Wireless Communication in the Brain: III. Where is Working Memory Located?

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Abstract

Working memory is the small amount of information that can be held in mind and manipulated for cognitive tasks. A traditional view of working memory is that the information is maintained in stationary persistence of neural activity. Recent studies suggest that the neural activity is highly dynamic during the maintenance period. It could drop to baseline when attention shifts away. The mechanism of dynamic coding and "activity-silent" working memory is largely unknown. It was proposed that the information could be stored in the short-term synaptic plasticity. However, the model lacks the flexible, precise pattern and timing needed for accurate neural representations. Computer modeling also shows that the synaptic model cannot manipulate the stored information. This paper shows that the working memory could be located in the mind which is distinct from the brain. As discussed in Paper 12, the mind is a Bose–Einstein condensate (BEC) of gravitational (GR) and electromagnetic (EM) waves, also known as a "geon". The Geon Hypothesis can explain how the working memory comes from **attention** which is controlled by the alpha rhythms in the central executive network. The working memory information is encoded in gamma-modulated GR/EM waves which serve as qubits (quantum bits). The maintenance of working memory depends on the coherence time of qubits, which

may last longer than 10 seconds if embedded in BEC. The central executive network could employ theta rhythms to manipulate the information stored in the mind geon.

Introduction

Working memory is the small amount of information that can be held in mind and used in the execution of cognitive tasks (Cowan, 2014). For example, when someone tells you his phone number, the information can be kept in your mind for a few seconds so that you have time to write it down. Since the term "mind" was not explicitly defined, the working memory was sometimes defined as "the information kept in a temporary state of heightened accessibility" (Cowan, 2017). Paper 12 proposes that the mind could be a Bose–Einstein condensate (BEC) of gravitational (GR) and electromagnetic (EM) waves, also known as a "geon". This paper will show how the geon may store information in a temporary state of heightened accessibility, and how the information can be manipulated for cognitive tasks.

Working Memory Test

Figure 1 shows an example of testing working memory. Each digit is displayed to a subject for only one second. Then there is a pause of one second before the next digit is shown. After the last digit is displayed, the subject is asked to write down all digits. Most people can remember 5-8 digits. How can a person still remember the previous digits while he or she is paying attention to subsequent digits? Where is this working memory maintained?

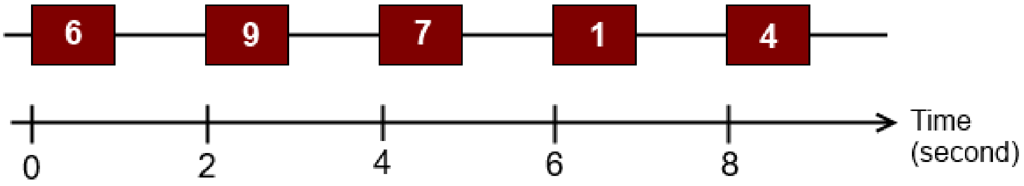

Figure 1. An example of working memory test. At time (T) = 0 second, a digit (e.g., 6) is displayed to a subject. Remove this digit after 1 second. At T = 2 s, display another digit (e.g., 9). Remove it at T = 3 s. Repeat the process until the last digit is displayed. Then ask the subject to write down all digits.

Neuronal Models of Working Memory

A traditional view of working memory is that the information is maintained in stationary persistence of neural activity. For instance, when a digit (e.g., 6) appears, it could stimulate the firing of a group of neurons representing the digit. The stimulated neuronal firing was assumed to last for a few seconds even after the digit has disappeared. However, a growing number of studies have suggested that the neural activity is highly dynamic during the maintenance period of working memory. It could drop to baseline when attention shifts away (Stokes, 2015; Rose et al., 2016; Kamiński and Rutishauser, 2020; Masse et al., 2020). How can the brain store "activity-silent" working memory? It was proposed that the information could be stored in the short-term synaptic plasticity. However, the model lacks the flexible, precise pattern and timing needed for accurate neural representations (Constantinidis et al., 2018). Computer modeling also shows that the synaptic model cannot manipulate the stored information (Masse et al., 2019).

As defined by Masse et al. (2020), "short-term memory" refers to the temporary storage without information manipulation. Therefore, the synaptic model can at best explain short-term memory, not the working memory capable of manipulating stored information. To date, the failure to localize the working memory inside the brain supports the "mind-body dualism" which posits that the mind is an immaterial substance, distinct from the brain. Working memory could be located in the mind, not the brain.

Information Encoding in the Geon

The frequency of GR/EM waves emitted from ionic currents through ion channels is estimated to be around 10 MHz (Paper 12). This frequency is equivalent to the carrier frequency in wireless communication such as mobile phones. Brain waves are the modulating frequencies which encode signal information. Compelling evidence indicates that the information processed by the brain, either from sensory input or memory retrieval, is encoded in the gamma rhythms, which are organized into a sequential order within theta rhythms (Lisman and Jensen, 2013; Roux and Uhlhaas, 2014; Lundqvist et al., 2018a). For instance, when you play tennis, you may see "a white, round ball moving quickly in a certain direction." This scene consists of four items: color, shape, direction and speed of the ball. Each item is represented by the firing status of a neuronal population within a gamma cycle. Different gamma-encoded items are placed at distinct phases of the θ cycle (Figure 2). All items in the same theta cycle can be simultaneously perceived as an integrated scene.

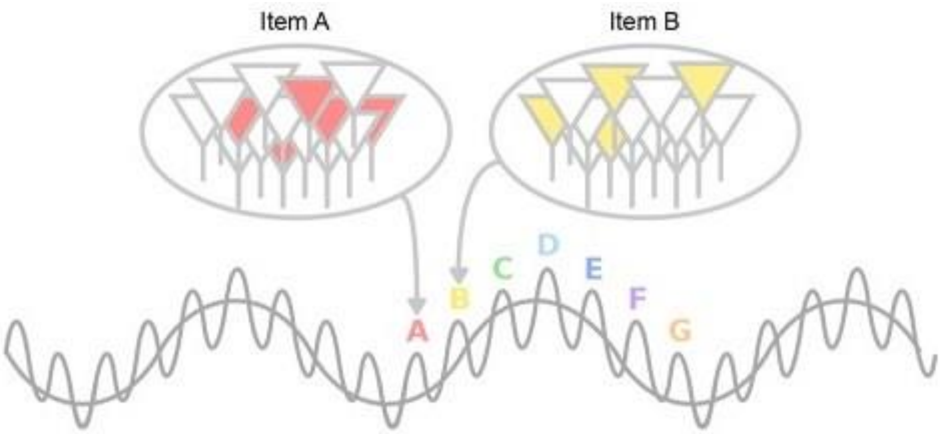

Figure 2. The θ-nested-γ code. Information about an item is represented by the firing status of a neuronal population within a γ cycle. Different γ cycles representing distinct items are placed at different phases of the θ cycle. The harmonic α-θ coupling enables all items in a theta cycle to be consciously perceived at the same time, resulting in an integrated scene. [Image source: Drieu and Zugaro, 2019]

The alpha rhythms do not encode physiological information, but they play a critical role in "attention" which regulates the content of working memory.

Working Memory and Attention

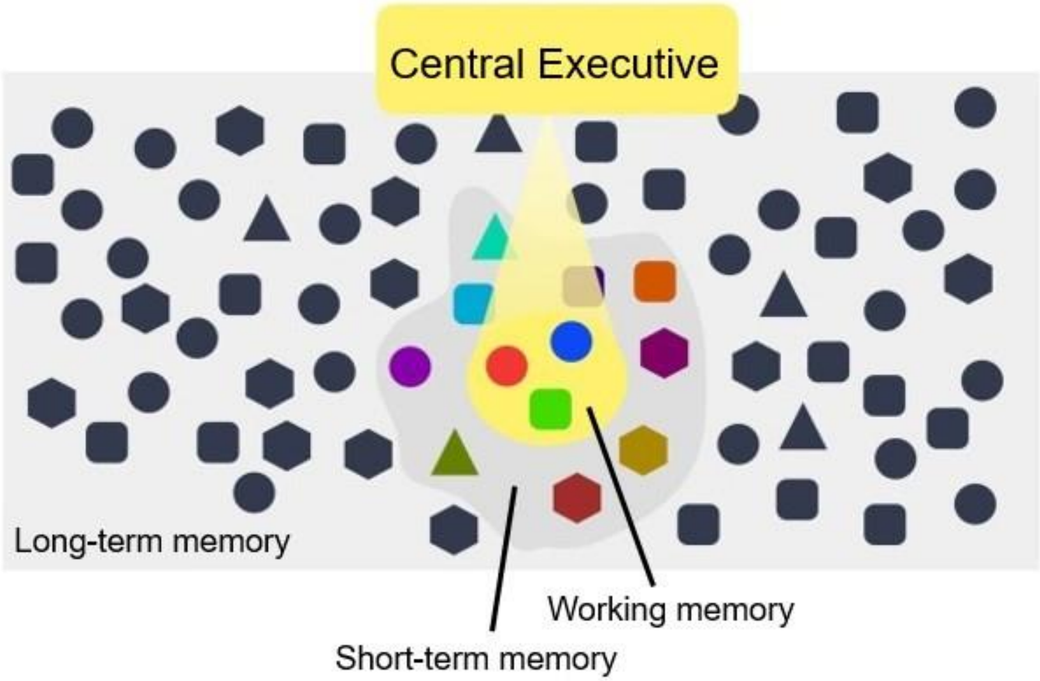

Figure 3. The embedded-processes model of working memory proposed by Cowan. The short-term memory is activated from long-term memory through sensory stimulation. The working memory comes from a subset of short-term memory through **attention** which is controlled by the central executive network. [Image source: Wikipedia]

In the embedded-processes model, Cowan proposes that working memory information comes from two levels: (1) temporarily activated from long-term memory, and (2) the subset of activated memory that is in the focus of attention (Figure 3). The two-level model is supported by experimental studies (Rose et al., 2016). Working memory is closely linked to consciousness (Persuh et al., 2018). Interestingly, in the Feature Integration Theory (FIT), Treisman and Gelade (1980) also proposes a two-stage model for consciousness with emphasis on attention.

According to FIT, conscious perception of an object requires two stages. During the early stage, features (or items such as color and shape) are detected unconsciously and in parallel by the visual system. In the later stage, **attention** is required to bind selected features, resulting in conscious perception of an object with these features.

In FIT, the early stage is called the "pre-attention" stage which resembles the short-term memory in Cowan's model. As a matter of fact, more than a century ago, Sigmund Freud has already proposed that, between the conscious and unconscious states, there exists a preconscious state which may readily become conscious through attention.

The Geon Hypothesis of Working Memory

In the Geon Hypothesis, the mind is a Bose–Einstein condensate (BEC) of GR and EM waves, also known as a "geon" (see this article), which is created by globally synchronized alpha rhythms (Paper 12). In the brain, information about an item is carried by a population of gamma-oscillating neurons representing the item. The ionic currents in these neurons will emit GR/EM waves capable of interacting with the geon. Thus, in the geon, information about an item is carried by gamma-modulated GR/EM waves that are emitted from a population of gamma-oscillating neurons representing the item. Short-term memory is defined as the information that has little interaction with the geon. It is not consciously perceived. Information in the working memory is significantly bound to the geon. It can be consciously perceived to various extents (Figure 4).

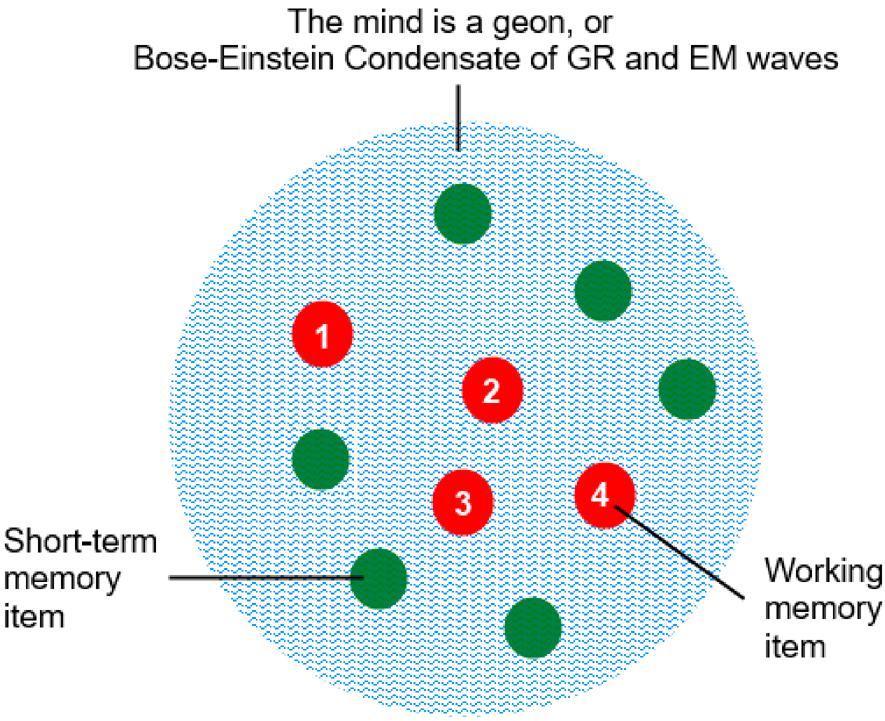

Figure 4. Working memory in a mind geon. The large circle with blue wavy background represents the geon which is created by globally synchronized alpha rhythms. A dot denotes gamma-modulated GR/EM waves that are emitted from a population of gamma-oscillating neurons representing an item. Green dots have little interaction with the geon, belonging to the pre-conscious domain or short-term memory. Red dots are significantly bound to the geon, constituting the working memory. In this example, four red dots may encode four items: color, shape, direction and speed of a ball. If they are organized into the same theta cycle, the mind may perceive an integrated scene such as "a white, round ball moving quickly in a certain direction." Note

that a dot is a simplified schematic representation. It does not mean that the GR/EM waves carrying the information of an item is localized to a specific area.

It has been well established that "**attention**" is required for transforming an item from the preconscious domain (short-term memory) into the conscious domain (working memory) and the alpha rhythms play a critical role in attention (more info). This physiological finding can be explained by the Geon Hypothesis at the physical level.

Memory Induction in the Geon

Sensory stimulation will activate a variety of short-term information. Within the mind geon, information about an item is carried by the gamma-modulated GR/EM waves that are emitted from a population of gamma-oscillating neurons representing the item. Through attention, a subset of short-term information may transform into working memory. By definition, short-term information has little interaction with the geon whereas working memory information is significantly bound to the geon. How can **attention** cause the binding of selected information to the geon?

Attention is controlled by the central executive network where the alpha power **increases** with attention, just opposite to the occipital cortex whose alpha power decreases with attention (see this article). Experiments have demonstrated that cognitive tasks can be improved by the harmonic alpha-theta coupling in which the frequency ratio between alpha and theta is about 2:1, and they are in phase. Physically, the harmonic alpha-theta coupling may optimize the constructive interference between alpha-modulated and theta-modulated GR/EM waves, thereby enhancing the binding of the theta-modulated GR/EM waves to the geon which is created by globally synchronized alpha rhythms. Hence, at a given moment, if a population of gamma-oscillating neurons representing an item is strongly coupled to the theta rhythms, attention (increase of alpha power in the central executive network) should induce the transformation of the item from short-term memory into working memory.

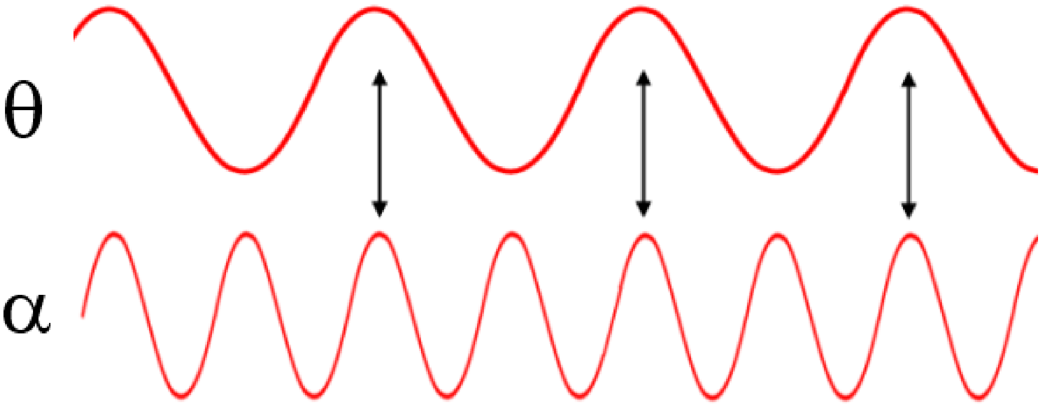

Figure 5. The "harmonic alpha-theta coupling" in which the frequency ratio between alpha and theta is about 2:1, and they are in phase.

Memory Retention in the Geon

The gamma-modulated GR/EM waves serve as qubits in quantum information processing within the mind geon (Paper 12). The duration of memory retention depends on the coherence time of qubits encoding a specific item. For a pair of photons, their coherence time is on the order of 10^{-12} second. Gravitational fields may dramatically increase the coherence time (Ghoshal et al., 2020). Furthermore, the formation of BEC can protect qubits from rapid decoherence (Paper 12). Therefore, it is possible that the working memory information within a geon may last longer than 10 seconds. The short-term memory, by definition, is the information that has little interaction with the geon. Such information would be lost rapidly, because it is not protected by BEC. As a result, short-term memory cannot be used in the execution of cognitive tasks. By contrast, working memory information is long enough for manipulation.

Manipulation of Working Memory

The working memory information, but not short-term information, can be manipulated to accomplish cognitive tasks. Manipulation has been found to correlate with neural activity (Masse et al., 2019). This implies mind-brain interaction. Paper 1 has suggested that the EM waves may influence neuronal activity by interacting with microtubules. Of noteworthy, while the geon covers the entire brain, its EM power is too weak to excite a neuron from the resting membrane potential. Therefore, only the neurons with subthreshold oscillations will be affected. More specifically, the gamma-modulated EM waves in the geon will affect only the subthreshold gamma-oscillating neurons that are in resonance.

This model is consistent with the observation that during working memory maintenance a sparse population of gamma-oscillating neurons are activated briefly (Lundqvist et al., 2018b). The sparse population of neurons are likely to exhibit subthreshold oscillations at the gamma band so that they can be activated by the EM waves of the geon. Importantly, the subthreshold oscillation of a neuron may vary with time during the maintenance period. Therefore, the population of spiking neurons activated by the geon can also change. This explains the dynamic population coding (Spaak et al., 2017). Despite the dynamic change of activated neurons, the content of working memory remains stable (Kamiński and Rutishauser, 2020), in agreement with the Geon Hypothesis which asserts that the working memory is located in the mind geon, not the brain.

The dynamic population coding is commonly observed in the prefrontal cortex, suggesting that it could be under the executive control. According to the Geon Hypothesis, spiking of the gamma-oscillating neurons during maintenance depends on the magnitude of their subthreshold oscillations. Since gamma oscillations are often coupled to theta rhythms, the wax and wane of subthreshold gamma oscillations could be governed by the coupled theta rhythms. Therefore, it seems that the central executive network may employ theta rhythms to manipulate the information stored in the mind geon. This notion is supported by the finding that theta rhythms play an important role in working memory (Kang et al., 2018; Liu et al., 2020). Abnormal theta-gamma coupling impaired working memory performance in schizophrenia (Barr et al., 2017).