down version of (C). In this figure, we emphasize our inner space (i.e., the brain) as the center of the process.

This specific condition of a point interaction continues through the succeeding signal processing stages, at any single step, sequentially, as shown by the red star in this figure. In other words, neural signal propagation is based on deterministic classical mechanics. At the neuronal or synaptic level, the neuron must make its own decision at a given time and location, based on incoming signals from the past only.

If this were the only thing that each neuron/synapse could perform, none of them would be able to generate spatial information. This fundamental problem that neurons cannot perceive space as space seems to have been neglected in neuroscience, and the resolution to this problem is the heart of this paper. There must be an alternative model that overcomes the stringent constraint of causality and locality. Otherwise, no matter how hard neural networks are at work, we would not be able to perceive external space and navigate.

Before we move on, one should point out that the requirement of causality and locality was not always neglected historically in neuroscience. Donald Hebb proposed the critical concept of Hebbian plasticity (Hebb, 1949). He claimed that "*when an axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased.*" This concept is completely consistent with causality and locality. It clearly states that any signal processing or enhancement is based on time coincidence at the local point. Nevertheless, its profound implication of a stronger constraint to wider brain-wide neural networks has not been thoroughly explored following this finding. We will establish a completely new model of the brain that is 100% consistent with Hebbian plasticity, step by step, throughout the remainder of this paper.

2.3 Top-down vs. Bottom-up: Memory, Prediction, Motion, and Sensing (MePMoS)

Now comes the heart of the resolution. How can the brain reconstruct external space internally, despite the formidable constraint of causality and locality? The solution must rely on utilization of the rhythmic motion of sensors attached to the body. Suppose we were trapped in a completely dark and silent room, then we must find the boundaries (i.e., walls) of the room by moving forward one step at a time, while moving our hands around to sense space. If we touch the wall while our hand moves to the right, then we perceive that the wall is on our right. Even though touch sensors on the skin surface sense only the pressure at that moment as a function of time, the fact that pressure is detected when a hand is at the right indicates that the wall is indeed on the right.

This simple example is the essence of the perception of space. It is fundamentally based on sensory-motor integration. That is, a motion must come first, and sensing comes afterward. Typically, movement is initiated by the memory and prediction that there may be a wall on the right side. Therefore, the exact time sequence must be

Memory → Prediction → Motion → Sensing (MePMoS)

This process that we named **MePMoS** is the most fundamental principle of space perception in the time domain. For this process to be complete, any motional state must first be internalized, so that the brain sends an exact copy of the motor command towards the sensory cortices. Such an internalized copy is called a corollary discharge, or efference copy (Feinberg 1978; Stark & Bridgeman 1983; Crapse & Sommer 2008). Thanks to this internalization, when a sensory neuron receives a stimulus, the incoming bottom-up signal can be directly compared with the top-down prediction in a time domain. If the prediction is satisfied by the time coincidence with the sensory input, then spatial information (that a wall is on the right) can be effectively acquired.

This principle of **MePMoS** is illustrated in **Figure 2-C**, which should be directly compared with the traditional view given in **Figure 2-A**. As shown here, the corollary discharge predicts the incoming sensory signal in a time domain as a coincidence. Therefore, when the sensory signal is detected by the specific sensory neuron at the exact predicted timing, causality and locality are precisely satisfied.

To illustrate this motion-based top-down approach, from now on, we propose to flip the space, or the vertical axis of **Figure 2-C** upside down as shown in **Figure 2-D**. In this figure, we emphasize our inner space (i.e., the brain) as the center of the action, rather than the outer space (i.e., environment). This way, the so-called "top-down" signals of the prediction literally go downward, whereas the "bottom-up" signals from the sensory input go upward. **Figure 2-D** is the essence of our theory, and it will become the critical constraint to construct the entire space-time diagrams for *C. elegans* and humans in the following **Section 3** and **4** respectively.

Figure 2-D by itself gives a profound insight into the general principle of the brain. That is, a brain must predict and simulate possible external environment, before it receives incoming sensory signals (Llinás, 2002). The prediction by the neural networks must come first, whereas sensing comes afterward. This time coincidence between prediction and sensing is the only effective way for the brain to construct and perceive external space, although it is purely represented in the time domain. This diagram of the **MePMoS** strictly satisfies the principles of causality and locality.

2.4 Summary – A New Concept of MePMoS

In this **Section 2**, we argued that the fundamental principle of physics, Causality and Locality, must be imposed strictly at every single synaptic connection. This is such a strong constraint that the traditional view of neuroscience in textbooks must be rewritten by a radically new approach. The critical new concept is that brain is a top-down organization, acting in order of **Memory → Prediction → Motion → Sensing**, which is named **MePMoS**.

It is worth noting that causality and locality were considered a half-century ago by Donald Hebb in the famous concept of Hebbian plasticity (Hebb, 1949). It clearly states that any signal processing and memory is based on time coincidence at a local point. Unfortunately, its implication to wider brain-wide dynamic neural networks has not been explored until now.

One should also note that **MePMoS** is compatible with the Internal Model Principle (Francis & Wonham, 1976), as well as the general concept of top-down models on visual signal processing (Engel, Fries, & Singer, 2001; Gilbert & Li, 2013). What **MePMoS** does is to provide the rigid mathematical and physical foundation for their models. Consequently, it can reveal the exact dynamic connectome of brains, from *C. elegans* to Human.

In the following **Sections 3 and 4**, we will construct the entire dynamic connectome of *C. elegans* brain. Finally, in **Section 5**, we will attempt to build the flowchart of the human brain's dynamic connectome.

3 MePMoS of *C. elegans* Brain by CPG

3.1 MePMoS by CPG for Sensorimotor Integration

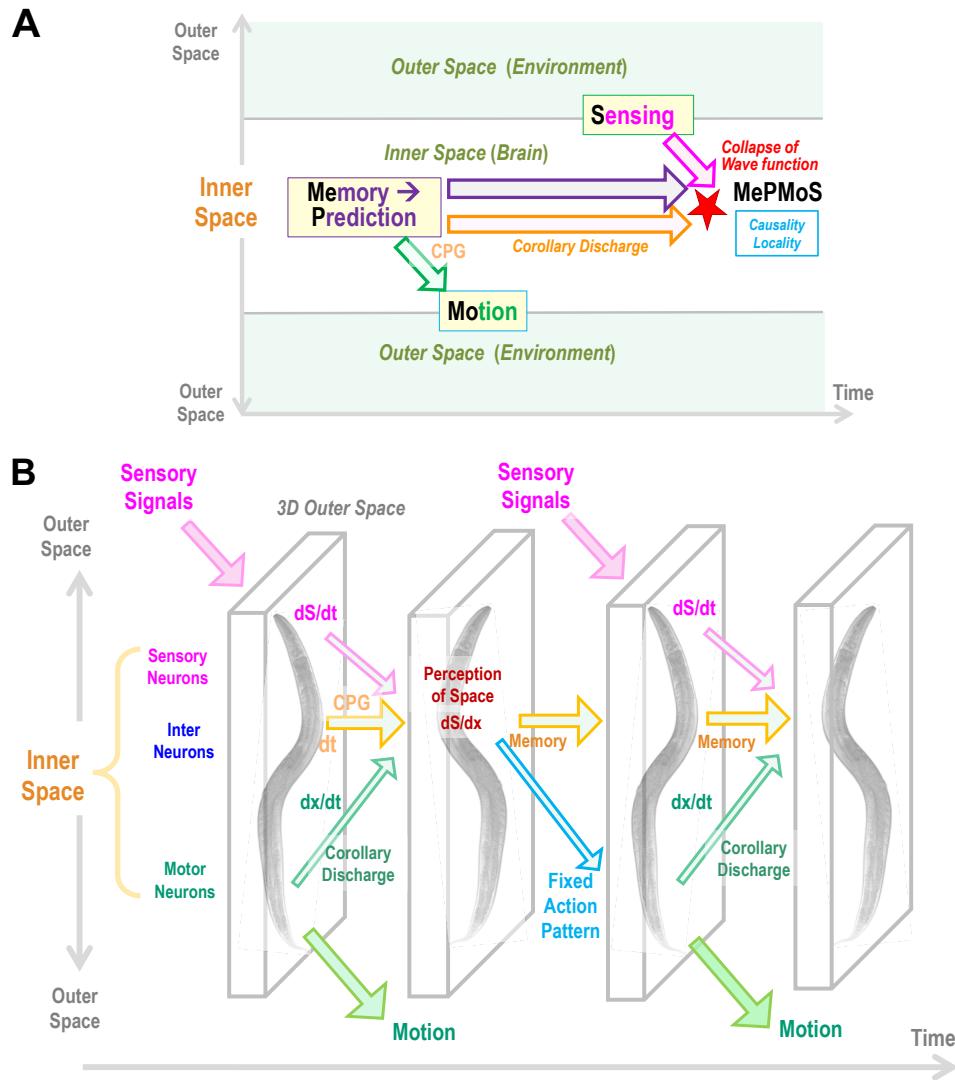


Figure 3. (A) Modified version of **Figure 2-D**. Outer space was split into the sensory side (up) and the motion side (bottom) for convenience. **(B)** 4D space-time diagram of navigation of *C. elegans*, which is consistent with (A) and satisfies causality and locality. The 3D external environment at a given time is represented by a rectangular box where the worm is physically located.

To demonstrate the critical importance of **MePMoS**, let us first consider a tiny round worm, *C. elegans*. *C. elegans*' brain has been extensively studied as the simplest model animal since the initial work by Sidney Brenner (Brenner 1974). It is well-known to have 302 neurons and their complete ~7,000 connections have been examined and established (Ardiel & Rankin, 2010; Bargmann, 2012;

Bargmann & Marder, 2013; Gjorgjieva, Biron, & Haspel, 2014; Rankin 2002; Meneely 2019). The connectome matrix has been kept updated by the Worm Atlas Project (Altun et al. 2021).

It is worth noting that it took one billion years for Eukaryote (single-cell lives) to evolve to the complexity of a creature like *C. elegans* (with 302 neurons). And then, it took another one billion years from that to humans (with 10^{11} neurons). Thus, *C. elegans* represents a stage of animal evolution that is *halfway* to the level of reached in the evolution of the human brain. Therefore, it is natural to consider that, evolutionally, the human brain's basic principle must have originated at the origin of all extant animal phyla that are as sophisticated as *C. elegans*'.

Let us first consider the concept of **MePMoS** in *C. elegans*' brain by investigating its motional states. Under normal conditions, it navigates a given 3D space (= inside of soil) by a snake-like rhythmic motion, searching for food such as *E. coli*. Their motion superficially looks like a snake, but it is based on a dolphin-kick-like vertical swinging (Vidal-Gadea 2011; Karbowksi 2006). To visualize its mechanism of sensory-motor integration, it is essential to illustrate both the motion of a worm (within the external space-time) and the corresponding neuronal network (within the internal space-time) in a 4D space-time diagram.

Let us start with **Figure 2-D**, which shows the process: **Memory** → **Prediction** → **Motion** → **Sensing**. For convenience, one could hypothetically split outer space (environment) to the sensory side (up) and the motion side (bottom), resulting in **Figure 3-A**. Please note that **Figures 2-A** and **3-A** are identical. This is because, in the real life of *C. elegans*, it continuously navigates the given outer space without stopping while constantly sensing the environment. Therefore, we'd better repeat the pattern in **Figure 3-A** again and again, which results in **Figure 3-B**. This space-time diagram also tells us how memory is formed as a consequence of repeated patterns of **MePMoS**: **Memory** → **Prediction** → **Motion** → **Sensing** → **Memory** → ..., which must be the origin of memories. Such an illustration is the first of its kind, strictly following space-time (*Feynman*) diagrams that are widely used in particle physics.

Here, the horizontal axis represents time, and the vertical axis represents 3D space (but expressed only by one dimension, due to the limitation of flat paper). The 3D external environment at a given time is represented by a rectangular box where the worm is physically located. In the case of *C. elegans*, typical physical parameters are: length ~ 1 mm, width ~ 100 μm , speed ~ 0.2 mm/s, Frequency ~ 0.35 Hz, thus Period ~ 3 seconds (Vidal-Gadea 2011; Izquierdo & Beer 2018). That means that the head swings left and right, between one rectangular box to another in **Figure 3-B**, every ~1.5 seconds.

On top of 3D external space (on the order of 1 mm and 1 second), its own internal space (= neural network) is superimposed in this figure. A majority of the neurons are concentrated in the nerve ring (= the central nerve system), within the ~100 μm cube near the neck (Meneely et al. 2019), but in this figure, locations of neurons are ignored for simplicity. When a sensory signal reaches the worm from the top-left corner of the diagram, it is sensed by the appropriate sensory neuron, resulting in a neural activation (change in membrane potential) that propagates to the interneurons. Then the worm must decide to go forward or backward, left or right, in response to the sensory input. Rapid decision-making is essential for survival - however, it requires an immediate internal conversion of signals changing in time at the locations of the sensors, into a sufficiently accurate judgment of the surrounding space.

What is the simplest mechanism for the necessary conversion of signals in time to signals in space? As far as the worm's physical locomotion in space is rhythmic and periodic (*as it is*), the rhythm can be fully exploited as a common clock operating within the neural network. Indeed, animal locomotion is generally rhythmic, including our walking. Such rhythmic movements are known to be generated by the Central Pattern Generator (CPG) (Dimitrijevic 1998; Duysens 1998; Grillner 1998; Marder & Bucher, 2001). If so, rhythmic body swinging by the CPG should be able to produce a predictable, reliable corollary discharge for sensory-motor integration.

Essentially, some internal determination of dt tied to effects of the dx of motion could provide necessary and sufficient quantities for spatial perception via sensorimotor integration. **Figure 3** demonstrates this mechanism precisely- while temporal changes of the sensory signal (dS/dt) are detected by a sensory neuron, the head and body are making a periodic motion (dx/dt), controlled by the CPG (dt). A corollary discharge (or Efference copy) of the motion itself is then fed (*forward in time*) to the inter-neurons, where the sensory signal is received, and thus converted to spatial change of the signal $dS/dx = (dS/dt) / (dx/dt)$. As a result, the external space is perceived by interpreting the change in sensory signal with respect to the organism's own motion to enable proper spatial navigation through Fixed Action Patterns (FAP).

Based on the above logic, we have come to the following hypothesis:

- 1) In any organism, from *C. elegans* to humans, locomotion can be described as a superposition of the well-defined rhythmic motional Eigenstates that act as “Motional Attractors”.
- 2) These motional attractors originate from a corresponding Central Pattern Generator (CPG) within the neural networks, which may be considered an “Attractor Neural Network”.
- 3) External stimulations are detected by sensory neurons only in the time domain (dS/dt). It is combined with Corollary discharge or Efference copies from motor neurons, representing dx/dt .
- 4) Sensory-motor integration then effectively produces internal (neural) representations of external space $dS/dx = (dS/dt) / (dx/dt)$.
- 5) Here, the clock period of the CPG plays a critical role as a discrete unit of time, dt .

To our best knowledge, this is the only model of the neural mechanism behind spatial navigation which strictly follows the requirements of causality and locality. We can consider that this is the simplest mechanism of **MePMoS**, based on predictable, periodic motion.

Furthermore, one could argue that this CPG-based mechanism naturally explains the origin of short-term (working) memory, as shown in **Figure 3**. Following the time axis to the future (right) direction, the decision made at $t = t_0$ can be stored in the network of the interneurons until the next sensory signal arrives at $t = t_0 + dt$, then two sequential signals can be compared. This intriguing possibility of the origin of working memory will be discussed to explain the isothermal behavior of *C. elegans* at the **later Section 4.3**.

3.2 Space-Time Dynamic Connectome of the *C. elegans* Brain

Now we are ready to apply our hypothesis of the CPG-based sensorimotor integration to the actual neural networks of *C. elegans*. As a starting point, let us revise **Figure 3-B**, explicitly in terms of 302 neurons in a column. In the case of *C. elegans*, their inner space composed of 302 neurons can be presented simply as a column vector containing values for each neuron's electrical state at any given time, as shown in **Figure 4-A**. Therefore, a testable mathematical model can be developed relatively easily. Please note that **Figures 3-B** and **4-A** are identical, except that **Figure 4-A** explicitly presents the inner space as a column of 302 neurons in three categories: Sensory neurons, Interneurons, and Motor neurons. Otherwise, the propagation of the signal is the same, from the left to the right. This column of 302 neurons can be regarded as a neural state at a given time, represented as a vector.

The next and the most critical step is the realization of the fact that, from $t = t_0$ to $t = t_0 + dt$, the neural vector, consisting of the column of 302 neurons, is transferred by the connectome matrix, as shown in **Figure 4-B**. This 302 by 302 matrix was established decades ago, and the most updated one is available from Worm Wiring (Altun et al. 2021). Here, chemical synapses are marked red, whereas electric gap junctions are grey. As indicated in **Figure 4-A**, the Corollary discharge from the motor neurons to interneurons is presented clearly as the off-diagonal elements of the matrix, even though these matrix elements are less populated than the elements from the motor neurons to interneurons.

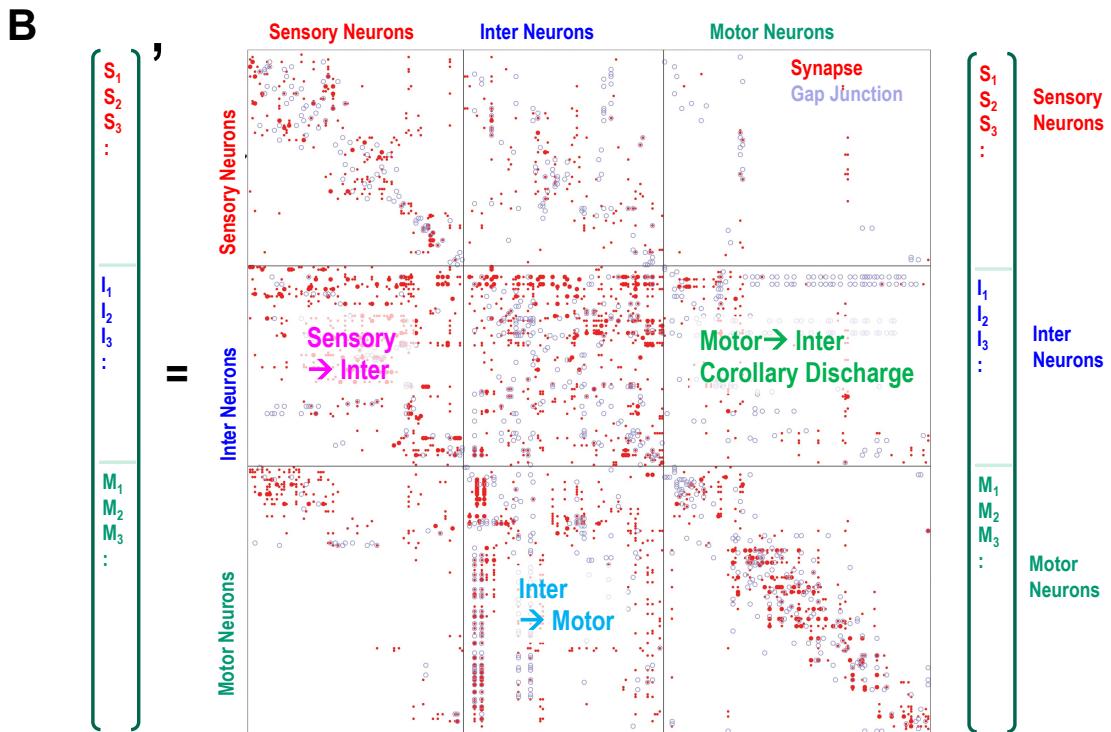
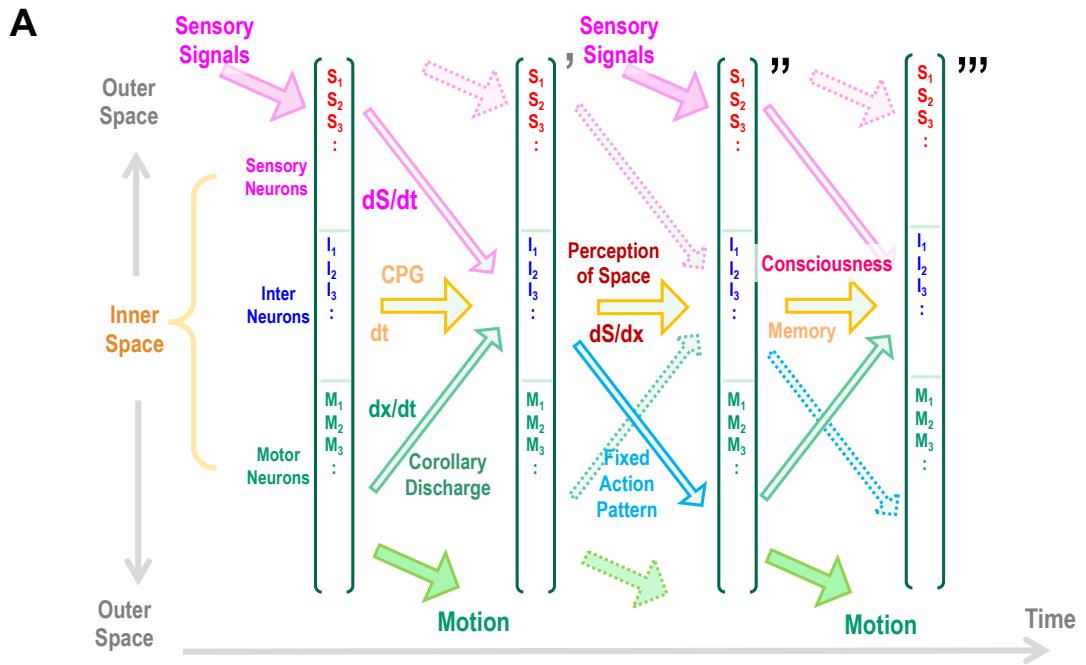


Figure 4. (A) The same diagram as in Figure 3, except that the inner spaces are explicitly presented by a column of 302 neurons. **(B)** The matrix of connectome transfers the inner space presented by the neurons vector, consisting of 302 neurons, from $t = t_0$ to $t' = t_0 + \Delta t$. The connectome matrix is from (Altun et al. 2021), where chemical synapses are marked red, whereas electric gap junctions are marked grey.

The combination of **Figures 4-A** and **4-B** is significant in a sense that it gives an entirely new meaning to the static connectome as a dynamical operator, acting on the vector consisting of 302 neurons. If the neural networks were a linear system, i.e., presented by a 302×302 matrix of numerical values, then we would have a completely predictable solution. By multiplying the matrix to the vector state, the propagation of neural signals could be determined as a function of time.

3.3 CPG Candidates in *C. elegans* – RMD and SMD

Since we are proposing the CPG as the central network for sensorimotor integration, let us review the basic concept and known facts of the CPG in detail. The CPG is a well-established concept, describing various rhythmic motions of diverse animals, including those below:

- 1) Heartbeat (DiFrancesco and Borer 2007)
- 2) Digestive pumping (Trojanowski, Raizen, and Fang-Yen 2016)
- 3) Respiration (Bellingham 1998)
- 4) Walking (Zehr 2005)
- 5) Swimming (Katz and Frost 1995)

Generally, a CPG is defined as a neuronal circuit that produces rhythmic motor patterns without sensory or descending inputs that carry timing information (Gutierrez, O’Leary, and Marder 2013). The simplest CPG can be formed by a pair of neurons mutually connected by inhibitory synapses, as shown in **Figure 4-A**. This so-called half-center oscillator, proposed by (Wang and Rinzel 1992) and discovered by (Gutierrez et al. 2013), appears universal throughout the animal kingdom (E. Marder and Bucher 2001) from leech (Eisenhart 2000; Friesen 2007), lobster (Elson and Selverston 1992) to human (Dimitrijevic 1998).

To date, a CPG in *C. elegans* has been postulated (Dal Santo 1999; Deng and Xu 2014; Karbowski 2006), but popular opinion tends toward the assumption that its lack of discovery proves its non-existence. As such, the topic needs greater exposure; *C. elegans*’ behavior is so intrinsically rhythmic, yet no mechanism to generate such a rhythm has been identified, leaving a void in understanding. Further, CPGs have been discovered in such a variety of higher animals to provide elegant models of rhythmic behaviors; it should be disturbing if *C. elegans*’ primitive neurological ‘base case’ lacks this feature.

To overcome this circumstance, we investigated the entire *C. elegans* connectome (Altun et al. 2021), and were able to uncover the exact pattern of possible CPGs within the motor neurons, RMD and SMD, as shown in **Figure 5**. RMD and SMD consist of three and two pairs of neurons respectively, with each pair consisting of reciprocally connected diagonal elements, which together form the exact structure of the well-established half-center oscillator. These neurons are known to use Acetylcholine as their neurotransmitter, which was conventionally regarded as predominantly excitatory in the *C. elegans* nervous system (Bargmann 1998). However, recent research has unveiled the presence of Ach-gated anion channels, implicating ACh’s function as a broadly inhibitory transmission signal as well (Pereira 2015). Thus, it is feasible to predict potential inhibitory cholinergic connections by examining the neurons expressing these ACh channels. The *C. elegans* nervous system expresses four ACh-gated anion channel species (acc-1 through acc-4) and both acc-1 and acc-2 have been electro-physiologically substantiated as inhibitory receptors. It was found that the acc-1 channel is expressed in a select subset of cholinergic head neurons, particularly the SMD and RMD motor neurons—the culprits of the half-center cross-inhibition network mediating CPG emergence.

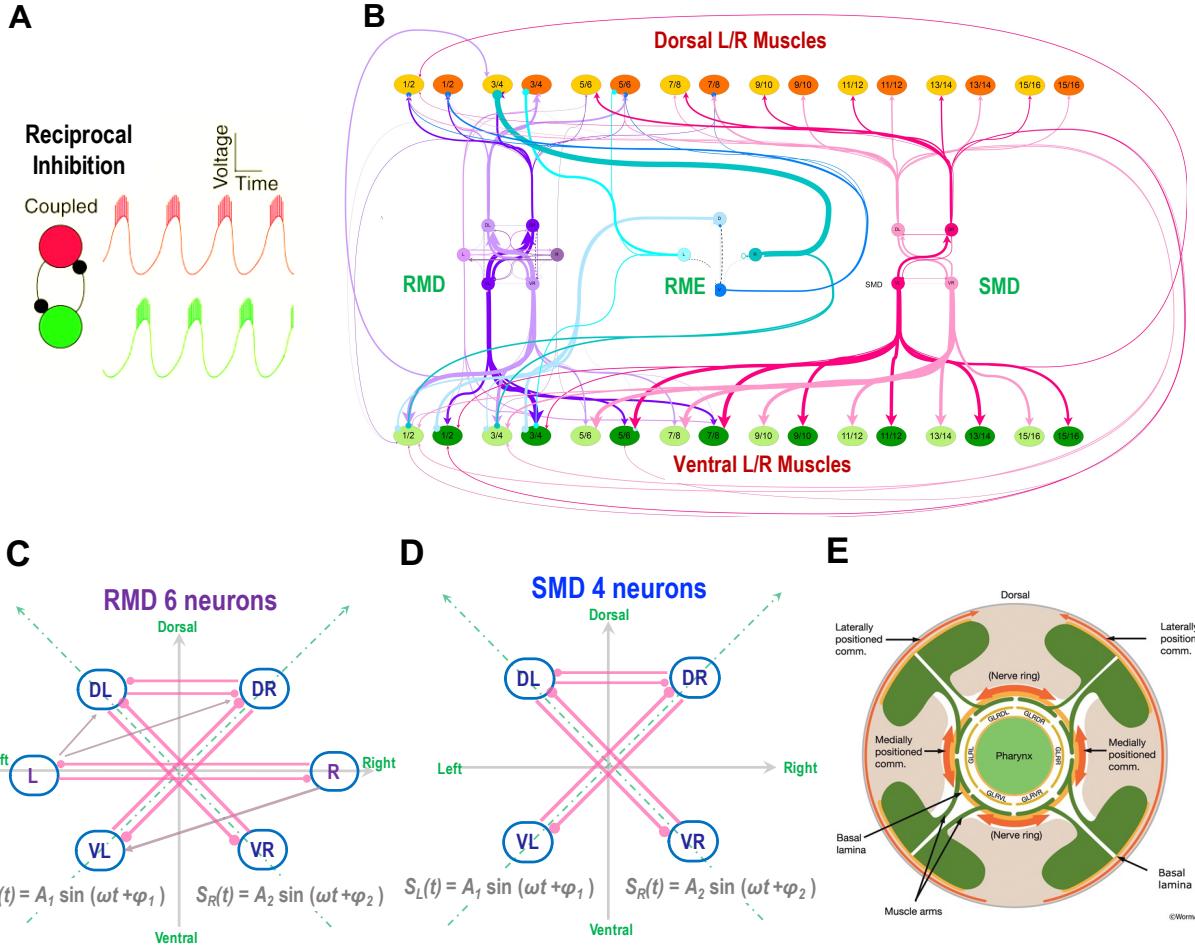


Figure 5. (A) The simplest CPG, composed by a half center oscillator by reciprocal inhibition (Marder & Bucher, 2001). A pair of neurons mutually connected by inhibition forms a CPG. **(B)** The connectome diagram based on the matrix given by (Altun et al. 2021) (prepared by Suying Jin). RMD, RME, SMD are connected to muscles from the head (#1 on the left) down to the mid body (#16 on the right). **(C)** Six neurons of RMD, forming the CPG. **(D)** Four neurons of SMD forming the CPG. D = Dorsal, V = Ventral, L = Left, R = Right. **(E)** Muscular structure of *C. elegans* (Altun et al. 2021).

As already mentioned, CPGs have been recognized as the driving force for rhythmic movements across the animal kingdom. Here we investigate how the proposed CPG, RMD and SMD neurons are expected to drive the locomotion of *C. elegans*. The neuro-muscular connections as well as the muscle structure of *C. elegans* is well understood as given by the Worm Atlas project (Altun et al. 2021). Their body muscles are segmented to four quadrants (DL, DR, VR, VR, where D = Dorsal, V = Ventral, L = Left, R = Right), and then each quadrant is further segmented into 24 sequential units from #1 to #24, from head to tail.

Figure 5-B illustrates the connections from RMD, RME, and SMD to the body muscles. As shown here, 4 neurons of RMD are driving the Muscle #1 – 8, and 4 neurons of SMD are driving the Muscle #1 – 16, out of the entire body covered by the Muscle #1 – 24. This fact indicates that RMD is responsible for the higher frequency oscillations of the tip of the head, while SMD controls the anterior half of the body for forward locomotion (Altun et al. 2021).

It is essential to note the strong diagonal internal connections within RMD and SMD, with only weak connections between the diagonal pairs, as shown in **Figure 5-B**. This structure keeps the opposite sides of muscles appropriately synchronized (muscles on opposite sides of the worm should never be contracted/relaxed at once) in a relax-contract cycle, while leaving the freedom of a phase difference between the diagonal pair cycles which accounts for the different motional states described below.

For simplicity, consider the connection between DR (Dorsal-Right) and VL (Ventral-Left) neurons in SMD, as shown in **Figure 5-D**. The rhythmic oscillation as a CPG can exhibit a sine-wave motion to the DR-VL direction, given by $S_R(t) = A_1 \sin(\omega t + \varphi_1)$. Likewise, a pair of DL (Dorsal-Left) and VR (Ventral-Right) neurons of SMD generate another sine-wave motion of $S_L(t) = A_2 \sin(\omega t + \varphi_2)$ to the orthogonal direction DL-VR. Consequently, in principle, superposition of these two waves can generate three types of locomotion in 3D, depending on their phase difference.

- 1) $\Delta\varphi = \varphi_1 - \varphi_2 = 0$ → Dolphin kick (Dorsal – Ventral oscillation)
- 2) $\Delta\varphi = \varphi_1 - \varphi_2 = \pm \pi/2$ → Helical mode (Corkscrew oscillation with helicity ± 1)
- 3) $\Delta\varphi = \varphi_1 - \varphi_2 = \pm \pi$ → Snake motion (Left – Right oscillation)

This exhibits a strikingly elegant mechanism to perform three distinct locomotion patterns while navigating the natural three-dimensional environment of soil, so that the worm can orient and navigate to any direction.

3.4 RMD and SMD as CPGs for sensorimotor integration

Finally, we will address the heart of this paper, the existing proof of **MePMoS**. So far, we have demonstrated that RMD and SMD are indeed acting as conventional CPGs, i.e., driving force for rhythmic locomotion. Further investigation of the connectome has revealed an amazing fact that, a pair of interneurons, called RIA, are strongly connected to each of the 10 neurons of RMD and SMD, as shown in **Figure 6**. RIA is known as the important second layer neurons which receive the signals from the first later interneurons: AIB, AIY and AIZ. Since these neurons directly receive sensory signals from sensory neurons (shown later in **Figure 8**), it is fair to say that sensory signals are copied onto RIA, and then transferred onto RMD and SMD.

This circuit is made more intriguing by the fact that, RMD and SMD are also sending signals back to the two neurons of RIA (RIAL, RIAR), as shown in **Figure 6**. This is a clear example of Efference copy or Corollary discharge. And these connections are among the strongest in the entire connectome! In other words, these motor neurons are sending copies of motor commands back to RIA, while RIA is sending the sensory signals in time to RMD/SMD. All of them are synchronized, utilizing the RMD/SMD as a universal clock. This exquisitely demonstrates the realization of **MePMoS** even within one of the most primitive brains. As a matter of fact, this could well be the true origin of the brains for multi-celled animals, necessary for goal-oriented spatial navigation.

Why is this process so essential? It is because, through this process, temporal sensory information can be converted to spatial information – that is the origin of perception of space. Let's go back to **Figure 3** to make this point clear. At $t = 0$ (left side), a head is left and a sensory signal comes in time. When this signal comes into the inter neuron RIA, it does not carry any spatial information whether the head was left or right. It is the SMD and RMD that assign the special information (= left) to the RIA.

In conclusion, RMD and SMD as CPGs provide the information of head location for the incoming sensory signal from RIA. This is the heart of our proposed **MePMoS** essential for perception of space, conducted by CPG-based sensorimotor integration.

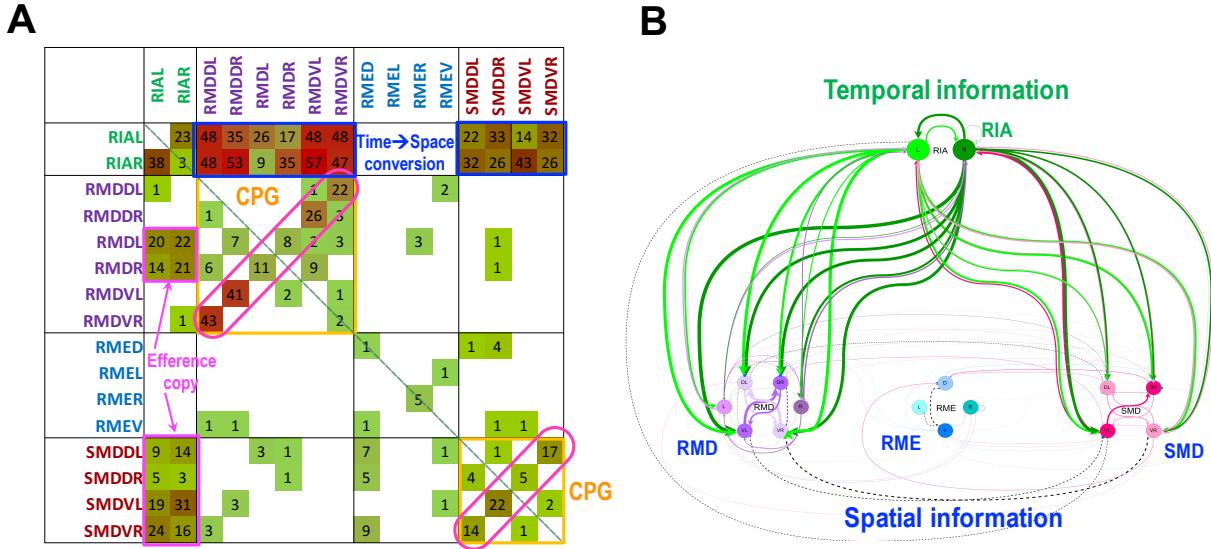


Figure 6. (A) The central marix of the connectome (Altun et al. 2021) responsible for sensorimotor integration. (B) The temporal signals from sensory neurons are received by the RIA neurons, then transferred to six neurons of RMD and four neurons of SMD in parallel. RMD and SMD are the CPG, and their rhythmic patterns are sent back to RIA for synchronization as an efference copy. This mutual communication between RIA \leftrightarrow RMD, SMD is the heart of **MePMoS**. (The diagram is prepared by Suying Jin.)

3.5 Summary – MePMoS of *C. elegans* by CPG

C. elegans is one of the most well-studied model animals. Its brain consists of only 302 neurons, and its connectome has been extensively studied for four decades. However, its sensorimotor integration for navigation was poorly understood due to a lack of the first principle from physics. In this Section 3, we imposed the new concept of **MePMoS** and successfully identified the CPGs: RMD and SMD. By their rhythmical motion, incoming sensory signals in time are effectively converted to spatial information.

This demonstrates that causality and locality, the foundation of **MePMoS**, is a critical requirement even for the simplest neural networks. It certainly makes sense because the primary purpose of brains is to navigate the space to the right direction. For the first animals with brains, it must have been a daunting task since any single neuron could not perceive space by itself.

4 Dynamic Connectome and Behaviors of *C. elegans*

4.1 Derivation of the Complete Dynamic Connectome

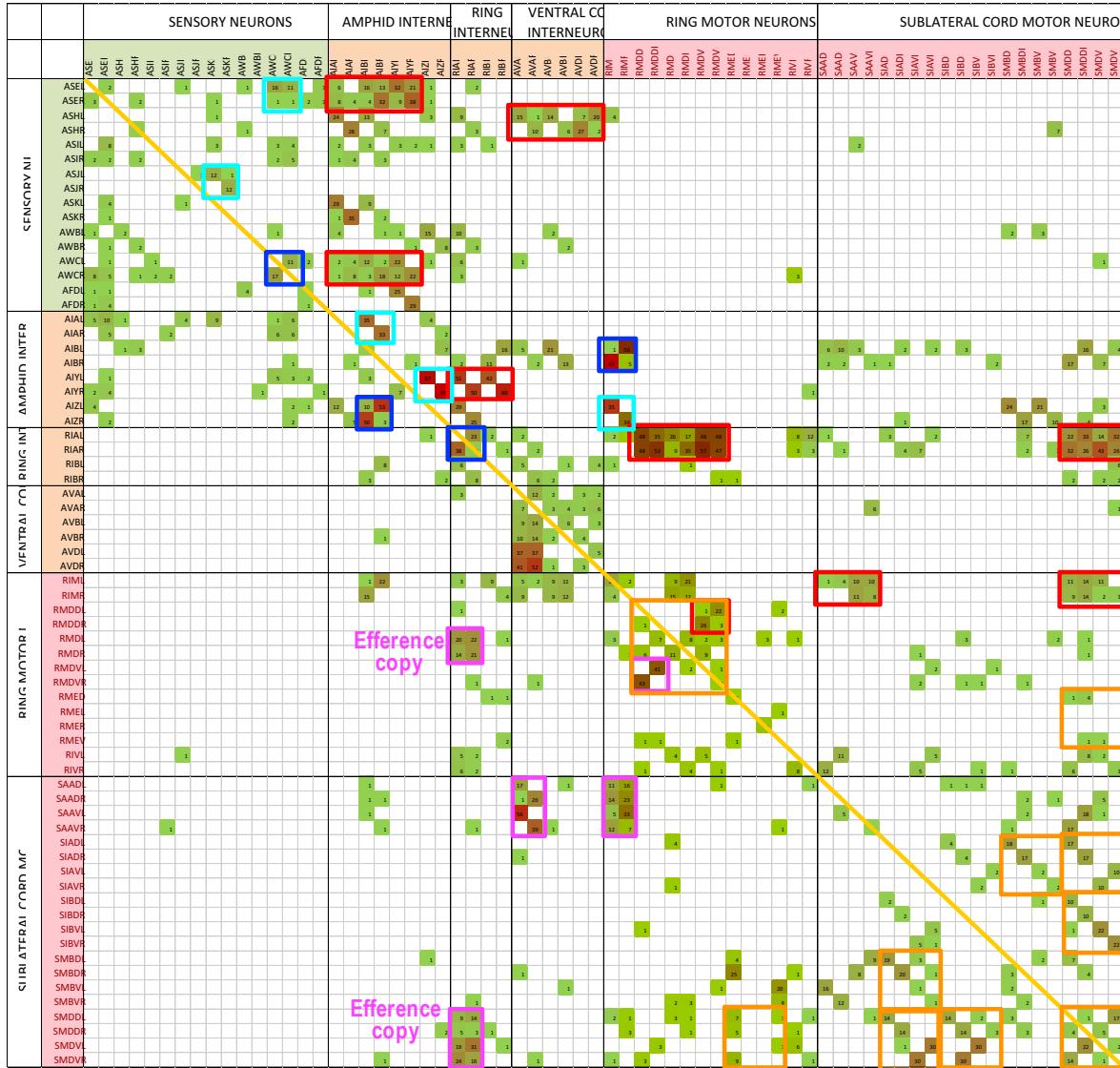


Figure 7. The connectome matrix (164 x 164) that is responsible of sensorimotor integration (Altun et al. 2021). This matrix shows the primary inputs to construct the complete functional connectome in **Figure 8-A** (prepared by Suying Jin.)

Since the central neural network of sensorimotor integration has been established based on the CPGs at SMD and RMD, extracting the complete dynamical connectome is well in order. The starting point is **Figure 7**, which is a partial connectome matrix among 164×164 neurons, extracted from (Altun et al. 2021). This matrix includes all the sensory, motor, and inter neurons which are related to sensorimotor integration.

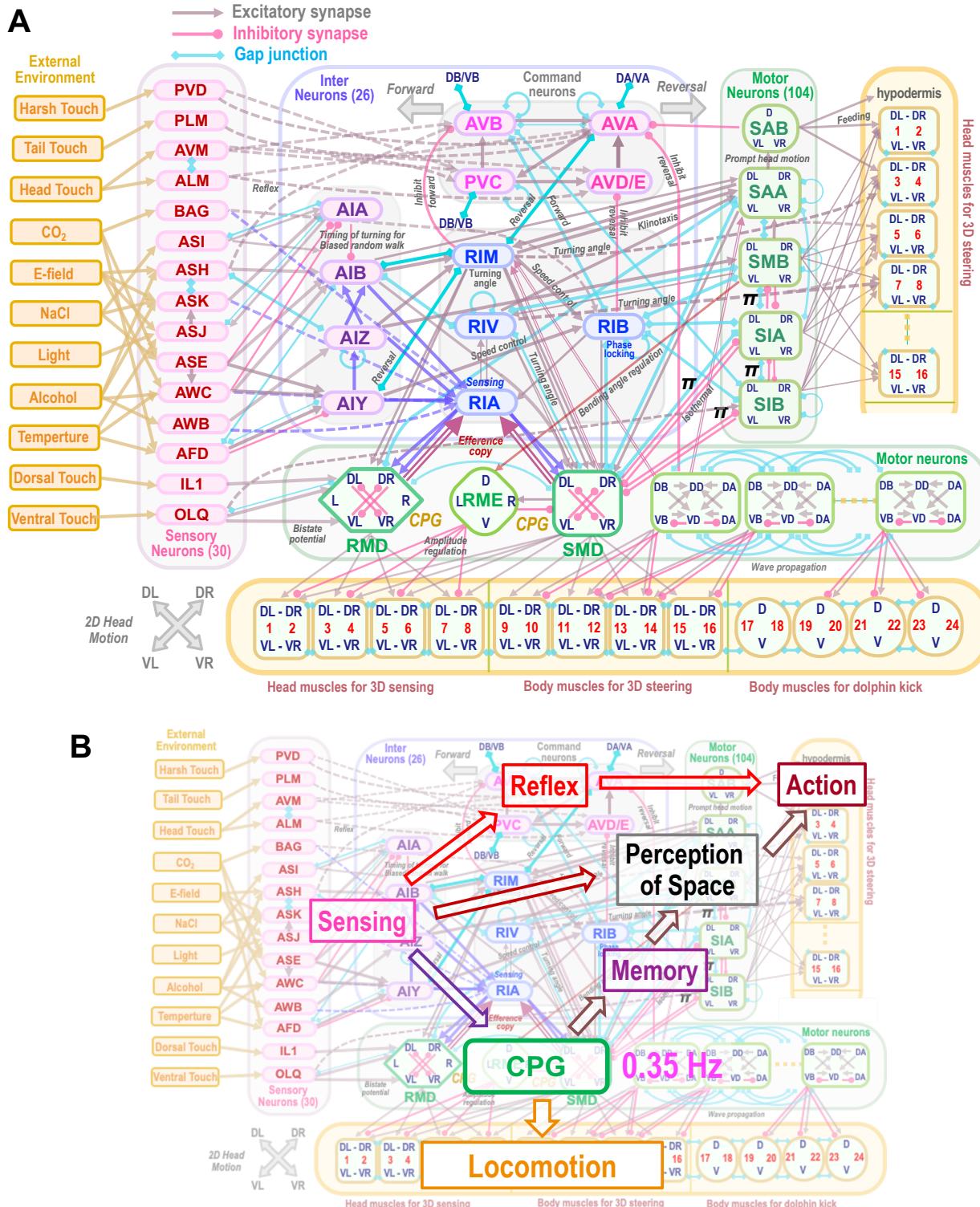


Figure 8. (A) The complete dynamic connectome of neural networks of *C. elegans*. This diagram includes all 164 neurons (out of 302 total neurons) which are responsible of behavior in the 3D environment. This diagram is derived from and consistent with the matrix in **Figure 7**. **(B)** The flow chart of signal propagation in the functional connectome of *C. elegans*, superimposed on top of (A). The CPG holds critical functionality in sensory-motor integration, besides its original purpose to generate and regulate rhythmic locomotion.

After extensive investigation of the structure of this matrix as well as hundreds of past publications, by strictly applying the top-down concept of **MePMoS**, we were able to construct the complete functional dynamic connectome shown in **Figure 8-A**. This diagram includes 164 neurons (out of 302 total) which are responsible for various types of behavior in the 3D environment. Among them, 30 are sensory neurons, 26 are interneurons, and 104 are motor neurons. **Figure 8-B** is an overall flow chart of signal propagation within **Figure 8-A**. As demonstrated here, the CPGs (RMD and SMD) have the critical function for sensorimotor integration, besides producing rhythmic locomotion. Generally, signals propagate from left (and top) to the right (and bottom), following the concept of the space-time diagram in **Figures 3** and **4-A**.

Please note that, to the best of our knowledge, this diagram is consistent with all partial networks given in hundreds of past *C. elegans* publications (Altun et al. 2021). Furthermore, it is the first diagram to describe the complete functional connectome of *any animal*, capable of explaining the fundamental principle of spatial navigation, from sensory stimulation to decision making through sensorimotor integration. The detailed functions of this diagram will be given in the subsequent **Sections 4.2** and **4.3**. Here we highlight the significant features of the diagram in **Figure 8** briefly.

- 1) The overall flowchart of the signal pathways is given in **Figure 8-B**. Generally, signals propagate from left (and top) to the right (and bottom), following the concept of the space-time diagram in **Figures 3** and **4-A**. Strictly speaking, all the signals are supposed to propagate from left to right to satisfy causality. However, a few exceptions exist around RIA and RIM where the corollary discharges from the CPGs (RMD and SMD) feedback to them.
- 2) Chemical synapses are divided into excitatory ones (gray arrows) and inhibitory ones (pink lines), mostly based on our assumptions. This distinction is deducted by considering the required functions at specific individual connections, case by case. However, it has not been proven experimentally for almost all cases. In addition, gap junctions (cyan lines) are added.
- 3) AIA, AIB, AIZ, and AIY (two neurons each: Left and Right) form the first layer of inter neurons. They directly receive sensory inputs from the sensory neurons. During the biased random walk, the turning frequency is determined by AIA – AIB.
- 4) Each of AIY, AIZ and AIB has two outputs for two distinct functions: One is connected to RIB for changing the turning angle immediately. The other is connected to RIA for sensorimotor integration for later use.
- 5) RMD and SMD consist of six and four neurons respectively, and they form the CPG, as a half center oscillator with reciprocal inhibition. A typical clock frequency of SMD is 0.35 Hz, corresponding to regular locomotion. Its amplitude is regulated by RME via inhibitory synapse. A typical clock frequency of RMD is faster, at about 1 Hz, corresponding to the head swing for searching local food.
- 6) A pair of RIA neurons are connected to all the neurons in RMD and SMD, and vice versa. This is the central part of the sensorimotor integration. These neurons are synchronized and phase-locked by the RMD and SMD as a universal clock.
- 7) Muscles consist of four quadrants (DL, DR, VL, VR), and these are further divided into 24 sections from # 1 to # 24. To simplify the diagram, The head muscles (#1 - #8) are duplicated on the right side. All these muscle neurons are driven by several types of motor neurons.
 - a) RMD (as CPG): Muscle # 1 – 8 (Head)
 - b) SMD (as CPG): Muscle # 1 – 16 (Head and mid body)
 - c) SMB, SIA, SIB (as CPG): Muscle # 1 – 16 (Head and mid body)
 - d) SAB: Muscle # 1 – 2 (Head tip)
 - e) DBn, DDn, DAn: Muscle # 9 – 24 (Mid and body and tail)

- 8) The networks for the avoidance reflex are located at the top part of the diagram, by directly connecting sensory neurons to key interneurons for reversal (AVA, AVD/E), or for forward (AVB, PVC) movement. See **Figure 9-A**. For example, four types of avoidance response by reversal movement are given by:
- Harsh touch: PVD → AVA
 - Head touch: ALM → AVD/R → AVA
 - Heat: AFD → AIY ↔ RIM ↔ AVA
 - UV Light: ASJ → ASK ↔ ASH → AIB ↔ RIM ↔ AVA
- (Here →: chemical synapse, ↔: electric gap junction)
- 9) For more sophisticated navigation such as thermotaxis, sensory signals are transferred to AIY → AIZ → AIB. All of them (AIY, AIZ, AIB) have chemical synapses to RIA. Temporal signals at RIA are converted to spatial information at RMD and SMD. The mutual communication between RIA and RMD/SMD is the essence of sensorimotor integration. Klinotaxis use a similar mechanism as isothermal behavior.
- 10) RIB is acting as a hub of gap junctions to establish a common potential at relevant neurons. It is connected via gap junctions to RIA ↔ SMD, SIA, SIB, SMB, and AVB. The analog potential level represents the speed of forward motion, which is modulated via chemical synapse from AIY and RIB.
- 11) RIM (and RIV to some extent) determines the large turning angle, including Omega turn.
- 12) The network of SMD – SIB – SIA – SMB forms a larger-scale network of CPG, acting together. All these motor neurons drive Muscle # 1 – 16 directly. This network also acts as a working memory which is necessary for isothermal behavior.

4.2 Five types of *C. elegans*' Behaviors

The network diagram in **Figure 8** is specifically constructed to explicate observed *C. elegans* behavior in a unified manner via specific signal paths, on a case-by-case basis. These behaviors can be categorized to five types as shown in **Figure 9**, enumerated in order of increasing complexity. These are

- 1) Avoidance reflex: **Figure 9-A** (Rankin 2002; Crapse and Sommer 2008)
- 2) Feeding: **Figure 9-B** (Altun et al. 2021)
- 3) Biased random walk: **Figure 9-C** (Gray, Hill, and Bargmann 2005)
- 4) Klinotaxis: **Figure 9-D** (Ward 1973)
- 5) Isothermal behavior: **Figure 9-E** (Hedgecock and Russell 1975; Luo et al. 2006)

To begin with, **Figure 9-A** exhibits the avoidance reflex. It can be triggered by a harsh touch, head touch, light, or heat, which stimulate the sensory neurons of PVD, ALM, ASJ, or AFD, respectively. These are linked to the AVA motor-command neurons, which immediately retract the body backward. Please note that AVA receives the inhibitory signals from the motor neurons (DB/DD, VB/VD) for forward motion. Thus, the avoidance reflex is suppressed if head touch is caused by its own forward motion by approaching a stationary wall. This should be considered as the most primitive type of sensorimotor integration.

In the case of feeding, shown in **Figure 9-B**, attractants, such as NaCl and temperature associated with food's location, trigger ASE or AWC/AFD, then excitatory signals are propagated to the first layer of interneurons, AIB/AIZ/AIY, then further go to RIM that determines the running angle, then finally motor neurons SAA/SAB for the prompt head motion for feeding (Altun et al. 2021).

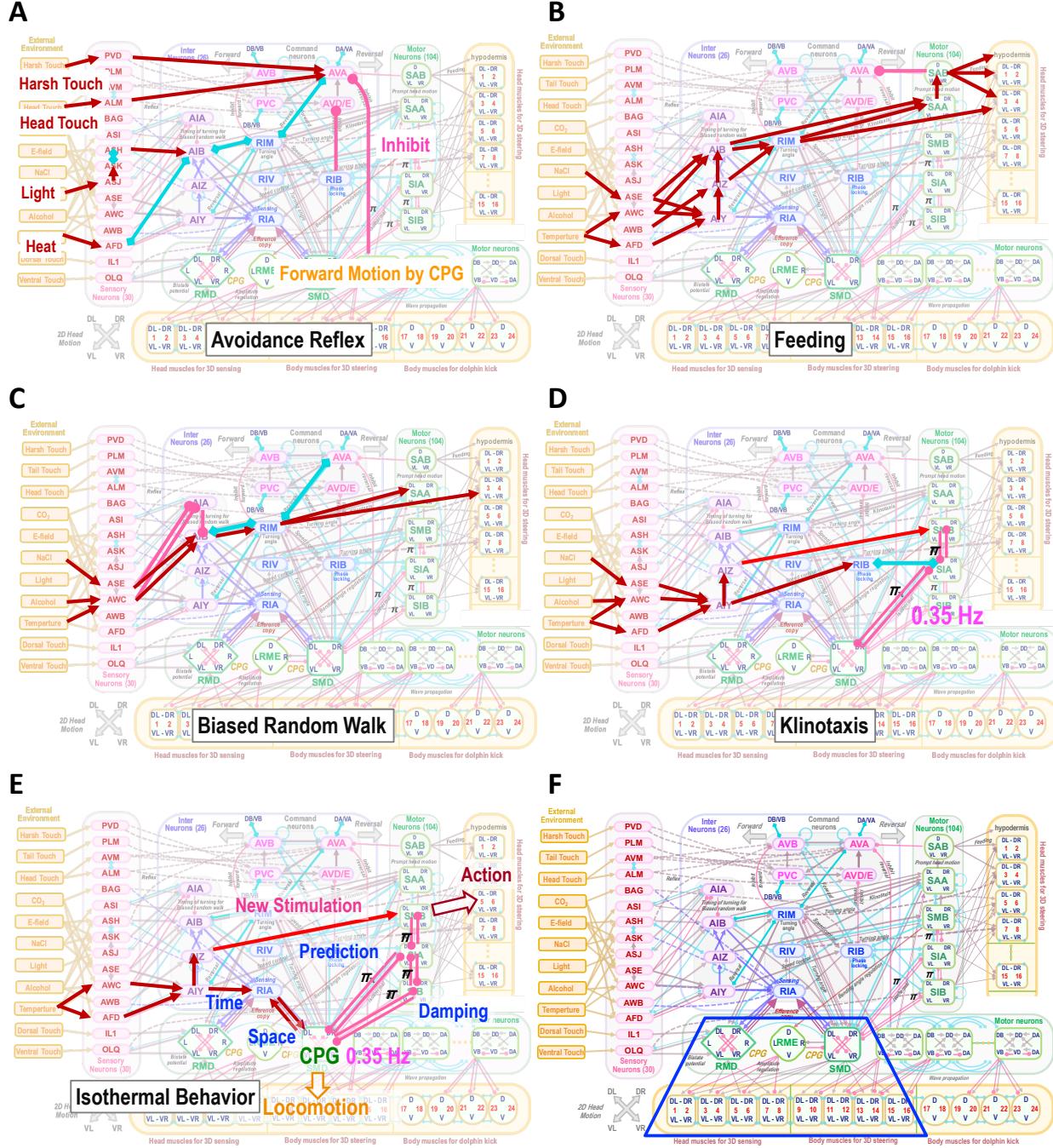


Figure 9. The signal flow of the five different types of behavior, from the most primitive to more complex ones. **(A)** Avoidance reflex, triggered by four kinds of stimulation: harsh touch, head touch, Light, and Heat. Also shown here is the inhibitory signal from forward motor neurons to AVA. **(B)** Attraction to food and the feeding behavior to bite food. **(C)** Biased random walk for three types of stimulations: NaCl, Alcohol, and temperature gradient. **(D)** Klinotaxis for the chemical gradient. **(E)** Isothermal behavior that requires sensory-motor integration by MePMoS. **(F)** The Trapezoid shows the CPG (RMD, SMD), which drives head/body muscles.

Figure 9-C shows the pathway for the biased random walk, which has been well studied in the cases of salt, alcohol, and temperature gradients (Gray et al. 2005). These stimulations are received by ASE, AWC, AFD respectively, then go to the interneurons, AIY and AIZ, where AIZ monitors the temporal change of the sensory signals. If a good signal (= a hint of foods) is increasing, then the head/body rotation is suppressed. On the other hand, if it is decreasing, the head/body rotates more frequently.

One should however keep in mind that the behavior of single-cell life like *E. coli*, has been studied and shown to be capable of performing almost all the behaviors listed above: (1) avoidance reflex (Chalfie et al. 1985), (2) feeding, and (3) biased random walk (Hill and Häder 1997). Therefore, these three types of behaviors do not really require a brain with multiple neurons.

So why did *C. elegans* evolve a brain? Let us consider a smooth curved navigation, so-called klinotaxis in **Figure 9-D**. Assume that a worm is looking for food, like *E. coli*, which is associated with a specific salt (NaCl) concentration. Let's further assume that *E. coli* is localized in the left-forward direction relative to the worm. When the worm swings its head to the left, the NaCl sensitive sensory neuron (ASE) is going to flash in time (Luo et al., 2014). Then, this sensory signal is subsequently forwarded to the interneuron, RIA. Thanks to the mutual connection between RIA and RMD/SMD, the flashing signal at RIA in time is transferred to RMD/SMD (i.e., the CPG). Since it happens when the head is on the left side, controlled by RMD/SMD, this timing signal is effectively converted to the spatial information that NaCl, as a result of *E. Coli*'s presence, is on the left side. As a result, the worm turns its head/body direction toward the left successfully, exhibiting the behavior known as klinotaxis (Pierce-Shimomura 2005; Pierce-Shimomura 1999). This process illustrates the essence of the **MePMoS** concept.

Nevertheless, one should note that klinotaxis has been discovered by certain types of bacteria as well (Thar and Kühl 2003). What is remarkable is that the electric membrane potential on the surface of bacteria is rotating at a constant angular velocity, like a CPG-based rhythmic motion of multi-celled organisms. As a result, even single-celled bacteria (without a brain) can effectively achieve the sensory-motor integration of **MePMoS**.

If that is the case, why did *C. elegans* have to evolve its tiny brain? We argue that the driving force of emergence of the brain was (5) isothermal behavior in **Figure 9-E**, which is very specific and peculiar to *C. elegans*. (Hedgecock and Russell 1975 ; Luo et al. 2006).

4.3 Isothermal behavior – Perception of space by the CPG

To understand evolutionary neurodevelopment, the isothermal behavior of *C. elegans* is essential. Furthermore, it should provide an ideal opportunity to recognize why and how brains evolved in animals by comparing the specific neural circuit for isothermal behavior with other primitive behaviors such as biased random walk. As a matter of fact, the underlying neural circuit for isothermal behavior is likely to be among the first instantiation of **MePMoS** in animal evolution.

C. elegans' natural search for food occurs in a dark, soil environment. In addition to chemical cues, the surrounding thermal environment also aids *C. elegans* in navigation towards abundant food sources. They have evolved the capability to detect extremely shallow temperature gradients. Here are some key facts exacted from previous publications (Hedgecock 1975; Luo 2006; Luo 2014; Mori 2007; Ramot 2008; Ryu 2002; Clark 2007; Clark 2006; Russell 2014).

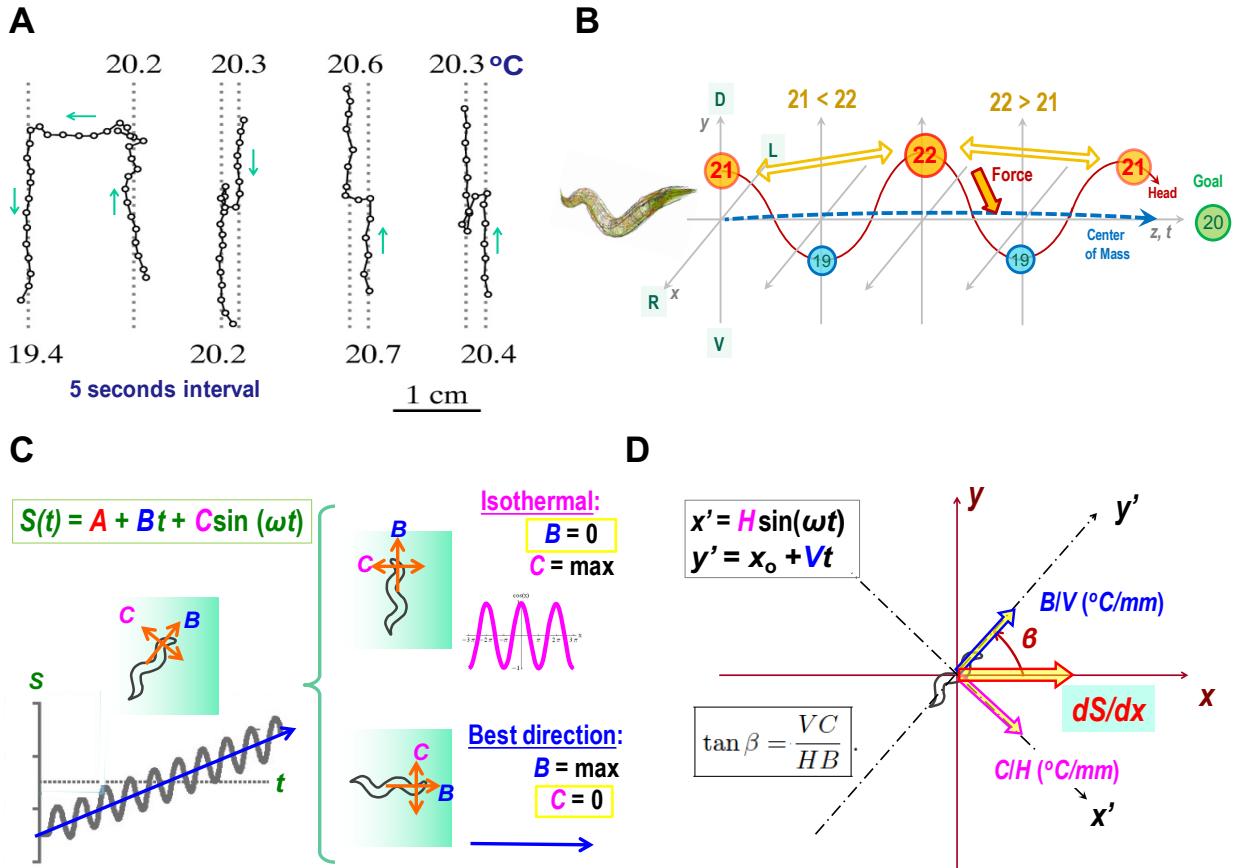


Figure 10. (A) Examples of isothermal behavior from (Luo et al. 2006). Note that after about a minute of isothermal trajectory, worms tend to make 90° turns towards negative temperatures. (B) illustrates how temperature is measured and memorized for one period during isothermal behavior. (C) Temperature (S) is measured by the AFD neuron as a function of time, when it is moving towards higher temperature. Here the gradual pattern of background green shows the temperature gradient. Temperature is given by $S(t) = A + Bt + C \sin(\omega t)$. Isothermal condition is given by $B = 0$, $C = \text{max}$. When it moves to the best direction (either during negative or positive thermotaxis), the condition is given by $B = \text{max}$, $C = 0$. (D) If a worm moves in the direction with the bearing angle β , along the y' -axis, then the head motion is given by $x' = H \sin(\omega t)$ with $y' = x_0 + Vt$. The temperature gradient is given by $B/V (\text{°C/mm})$ along y' -axis, and $C/H (\text{°C/mm})$ along x -axis. Then the bearing angle β satisfies $\tan(\beta) = VC/HB$.

- 1) The preferred, genetically-encoded temperature of wild-type *C. elegans* (N2) is 20 °C.
- 2) Temperature preference can be overridden by culturing *C. elegans* with food sources located at a different temperature over a period of a few hours.
- 3) Negative thermotactic behavior is exhibited when starved worms are placed at higher temperatures.
- 4) Likewise, worms placed at low temperatures without food demonstrate positive thermotaxis.
- 5) *C. elegans*' absolute thermal specificity holds an accuracy of ± 0.5 °C.
- 6) Isothermal behavior is achieved when worms reach within ± 0.5 °C of a memorized temperature range.
- 7) Once isothermal behavior occurs, they will stay within ± 0.05 °C of the memorized temperature.

Figure 10-A shows this extraordinary isothermal behavior reported by the Samuel Lab (Luo et al. 2006), observed on a 0.5 °C/cm linear temperature gradient. Please note that, after about a minute of isothermal linear trajectory within ± 0.05 °C, a worm tends to make an exact 90° turn (towards the lower temperature direction), making a striking grid pattern. This is the most deterministic pattern of all the reported *C. elegans* behaviors.

Why is this isothermal behavior so significant and intriguing? Let us consider the simplified example shown in **Figure 10-B**. Here, we assume that a worm is moving to the right (z -axis), by swinging its head up and down along the vertical direction (y -axis). Consider a linear temperature gradient along the y -direction, with a constant temperature of 20 °C on the x - z plane at $y = 0$ and assume that the worm's vertical head swing produces a temperature of 21 °C (up) and 19 °C (down) at the location of the thermo-sensory structure AFD.

During ideal isothermal conditions, the head senses a temperature of 21 °C (up), 20 °C (center), 19 °C (down), 20 °C (center), 21 °C (up) and so forth. It was established that the AFD neuron can only sense temperatures above its cultivation temperature (20 °C in this case) but can do so with great accuracy (Luo et al. 2006). This means that AFD can only register the 21 °C measurement as the head oscillates.

To achieve ideal isothermal behavior, the brain must remember the temperature from one cycle ago, and accurately compare it with the next cycle. If the temperature at the next cycle is higher, say 22 °C in **Figure 10-B**, then $22 - 21 = +1$ °C must be identified, resulting in a re-orientation of the worm's trajectory downward. The complication to the problem is that AFD only senses the temperature as a function of time without an internal awareness of the temperature sensor's absolute location. This is the crux of sensorimotor integration; the worm itself must know its own head location (up or down) at any given time during the temperature sensing cycle, and it should be able to do so within ± 0.05 °C.

Figure 10-C is another way to look at the required conditions of isothermal behavior from a mathematical point of view. If a worm is moving towards a higher temperature with the bearing angle β , then temperature (S) is measured by the AFD neuron as a function of time, given by $S(t) = A + Bt + C \sin(\omega t)$. Note that $\beta = 0$ ° is defined as the correct direction for thermotactic foraging, and $\beta = 180$ ° is the opposite direction. Here the gradual pattern of background green shows the temperature gradient. The Isothermal condition is given by $B = 0$, $C = \text{max}$. When it moves in the best direction (either during negative or positive thermotaxis), the condition is given by $B = \text{max}$, $C = 0$.

Figure 10-D shows the case when a worm moves in the direction with the bearing angle β along the y' -axis. Then the head motion is given by $x' = H \sin(\omega t)$ with $y' = x_0 + Vt$. Interestingly enough, the temperature gradient is given by B/V (°C/mm) along the y' -axis, and C/H (°C/mm) along the x' -axis. Then the bearing angle β satisfies $\tan(\beta) = VC/HB$. Obviously, from a mathematical point of view, isothermal behavior (i.e. bearing angle $\beta = \pm 90$ °) and 90° turn (to the bearing angle $\beta = 0$) presents a daunting mathematical task for the tiny brain of *C. elegans*; it requires not only the precise measurement of the temperature terms B and C (in unit of °C), but also the amplitude of the head H (in mm) and the speed V (in mm/s) must be conceived and taken into account by the interneuron networks. Certainly, it necessitates meticulous sensorimotor integration.

The above argument tells us the fundamental necessity of internal perception of the exact head location in 2D space represented by (H, V) as a function of time. Obviously, these quantities, (H, V) , are controlled by the motor neurons SMD/RMD as CPG. Therefore, the sensorimotor integration between these CPG and sensory neurons AFD → AIY → RIA by **MePMoS**, shown in **Figure 6**, plays a critical role in the isothermal navigation.

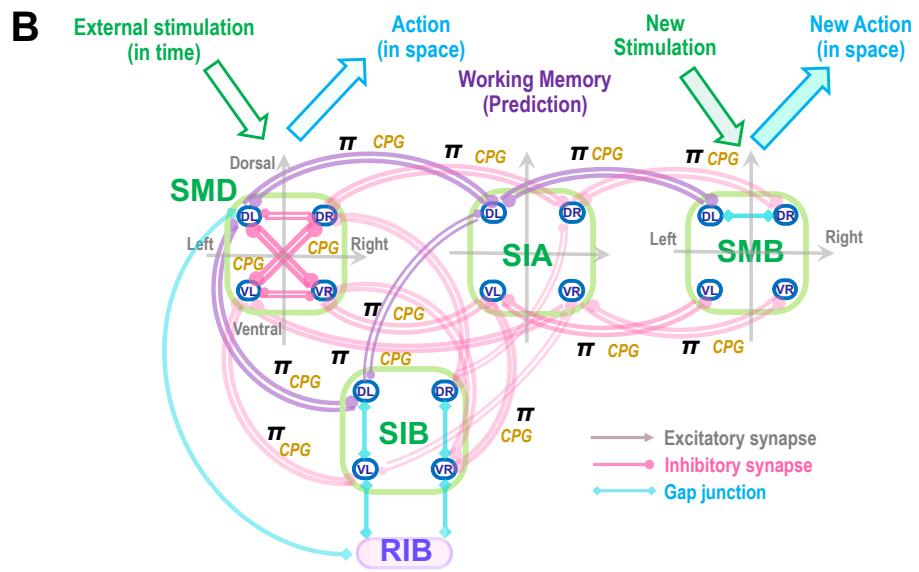
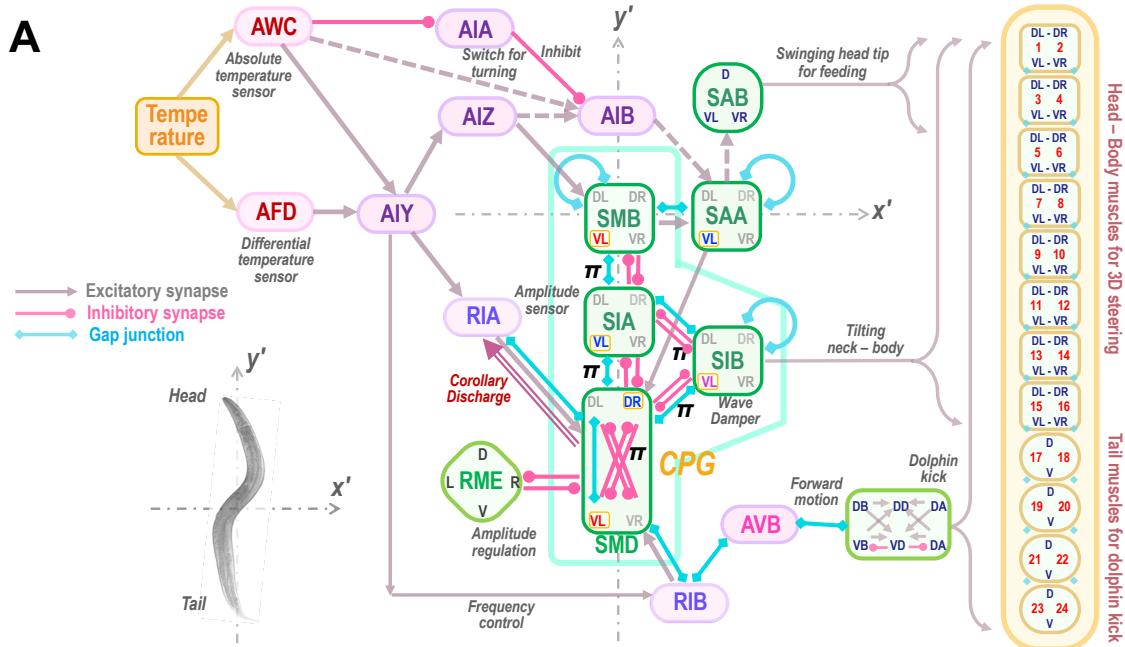


Figure 11. (A) A possible exact neural network for isothermal behavior. For isothermal behavior, the slightly higher temperature (even above 0.05 °C of the threshold) increases the graded potential. It is copied onto AIY → RIA → SMD, then to the CPG network of SMD – SIB – SIA – SMB. **(B)** The complete dynamic connectome between SMD, SIA, SMB and SIB, is deduced from the matrix in **Figure 7**.

Figure 11-A (which is a part of **Figure 8-A**) is a possible exact neural network responsible for isothermal behavior. Initially, the temperature is detected by the sensory neurons, AWC and AFD; AWC measures the absolute temperature, whereas AFD measures the differential temperature above the threshold. For the isothermal behavior, the slightly higher temperature (even 0.05 °C above the threshold) increases the graded potential. Then, it is copied onto AIY → RIA → SMD. As we discussed,

SMD is a CPG and sense back the efference copy to RIA. Thus, the slightly higher temperature, sensed as a function of time is effectively converted to spatial information, depending on the head direction at the same time of sensing. Then the graded potential is fed into the CPG network of SMD – SIB – SIA – SMB. The exact diagram of this CPG network is given in **Figure 11-B** (which is a part of **Figure 11-A**.)

To achieve isothermal behavior, the temperatures must be compared at every cycle of the head swing. The initial temperature is fed into SMD, and it will propagate through SMD → SIA → SMB. After one cycle of the head swing (left → right → left), the initial temperature has arrived at SMB. At this time, the new temperature will be fed into AIY → AIZ → SMB. Then, SMD works as a comparator to see the difference between the old and new temperatures; if the new temperature is higher, the head swings to the left. But if the new temperature is lower, the head swings to the right.

The above argument brings us to an intriguing speculation that this neural network of SMD → SIA → SMB may be at the very origin of working memory, which is defined by a neural function that keeps a small amount of information for a short time. If so, what is the purpose of SIB? The diagram in **Figure 11-B** shows that SIB receives the signal from SMD and SMB with a flipped phase of π . As a result, their signals cancel each other out, suggesting that SIB effectively acts as a wave damper. Such quick damping of ongoing oscillatory signals seems essential to updating the observed temperature in working memory.

Later in **Part IV**, the underlying principle of the Hippocampal network will be examined extensively. The hippocampus processes spatial information through navigation via CA3 → CA2 → CA1, and it is essential to form a new episodic memory. The simple structure and function of SMD → SIA/SIB → SMB in *C. elegans* appears strikingly similar to rodents' Hippocampus: CA3 → CA2 → CA1. If so, CA2 (whose function is poorly understood) may be acting as a wave damper analogous to SIB in *C. elegans*. If this analogy has some truth, then one could argue that SMD → SIA/SIB → SMB in the worm's brain could be the evolutionarily earliest example of the type of circuit that the Hippocampus also evolved to be. We will revisit this speculation in **Part IV** and **Part VI**.

The other aspect of SMD → SIA/SIB → SMB is their mutual connection as a CPG network, shown in **Figure 11-B**. If one keeps expanding such a CPG network to make a long chain, the oscillation could propagate smoothly through numerous CPG neurons. Such a propagation of continuous oscillation is known as a traveling wave, which must be the origin of brainwaves. This concept of traveling brainwaves becomes the focal point of the Grand Unified Theory in the next **Part II**.

4.4 Summary – Sensorimotor Integration for *C. elegans* Navigation

Through **Section 4**, we have constructed and investigated the functional connectome of *C. elegans*' brain. As one of the simplest animals with a tiny brain of 302 neurons, it exhibits remarkable navigation principles: from the avoidance reflex to feeding, biased random walk, klinotaxis, and lastly, isothermal behavior (**Figure 9**). The critical point is that its neural network for all these types of navigation satisfies causality and locality, and it faithfully follows the **MePMoS** model. This fact is most prominent in the extraordinary case of isothermal navigation.

At the beginning of **Section 2.3** in the introduction to **MePMoS**, our navigation in a completely dark room was explained below:

"Suppose we were trapped in a completely dark and silent room, then we must find the boundaries (i.e., walls) of the room by moving forward one step at a time, while moving our hands around to sense space. If we touch the wall while our hand moves to the right, then we perceive that the wall is on our right. Even though touch sensors on the skin surface sense only the pressure at that moment as a function of time, the fact that pressure is detected when a hand is at the right indicates that the wall is indeed on the right."

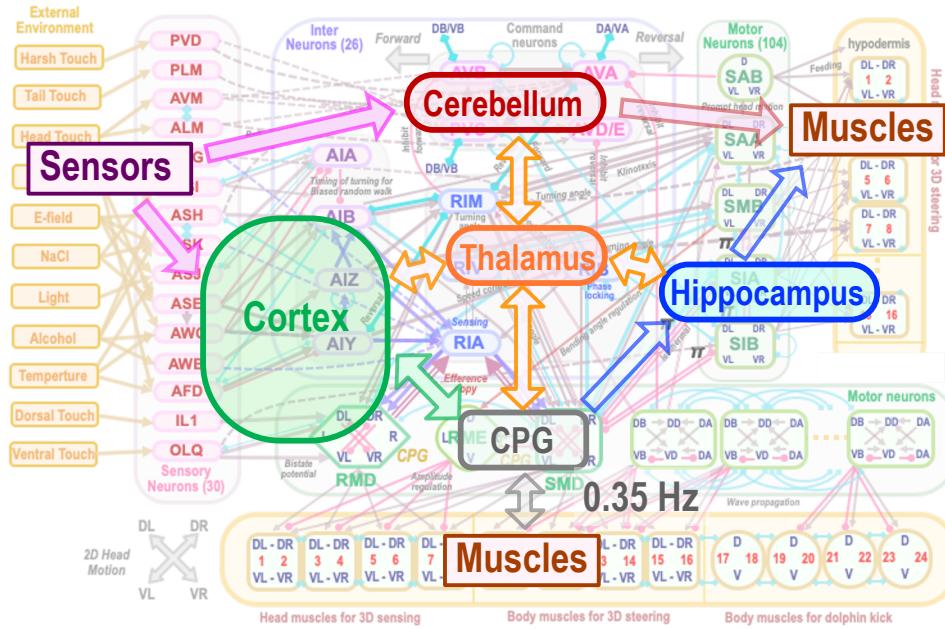


Figure 12. An analogy of the *C. elegans* brain to the Human brain. Such a comparison cannot be accurate, but we can identify loosely analogous components: Sensors, Cortex, Thalamus, Cerebellum, Hippocampus, CPG (motor neurons), and Muscles.

About 800 million years ago, the ancestor of *C. elegans* already developed the minimum brain to achieve the above brilliantly for isothermal behavior. On the other hand, such long years may make sense because it also took about a billion years for single-celled organisms to evolve into a creature like *C. elegans*. And these one billion years teach us how challenging it was for the first *multi-celled* animal to evolve a brain for navigating space toward food. After all, this process was the emergence of animals.

Lastly, considering the universal principles of any brain, **MePMoS**, we could attempt to overwrite the rough flowchart of the human brain on top of *C. elegans*' brain, which results in **Figure 12**. Of course, such a comparison would never be accurate, but one can identify similar components: Sensors, Cortex, Thalamus, Cerebellum, Hippocampus, CPG (motor neurons), and Muscles. The superficial similarity in this figure will become more evident once the entire functional connectome of the human brain is constructed in the following **Section 5**.

5 Space-Time Dynamic Connectome of Human Brain

5.1 From *C. elegans* to Human Brain

	C. elegans	Human
Total No. of Neurons	302	8.60E+10
Total No. of Synapses	7000	3.60E+14
Lifetime	~20 days	~80 years
Years from Single Cell Life	~ 1 Billion Years	~2 Billion Years
Inhibitory Neurotransmitter	Acetylcholine (ACh)	GABA
CPG/Brainwave Frequency	~0.35 Hz (CPG)	5 - 100 Hz
Information carried by	Graded Potential (mV)	Spike Timing (ms) - Phase of Brainwave
Navigation based on	Local Gradient - Allocentric Direction	3D Cartesian Allocentric Space

Table 1. Comparison between *C. elegans* and Human brains. Evolutionarily, *C.elegans* could be considered exactly a midway from single-celled organisms to humans in terms of complexity, even though its brain has only 302 neurons. From *C. elegans* to humans, CPGs are internalized as brainwaves. Information carriers are advanced from graded potentials to spike timing (= phase of brainwaves). This evolution was essential to acquire long-term memories of allocentric space.

Through the construction of the dynamic space-time diagram of *C. elegans*, we have witnessed how effective **MePMoS** is in revealing the underlying sensory-motor integration essential for prompt and reliable navigation. Encouraged by this fruitful outcome, we are finally well prepared to attack the human connectome. To begin with, **Table 1** highlights the differences between the brains of *C. elegans* and humans side by side. Despite dramatic differences in all kinds of aspects listed here, both brains must share a common principle because they have the identical purpose: reliable, prompt navigation of space to search for food. And we postulate that the essential underlining principle must be the **MePMoS** model that satisfies causality and locality.

Nevertheless, it is worth pointing out that *C. elegans* can only sense allocentric direction (such as the temperature gradient) locally. In contrast, more advanced animals like humans can perceive proper allocentric space, the absolute external world, which is essential for returning to their (our) nests. This disparity needs careful investigation; going back and forth between the nest and food locations requires long-term memories of allocentric space, which imposes a non-trivial challenge to the neural network. Essentially, 2D or 3D allocentric space must be internalized. And this must be taken into account for constructing human brain's space-time connectome.

We argue that such internalization requires brainwaves as an evolutionary advancement of CPGs. In the case of *C. elegans*, CPGs physically move the body rhythmically. When the CPG stops, movement stops and lose the perception of external space. In the case of humans, primarily thanks to visual stimulation, we can perceive outer space without body motion. In other words, our visual perception of space is not precisely based on **MePMoS** because “Motion” is not required for vision. How is it possible? It must be realized by internalizing CPG-based motion by propagating brainwaves. In a sense, brainwaves emulate anticipated action a priori.

This internalization of physical movement by electric signal propagation in a brain is highly efficient because it saves energy and can be used to predict the future; by internalizing and emulating real, external motion, the frequency can be sped up significantly. This “time compression” has been observed in the Hippocampus CA1, which provides the foundation of long-term **Memory** for **MePMoS** (Buzsáki, 2006, 2015, 2018; Lisman et al., 2017). We will discuss it later briefly in **Section 5.6** and extensively in **Part IV**.

5.2 Architecture of the Space-time Connectome of Human Brain

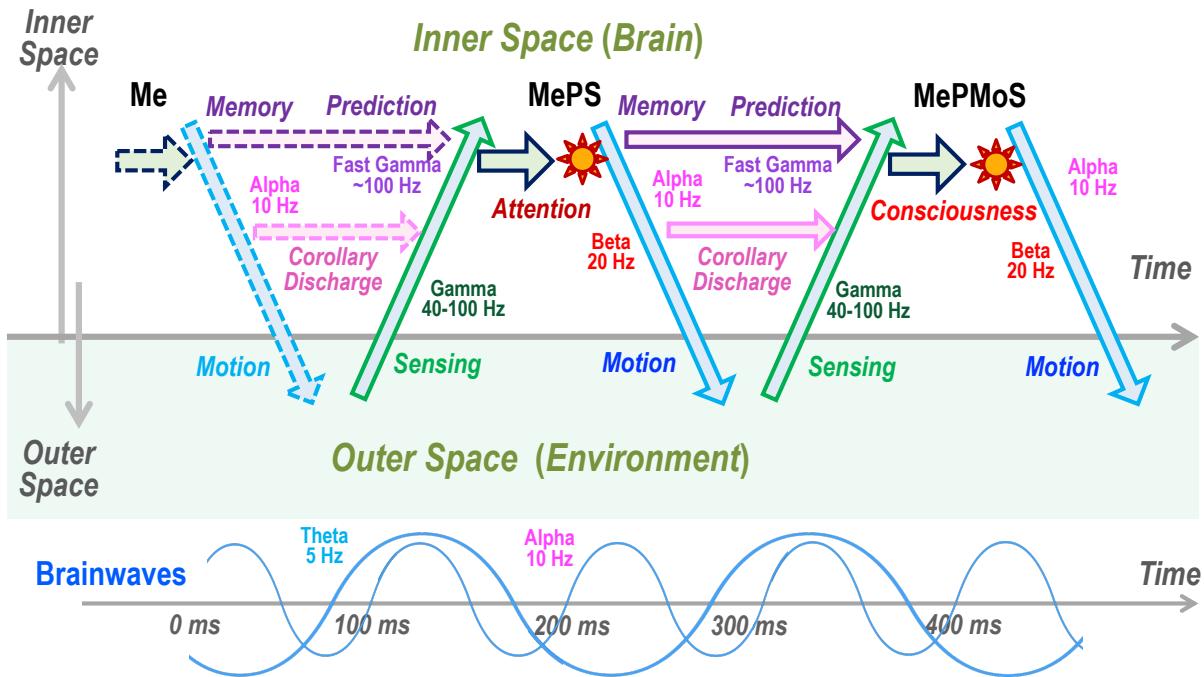


Figure 13. An overall space-time diagram of the human brain. Based on the **MePMoS** model in **Figure 2-D**, two cycles of **MePMoS** can explain the origin of both attention (at ~200 ms) and conscious awareness (at ~400 ms). The unit of ~200 ms is the period of the theta brainwave ($f \sim 5$ Hz), which is further segmented into two periods of the alpha brainwave ($f \sim 10$ Hz, $T \sim 100$ ms). This quantized phenomenon has been experimentally observed in simple reaction time (~200 ms) and choice reaction time (~400 ms) experiments.

Let us begin the construction of the space-time connectome of the human brain. Like we did for *C. elegans*, we will follow the concept of **MePMoS**. However, this time, we shall coordinate the time axis (horizontal axis) by two known brainwaves: theta and alpha waves. We will consider only the flowchart (as it is impossible to display 10^{11} neurons with 10^{14} connections.)

In **Section 2**, we introduced the concept of **MePMoS**, as illustrated in **Figure 2-D**, which highlights that **Memory** → **Prediction** → **Motion** → **Sensing** is the only proper order in space-time that satisfies causality and locality. In the subsequent **Sections 3** and **4**, this stringent requirement was directly applied to construct the dynamic connectome of *C. elegans*' neural network. How can we apply the same principle to human brain? The first step is to realize the fact that our daily activities are also continuous and often rhythmic; The V-shaped cycle in **Figure 2-D** of the **MePMoS** model is repeated over and over, following the pattern of **MePMoS** → **MePMoS** → ..., and so on.

As an example, **Figure 13** illustrates two of these cycles. In the beginning, let's assume at $t = 0$ ms, we take an initial guess (without sensory inputs) and decide to move in a specific direction (shown as **Me**). After that, a new sensory signal comes in and is compared with the brain's prediction, completing **MePS** at $t \sim 200$ ms. During the second theta cycle, we have a much better prediction, since we are taking the previous sensory input into account. Finally, **MePMoS** is completed at $t \sim 400$ ms, following the two theta cycles. This 200 ms cycle is the period of the theta brainwave with ~ 5 Hz frequency. Within one theta period, two cycles of the alpha wave with ~ 10 Hz are nested synchronously, as shown in **Figure 13**. Such rhythmic patterns in our visual perception have been abundantly studied and reported (Fiebelkorn, Saalmann, and Kastner 2013; Fiebelkorn, Pinsky, and Kastner 2018, 2019). Both theta and alpha brainwaves are illustrated at the bottom of **Figure 13**.

With these two theta cycles, as shown in the space-time diagram, **Figure 13**, we can clearly distinguish the timing of attention and consciousness. Attention is triggered by an unexpected sensory input, which is not yet rewarded by the time coincidence with the prediction. This process of unconscious attention occurs at around 200 ms, after **one theta cycle**. Next, consciousness occurs at $t = 400$ ms after the two theta cycles, when the prediction is rewarded by the second cycle of sensory input. These timings are consistent with our experimental observations of simple reaction time (at ~ 200 ms) and choice reaction time (at ~ 400 ms) (Afifa et al. 2022), as well as past research on conscious processing (Dehaene and Changeux 2011). We will address the origin of attention and consciousness in detail in **Part VI**.

5.3 Space-time Connectome Flowchart of Human Brain

Finally, we can apply **MePMoS** thoroughly to construct a complete space-time (Feynman) diagram of the human brain, as seen in **Figure 14**, with emphasis on visual signal processing, navigation, and memory. The most critical matter in establishing such a diagram is to ensure complete satisfaction of both causality and locality at each connection. In particular, causality demands that every arrow (i.e., signal pathway) is directed from the past (left) to the future (right). It is its fulfillment of this rigorous requirement that distinguishes **Figure 14** from similar drawings in the previous neuroscience literature.

The detailed functionality of the individual connections will be gradually introduced later, in **Parts III** and **IV**. Before then, we will be identifying a few essential facts here. Firstly, the outer space (i.e., external environment) is illustrated at the bottom, whereas the inner space (i.e., the brain), where our perception occurs, is on top. Secondly, this figure includes four nearly identical sections for every 100 ms of the period, horizontally. This corresponds to the alpha brainwaves ($f \sim 10$ Hz, $T \sim 100$ ms). The initial 0 – 100 ms range is flipped and mirrored onto a 100 – 200 ms range; then, the combined 0 – 200 ms range is copied onto the 200 – 400 ms range, corresponding to the first and second theta cycle. While the above ranges apply to the visual cortex, the motor cortex and its associated regions only exist in the range of 100 – 150 ms (and 300 – 350 ms). Hippocampus spans 50 – 150 ms (and 250 – 350 ms).

It should be noted that this diagram starts with unexpected sensory inputs from the bottom-left corner, unlike **Figure 13** (that begins from the top-down process of prediction.) As a result, initially, an unexpected bottom-up sensory signal goes up from bottom-left to top-right via the visual pathways, taking the first ~ 100 ms. In return, a corresponding top-down prediction goes from the top to the down-right direction for the next ~ 100 ms, resulting in an inverted V-pattern within ~ 200 ms of one theta cycle. Repeating the same process in a 200 – 400 ms time window yields a global “inverted W-shape” after ~ 400 ms, which is two theta cycles. Realistically, the “inverted V-pattern” would repeat again and again indefinitely in our daily life. It means that one could also say that a “not-inverted V-pattern” would repeat again and again if the diagram would start from the top-down prediction like **Figure 13** does. Since the top-down and bottom-up appear alternately every ~ 100 ms periodically and indefinitely, it does not matter which is drawn first in the space-time diagram of **Figure 13** and **Figure 14**.

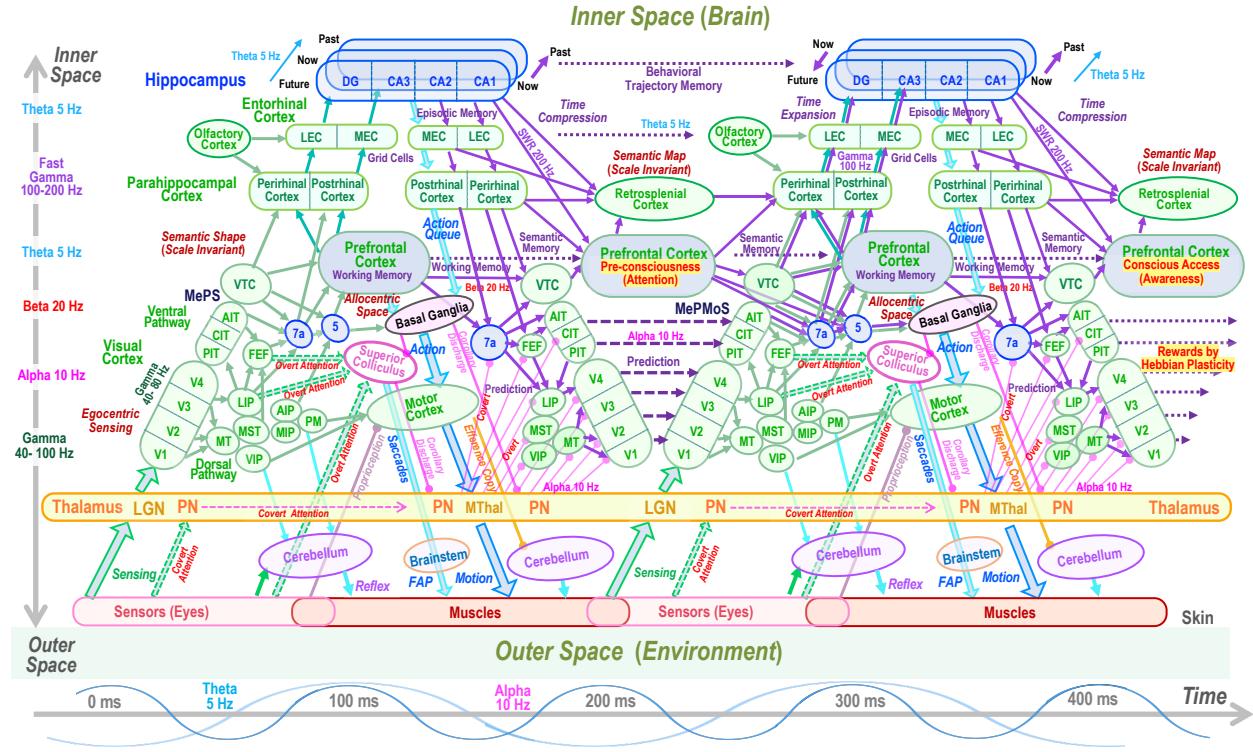


Figure 14. A complete space-time Flowchart (Feynman diagram) of the human brain. This diagram is the expanded version of **Figure 13**. Special emphasis is given to visual signal processing and sensory-motor integration of spatial navigation and memory.

A key feature of **Figure 14** is the clear distinction between attention and consciousness, by alternating theta cycles. Unconscious attention takes place within the first -200-ms-theta, whereas conscious visual awareness occurs after the second theta cycle (~400 ms) following initial visual stimulation. This two-theta-cycle model is consistent with extensive past studies on the attention and consciousness (Dehaene & Changeux, 2011; Pinto et al., 2013; Fiebelkorn et al., 2018). A more detailed assessment of attention and consciousness will be given in **Part VI**.

5.4 Visual Pathways: Egocentric Frame to Allocentric Frame

Figure 15 is the space-time of human visual pathways, which is extracted from **Figure 14**. As we choose to begin these figures with an unexpected visual stimulus, starting at $t = 0$, the bottom-up signal goes towards the upper-right through the primary visual pathway, in the order of eyes \rightarrow Thalamus LGN \rightarrow primary visual cortex V1. Then, the signal branches out to the ventral and dorsal pathways. The connectome of these visual pathways was first published by Felleman and Essen (1991), and then further advanced by several later studies (Gilbert & Li, 2013; DiCarlo, Zoccolan, & Rust, 2012; Kruger et al., 2013). This bottom-up process takes place in 0 – 100 ms. The visual pathways are controlled by alpha brainwaves. Detailed diagrams explaining the functions of the ventral and dorsal pathways will be given in **Part III**.

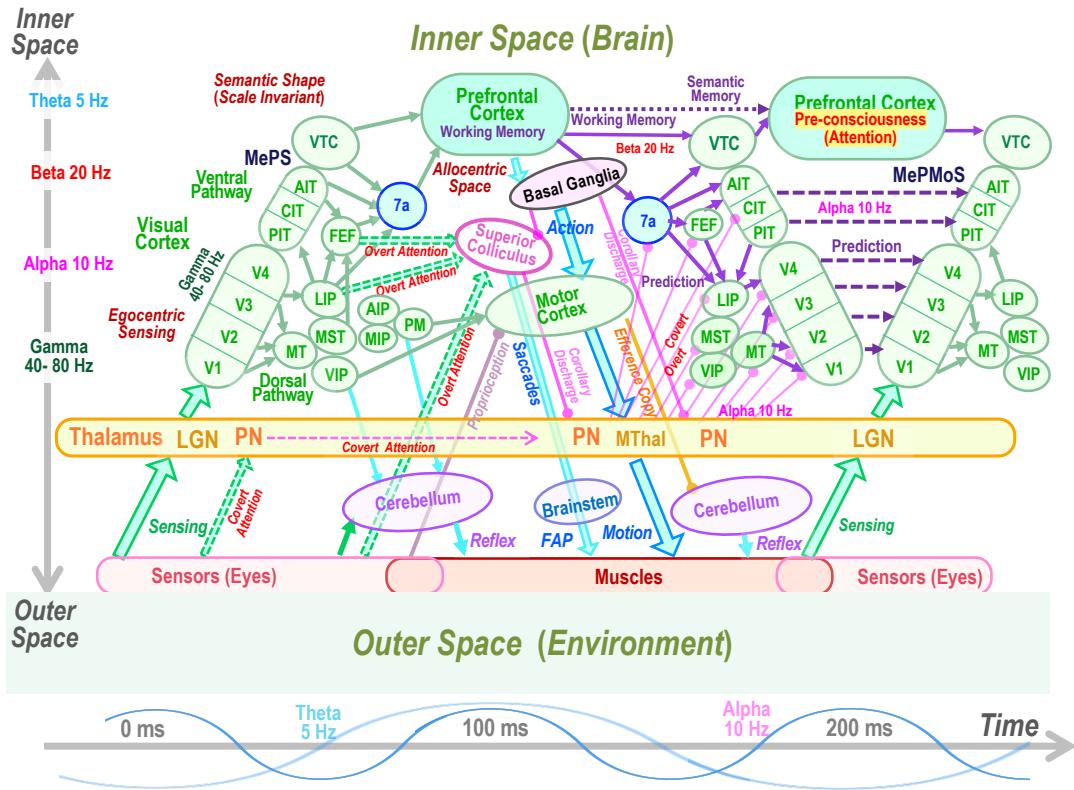


Figure 16. A space-time diagram of human visual pathways, which is extracted from **Figure 14**. Starting from an unexpected visual stimulus at $t = 0$, the bottom-up signal goes towards the upper-right through the primary visual pathway, in the order of eyes \rightarrow Thalamus LGN \rightarrow primary visual cortex V1. Then, the signal branches out to the ventral and dorsal pathways.

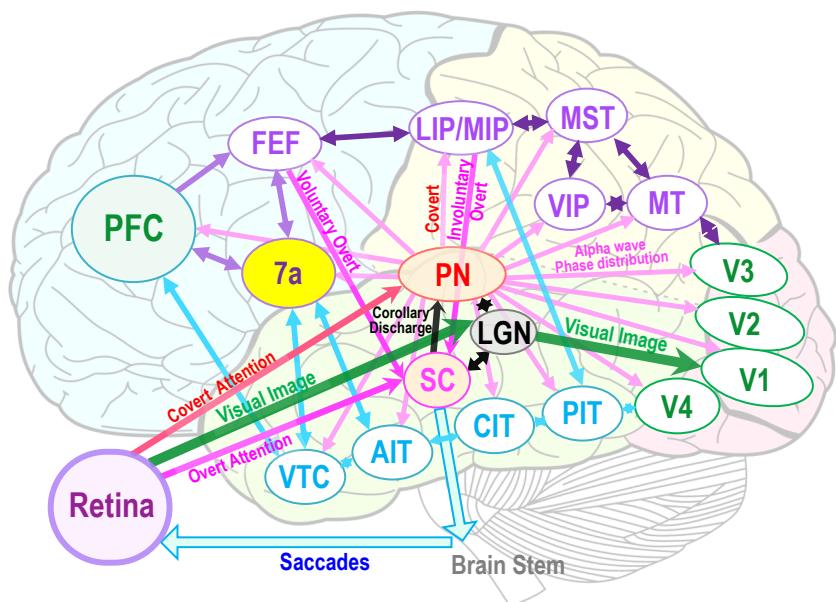


Figure 17. The conceptual flowchart of the dorsal/ventral visual pathways, together with the PN network that distribute brainwaves with specific phases to the entire visual pathways.

Besides the above visual pathways for retinotopic image processing, parallel signal pathways co-exist for both covert and overt attention through the bypass network (Spering and Carrasco 2015), which occupies the 100 – 200-ms range in **Figure 15**. Overt attention is triggered by a saccade that travels through the Eyes → Superior Colliculus (SC) → Brainstem pathway (Engbert, 2006; Martinez-Conde, Otero-Millan, & Macknik, 2013). Following the saccade, the appropriate corollary discharge is produced and propagated via SC → Pulvinar Nucleus (PN) (Bridge, Leopold, & Bourne 2016; Soares et al., 2017). On the other hand, covert attention bypasses SC and directly goes from the eyes to the PN. These attention networks will be further explained in **Part III**.

5.5 Corollary Discharge Network via Pulvinar Nucleus (PN)

Any eye/head/body motions must generate corresponding corollary discharges, which promptly update the observer's eye/head/body location and direction via PN while maintaining allocentric 3D space. This corollary discharge is orchestrated by the Pulvinar Nucleus (PN). In our **MePMoS** model, the PN is considered as a central clock that distributes the appropriate brainwaves with specific phase assignments to the entire cortex (Coulon & Landisman, 2017; Llinás, 2014).

This accurate delivery of brainwaves with certain phases lies at the heart of the **MePMoS** concept and is the essence of space-to-time conversion. Any eye/head/body motion will demand the PN to apply landmark-specific phase-shifts to brainwaves, so that the allocentric frame can be maintained. This phase distribution from the PN is illustrated between 100 – 200 ms in **Figure 15**, by the pink arrows connecting the PN and the Visual cortex. **Figure 18** is the physical distribution of the visual pathways and the PN network in the human brain. Details of this network, in particular, remapping mechanisms of overt and covert attention will be explored in **Part III**.

Let us elaborate on the essential function of the PN more carefully. By definition, any sensory stimulation resides in the egocentric frame of observer's eyes/head/body. But the observer must perceive and navigate the allocentric frame. The continuous mismatch between egocentric and allocentric frames is caused by the animal's constant motion, either of their eyes, head, or body. For every single movement, the egocentric frame must be reallocated within the allocentric frame in real-time. This remapping is orchestrated by the Pulvinar Nuclei (PN), which receive corollary discharges from motor neurons. It acts as the central clock that distributes appropriate brainwaves with specific phase assignments to the entire cortex.

Llinás demonstrated that the higher membrane potential of neurons in the PN increases the frequency of the brainwaves, whereas the lower potential of PN neurons reduces the frequency (Llinás, 2014). In an extreme case, if the potential falls below threshold during a moment, the brainwave would be shut off over that short period. Such a quick turn-off of the brainwave effectively increases its phase. The cortex-wide distribution of exact frequencies and phases are regulated by gap junctions (Coulon & Landisman, 2017). Further details will be presented in **Parts II** and **III**.

5.6 Hippocampal Networks: Navigation and Episodic Memory

The hippocampus is known as the brain's center for navigation and formation of episodic memories. (Buzsáki, 2006, 2015, 2018; Lisman et al., 2017). The signal processing sequence in Hippocampus, DG→CA3→CA2→CA1, takes place “on top of the mountain,” as shown in **Figure 17** (Jones & McHugh, 2011; Neves, Cooke, & Bliss, 2008), which is extracted from **Figure 14**. The Hippocampus is connected with both the entorhinal cortex underneath and the Parahippocampal cortex further below. At the end of the dorsal visual pathway (FEF→ 7a), 3D allocentric space is constructed with the host's location, direction, and speed.

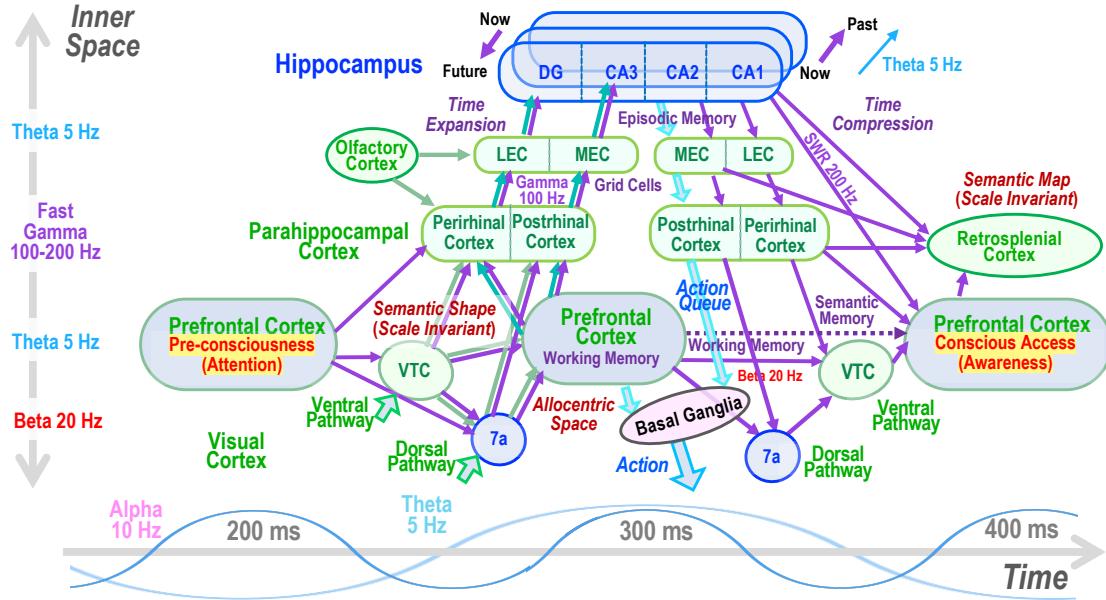


Figure 19. A space-time diagram of human's hippocampal network. This figure is extracted from **Figure 14**.

Then, it is inserted in the Parahippocampal Cortex → MEC → Hippocampus CA3 path (Preston and Eichenbaum 2013; Knierim, Neunuebel, & Deshmukh, 2014; Komorowski et al., 2013). Meanwhile, at the end of the ventral pathway, the VTC, semantic information extracted from observed landmarks in the form of 3D shapes is recognized and inserted into the LEC → Hippocampus DG path, while the memories of the identified landmarks are introduced to the Hippocampus DG.

A detailed diagram of the Hippocampal network based on previous studies (Burwell, 2000; Neves et al., 2008; Jones & McHugh, 2011) will be described in **Part IV**. At the entrance of the Hippocampal network, top-down memory and prediction must be compared with the bottom-up sensory inputs. This process, **MePMoS**, is initiated from the center that is the Prefrontal Cortex, as depicted in **Figure 17**.

The navigation map is first recorded at CA1 as an episodic memory. In our model, the map initially forms in the Cartesian coordinate frame, but it is likely to then be converted into the scale-invariant log-polar coordinate system for path integration at the Retrosplenial Cortex (RSC)(Mitchell, Sundberg, & Reynolds, 2007; Miller et al., 2014; Vann, Aggleton, & Maguire, 2009; Kinnavane et al., 2018).

The other essential function of the hippocampus is the formation of episodic memories. An episodic time sequence is first stored at CA1 as a series of theta cycles. Then, these theta cycles are time-compressed by sharp wave ripples (SWR) into one single theta cycle, which is later transferred to the prefrontal cortex (PFC) to form long-term episodic memories (especially during sleep). Afterwards, when navigating the same space again, the episodic memory in the PFC is time-expanded and inserted into the MEC → DG → CA3 path (Jones & McHugh, 2011; Diba & Buzsáki, 2007; Draguhn, Keller, & Reichinnek, 2014; Joo & Frank, 2018; Jaramillo & Kempter 2017). This function is illustrated as the purple lines in the 200 – 250-ms range in the top half of **Figures 14** and **19**. Further details will be presented in **Part IV**.

5.7 Reflex, Voluntary Motion, Fixed Action Patterns

As discussed in **Section 1.1**, the primary purpose of the brain is to enable prompt and reliable navigation. Thus, motor commands to muscles have gradually evolved to promote survival, resulting in parallel processing pathways, from the simple reflex to voluntary motion, and eventually the more complex series of motion (Llinas, 2002), which I name as Action Queue (AQ). The conceptual diagrams of these pathways are given near the bottom of **Figure 14**.

The brainstem and the spinal cord generate the most primitive motor commands, including the reflex. On the other hand, voluntary motion is generally created by the motor cortex (Proske and Gandevia 2012; Bosch-Bouju, Hyland, & Parr-Brownlie, 2013) and follows the final go/no-go signals that are delivered at the Basal Ganglia (BG) (Calabresi et al. 2014). Besides the simple reflex and voluntary motion, there is an additional network for directional reflex via the dorsal visual pathway, which involuntarily triggers head and/or body motion via the CIP/VIP/AIP/PMv(F5) → Motor Cortex path (Murata, Wen, & Asama, 2016).

Motor commands are always copied into the cerebellum. As a result, repeated practice of the same sequence of actions eventually hardwires a new circuit in the cerebellum, an Action Queue (AQ). The formation of AQs allows for the complex cognitive processes illustrated in the upper side of **Figure 14**, during the routine execution of AQs. Such high-level cognition includes conscious decision-making to create new thoughts or to handle unexpected situations.

5.8 Summary – Space-time Connectome of the Human Brain

In **Section 5**, starting from the two theta cycles of the **MePMoS** diagram of **Figure 13**, we have successfully constructed the whole space-time dynamic connectome of the entire human brain in **Figure 14**. This is a counterpart of that of *C. elegans* given in **Figure 8**. The main difference is that **Figure 8** (*C. elegans*) is the detailed diagram of 164 neurons with every single synaptic connection and gap junction. In contrast, **Figure 14** (human) is the overall flow chart of a total of $\sim 10^{11}$ neurons. Nevertheless, both are consistent with the fundamental physics principle of causality and locality, and these are the direct outcome of the **MePMoS** in **Figure 2-D**.

Clearly, without such stringent requirements, we could not have derived these extensive space-time diagrams in **Figure 8** (for *C. elegans*) and **Figure 14** (for humans) in parallel. Here, we have achieved the first step of the **Grand Unification**: the unification of neural networks from the simplest of brains (*C. elegans*) to the most complex brain (Human).

6 Toward Grand Unification on Mind and Brain

6.1 Particle Physics vs. Proposed Neurophysics

	Particle Physics	Proposed Neurophysics	Traditional Neuroscience
Unit	Particles	Neurons/Synapses	Neurons/Synapses
Underling Physics	Quantum Mechanics	Classical Mechanics	N/A
Wave	Wave Function	Brainwaves	Brainwaves
Wave Function	Complex	Real part only	Complex (in EEG analysis)
Wave-Particle Duality	Yes	Yes	N/A
Causality	Yes	Yes	N/A
Locality	Yes	Yes	N/A
Signal Propagation Speed	Speed of Light (3×10^8 m/s)	Propagation speed of neural signals (1-100 m/s)	N/A

Table 2. Comparison between Particle physics vs. proposed neurophysics. This table compares well-established particle physics theories, the proposed holographic model of neurophysics, and traditional neuroscience. The crucial shortcoming of conventional neuroscience is the missing constraint of causality and locality. (N/A = Not Applicable).

As discussed in **Section 5.1**, from an evolutionary perspective, CPGs could be internalized to produce a higher function: the rhythmic pattern of brain activity, resulting in brainwaves. For example, the rhythmic motion of a rodent's whiskers is synchronized with the theta rhythm of ~8 Hz (Carvell et al. 1991; Wineski 1983). Likewise, human saccadic eye motion seems to have a similar theta rhythm of 3 – 8 Hz (Hoffman et al., 2013). Therefore, it is quite natural to hypothesize that the origin of brainwaves is the CPG. The logical consequence is that rhythmic brainwaves can synchronize the motion and sensing of the host animal by **MePMoS**. This sensory-motor synchronization will provide a perfect mechanism to overcome the stringent constraint of causality and locality in synaptic interactions. In other words, brainwaves can be broadly distributed among the immense number of neurons, sharing and forming a higher level of cognitive information. Indeed, this is the motivation for this paper to consider holographic perception based on brainwaves, elaborated more in **Part II**.

Table 2 summarizes the similarities and differences among the well-established particle physics theories, the proposed holographic model of neurophysics, and traditional neuroscience. As shown here, the new model has formed on the foundation of particle physics theories. The fundamental shortfall of traditional (textbook) neuroscience is a lack of constraint from causality and locality.

The observed duality of spikes and brainwaves seems somewhat analogous to the wave-particle duality of quantum mechanics. However, it is crucial to emphasize that, in the case of quantum mechanics, wave functions are described by a complex variable; its phase is imaginary, and the square operation results in a probability density distribution in local space. In contrast, the brainwave is classical deterministic wave, presented only by the real part (i.e., electric potential of classical mechanics). The fact that brains follow classical mechanics imposes causality and locality. Although this distinction has not yet been recognized in the analysis of brainwaves, it must be thoroughly considered for constructing the holographic model, which will be addressed in **Part II**.

Why is the constraint of causality and locality so essential? It is due to the incredible slowness of neural signal propagation (1 – 100 m/s) compared with the speed of light (3×10^8 m/s). In particle

physics, phenomena running close to the speed of light must be treated by relativity under a so-called “relativistic regime,” where a unified treatment of 4D space-time is required. In the brain, we must also treat neural signal processing under the “relativistic regime.” Only with relativistic treatment can we accurately realize the proper dynamic process in the brain.

6.2 Multiple Brainwaves for Multiple Dimensions

So far, in **Figure 14**, we emphasized the functional connectome that satisfies causality and locality. Here, let us focus more on the critical role of various brainwaves in brain-wide synchronization. To grasp a rough idea, on the left side of **Figure 14**, multiple brainwaves are listed to illustrate how they govern different neural networks. Generally speaking, the top-down predictions are carried by the low-frequency brainwaves (Theta, Alpha, Beta), whereas higher-frequency gamma bands carry the bottom-up sensory signals. It is the mutual communication of top-down low frequency and the bottom-up high-frequency that establish the brain-wide perception of the 3D space. **Parts II – V** will go through this Grand Unification of brainwaves, step by step.

	Wave	Freq. (Hz)	Purpose	Dim.	Frame	Assignment of Eight Axes			
						1/2	3/4	5/6	7/8
Navigation									
	Theta	5	Space-time	4D	Allocentric	X	Y	Z	Time
	Beta	20	Direction Vector	3D	Allocentric	Yaw/Azimuth	Pitch/Altitude	Roll	Speed, Distance
Vision									
	Alpha	8-12	3D Location	3D	Body-centric	Yaw/Azimuth	Pitch/Altitude	Roll	Distance
	Alpha	8-12	2D Shape	2D	Object-centric			Roll	Log(Eccentricity)
	Gamma	50-80	Local Shape	3D	(Bottom-up)	Local Orientation	Curvature	Kink	
	Gamma	40	Color (HSL)	3D	(Bottom-up)	Green-Red	Blue-Yellow	Lightness	
Sound									
	Alpha	8-12	3D Location	3D	Body-centric	Yaw/Azimuth	Pitch/Altitude		Distance
	Alpha	8-12	Word	2D	Word-centric	Frequency	Modulation	Intensity	
	Gamma	70-150	Short Sound	2D	(Bottom-up)	Frequency	Modulation	Intensity	
Touch									
	Mu	8-13	3D Location	3D	Body-centric	Yaw/Azimuth	Pitch/Altitude		Distance
	Gamma	30-90	Pain, Texture	7D	Tactile	Pain A/B	Pressure A/B	Touch A/B	Touch C/D
Smell									
	Gamma	60	Olfactory	8D	Olfactory	Smell A/B	Smell C/D	Smell E/F	Smell G/H
Taste									
	Delta	3	Taste	5D	Taste	Salty/Sweet	Sour	Bitter	Umami

Table 3. A complete list of multiple brainwaves and their functions. These brainwaves are responsible for the holographic representation of a certain space: either the real 3D space, or extra sensory dimensions such as touch, smell, and taste. Generally speaking, the top-down predictions are carried by the low-frequency brainwaves (Theta, Alpha, Beta), whereas higher-frequency gamma bands carry the bottom-up sensory signals. Details will be given in **Parts II – V**, step by step.

Table 3 summarizes all the brainwaves and their functions. Throughout **Parts II – V**, all these brainwaves will be introduced where applicable. Roughly speaking, the top-down predictions are carried by the three low-frequency brainwaves: Theta (~5 Hz), Alpha (~10 Hz), and Beta (~20 Hz).

- 1) The theta wave (5 Hz) is for 3D/4D navigation via the Hippocampal network (**Part IV**).
- 2) The alpha wave (10 Hz) is for 3D vision via the visual pathways (**Part III**).

- 3) The beta wave (20 Hz) is to track 3D head direction in the polar coordinate system (**Part II**).

In **Part III** and **IV**, we will demonstrate how these brainwaves – especially the alpha and theta waves – holographically express 3D space and shape by their phases. Thanks to this space-to-time phase conversion, sensory inputs in the egocentric frame can be mapped onto the allocentric frame by simple phase shifts. This new concept will be introduced next in **Part II**.

In addition to visual perception of 3D space, we can localize sound sources in 3D space as well. Furthermore, tactile sensation can also be localized in 3D vividly. How can we obtain the three-fold agreement of the 3D location by three independent sensations so nicely? The solution seems to be by sharing the same brainwave frequencies (the alpha/mu \sim 10 Hz) and phases among the three modalities. This will be discussed in **Part V**.

The high-frequency gamma bands are primarily for bottom-up sensory signal processing for five senses, including:

- 1) Local shape (line orientation, kinks, curvatures)
- 2) Local colors (hue, saturation, brightness)
- 3) Pitch and amplitude modulation of instantaneous sound
- 4) Tactile sensation on the skin
- 5) Smell and taste

The detailed mechanisms of these bottom-up process for five senses will be presented in **Part V**. Lastly, the lowest frequency delta wave ($f \sim 2\text{-}3$ Hz) is associated with the breathing rhythm and encodes taste. The unified treatment of all these brainwaves on **Table 3** will be presented extensively in **Part V**.

6.3 Grand Unified Theory of Mind and Brain

The six articles of **Part I – VI** are jointly entitled “**Grand Unified Theory** of Mind and Brain.” This grandiose title has been assigned by the fact that vast topics and subjects in today’s neuroscience, listed below, can be so magnificently unified, starting from the simple fundamental physics laws of causality and locality. These are:

- 1) Unification of 4D space-time in brains, reflecting external 4D space-time: **Part I**
- 2) Unification of diverse brains with different complexity from *C. elegans* to human: **Part I, II**
- 3) Unification of signal carriers: local spikes and global brainwaves: **Part I, II**
- 4) Unification of various memories by the engram, named **HAL**: **Part II, IV, V**
- 5) Unification of 3D visual perception (by alpha) and navigation (by theta): **Part II, III, IV**
- 6) Unification of different coordinate systems: Cartesian vs. Polar, Linear vs. Log: **Part II, III, IV**
- 7) Unification of the ventral and dorsal visual pathways; a solution to the binding problem: **Part III**
- 8) Unification of the origin of depth perception: **Part III**
- 9) Unification of covert attention and overt attention: **Part II, III**
- 10) Unification of 7D frame translations (3D location/rotation, scale) for shape recognition: **Part III**
- 11) Unification of navigation: path integration (by beta) and place/grid cells (by theta): **Part II, IV**
- 12) Unification of top-down and bottom-up processes: **Part V**
- 13) Unification of 3D localization by vision, hearing, and touch (by alpha): **Part V**
- 14) Unification of five senses: vision, hearing, touch, smell, taste (by gamma): **Part V**
- 15) Unification of attention and consciousness: **Part VI**
- 16) Unification of the origin of language, intelligence, and creativity: **Part VI**

The concept and the name of **Grand Unified Theory (GUT)** were initially introduced in particle physics in the 1970’s (Georgi and Glashow 1974; Buras et al. 1978). In the original form of the **GUT**, it predicts that, at extremely high energy, the different fundamental forces in nature are merged into a

single force. To be exact, three gauge interactions of the Standard Model: electromagnetic (with U(1) symmetry), weak interaction (with SU(2) symmetry), and strong interaction (with SU(3) symmetry), are unified together into a larger special unitary group of SU(5). One striking prediction is that protons would decay, which has not been observed so far.

From a geometrical point of view, these forces can be viewed as the internalized extra dimensions attached to each particle. In a nutshell, the universe has its 4D space-time in which we live. But properties of various particles could be described by the extra dimensions that manifest the three fundamental forces. In the proposed **GUT** of neurophysics, the external 4D space-time is internalized by low-frequency brainwaves (theta/alpha/beta) with specific phase assignments. Fundamentally this is the top-down process based on **MePMoS**. Then, five senses are injected into the brain by the bottom-up process employing the high-frequency gammas, acting like “the forces in extra dimensions.” From this point of view, the assigned title, **Grand Unified Theory**, seems reasonably appropriate. We will elaborate in more detail on this point in **Part V**.

6.4 Conclusions – Space-time Diagram based on MePMoS

Through this “**Part I**: Space-Time approaches to Dynamic Connectomes of *C. elegans* and Human Brains”, we first introduced the most critical constraint of neural signal processing in brains: causality and locality. With this stringent requirement, a new principle of neurophysics, **MePMoS** was proposed. Remarkably, this approach was able to construct the complete space-time diagrams (Feynman diagram) of the dynamic connectomes for both *C. elegans* and human brains.

The derivation of the whole dynamic connectomes from the simplest animal to the most complex animal would be a solid testimony of the power of **MePMoS**. But its application will go far beyond. In the previous **Sections 6.2** and **6.3**, the concept of **Grand Unification** was briefly explored. In the following **Part II**, we will present another innovative concept of **Neural Holographic Tomography (NHT)** as the general principle of our navigation and visual perception of 3D space. Then, as a universal memory unit to realize **NHT**, we will introduce the **Holographic Ring Attractor Lattice (HAL)**. Once the solid foundations of all three, **MePMoS**, **NHT**, and **HAL**, are established, we can apply these concepts to explain all types of cognitive processes, as listed below

- 1) Extraction of semantic information (such as human face) via the ventral visual pathway: **Part III**
- 2) Visual perception of allocentric 3D space via the dorsal visual pathway: **Part III**
- 3) Navigation and Memorization of external 3D space by the Hippocampal network: **Part IV**
- 4) Conversion of episodic memories to semantic memories: **Section IV**
- 5) Unified 3D localization by vision, hearing, and touch (by alpha): **Part V**
- 6) Unification of five senses: vision, hearing, touch, smell, taste (by gamma): **Part V**
- 7) The origin of language and logical thought: **Section VI**
- 8) The origin of consciousness, intelligence, and creativity: **Section VI**

We are now ready to continue the whole story of the “**Grand Unified Theory of Mind and Brain**” in the following order.

- Part I.** Space-Time approaches to Dynamic Connectomes of *C. elegans* and Human Brains
Part II. Neural Holographic Tomography (NHT) and Holographic Ring Attractor Lattice (HAL)
Part III. Holographic Visual Perception of 3D Space and Shape
Part IV. Navigation and Episodic Memory by the Hippocampal Network
Part V. Grand Unification of Five Senses and Memories
Part VI. The Origin of Language, Consciousness, and Intelligence

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