

Review

An extended theory of global workspace of consciousness

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Abstract

Global Workspace theory and Global Neuronal Workspace hypothesis are frameworks about the mechanism of the consciousness, which argued that it is the global workspace that makes awareness. These two theories ignored an important fact that the content of consciousness is not only from the instant sensory input, but also from the inward mind representation. The existence of the default mode network of brain indicates that without the sensory input from instant environment, the brain can carry out organized activities which have intense relationship with inward information processing. This article combines the hypothesis of brain's default mode network and the classical Global Workspace theory, and put forward an extended theory about global workspace of consciousness.

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1. Introduction

Global Workspace theory proposed by Baars [1] and Global Neuronal Workspace hypothesis of Dehaene [2] are two famous theories explaining the phenomenon of consciousness. Both of them focus on the human awareness of external stimulus, and they agree on that the formation of a global workspace is the key to awareness. They have received many supports from experiments and have made successful computer simulation based on the working pattern of neurons. By offering an excellent framework for us to understand the potential mechanism of consciousness, they influenced the scientific study of consciousness extensively.

These two theories hereinbefore put their keystone on the phenomenon of awareness vs. unawareness for external stimulus, that is, the phenomenon of consciousness about instant information from environment. However, our attention is not always laid on the instant stimulus outside, memory, past

experience, knowledge and other “off-line” or “internal” information can become the content of consciousness too. The Global Workspace theory and the Global Neuronal Workspace hypothesis did not differentiate and explain the mechanism of awareness about this “internal” information. The finding of “Default Mode Network” and the spontaneous intrinsic activity of brain suggest that besides being confronted with the instant information coming from instant environment, the processing of internal information that has no direct relationship with external world is another important function of brain. In this paper we extend the Global Workspace theory with the involvement of the internal information processing, and propose a uniform model that attempts to explain the consciousness of all awake states.

2. The global workspace and the default mode network

2.1. Global Workspace theory and Global Neuronal Workspace hypothesis

Global Workspace theory (GW theory in short) proposed by Baars in 1998 is a framework about human

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consciousness. It proposed that in the consciousness system there is a structure named “Global Workspace”, and it is the only part accessible by consciousness of the whole cognitive system. There also exist unconscious modules including specialized processors and context [4–6]. The winner in competition of the mass of unconscious modules can have access to global workspace, broadcasting themselves to other modules, so the relative independent unconscious modules can communicate and cooperate with each other [6]. Conscious and unconscious processing can interact and transform into each other: unconscious modules come into global workspace and become accessible to consciousness by competition; conscious contents in global workspace will make the formation of newly specialized processors and context by broadcasting to other unconscious modules [7–12]. Unconscious processing makes people cope with routine events in automatic way, and the role of global workspace is to integrate a lot of unconscious modules in a controlled way and makes them accessible by consciousness.

Global Neuronal Workspace hypothesis (GNW hypothesis in short) is similar to the GW theory in the general configuration of the mechanism of consciousness [2]. The main difference is that GNW hypothesis makes its foundation in the working manner of neurons. GNW consists of the specialized processors, which limit the content of consciousness, and the workspace neurons whose main role is connecting the unconscious modules by long-distance connection, which are independent in function with others. The mechanism of awareness is that plenty of separated neuronal clusters work together and form a dynamic global workspace. The bottom-up feed forward process of unconscious modules and the top-down feed back process of workspace neurons make fast globalization of information. GNW hypothesis accords with many unconscious phenomena including attentional blink and inattention blindness [13,14]. And the long-distance connection network found in monkey brain tallies accords with GNW hypothesis too [15].

Although GNW is not a fixed neuronal network, the associative cerebral cortex including frontal, parietal and cingulate areas has an important influence on the top-down magnifying process of global workspace. Dehaene suggests that despite of the distribution in widespread areas, the workspace neurons are particularly dense in frontal and parietal cortices [2], so these regions have a special status in the formation of global workspace. Whatever the concrete content, the activation of these regions always comes along with the awareness, such as prefrontal cortex and anterior cingulate cortex. The evidence from physiology [16], cognitive neuroscience [17–22], neuropsychology [2,23,24], and pathology [25] supports the above suggestion.

However, besides the external stimulus, awareness can be induced by the internal information existed in brain too. GW theory and GNW hypothesis have not mentioned these activities. The finding of a default mode network

lightens the study of these internal information processings independent of instant environment.

2.2. The default mode network

In recent years it was found that there exist some regions in the brain which is more active during resting states than performing many goal-oriented tasks [26–28]. The distribution of these regions remains relatively invariable in diversified tasks in which subjects are asked to respond to an external stimulus [3]. Furthermore, in the state of goal-oriented tasks as well as resting, the spontaneous low-frequency BOLD signals in these regions show a high correlation in time, that means, these regions form a network by functional connectivity [27,29,30], and so comes the name of “default mode network”. Poster cingulate cortex/preccus, medial prefrontal cortex/anterior cingulate cortex are the core regions among them. The fact that the energy consumption of these regions is the highest in brain during resting state [31] suggests that some organized activities are going on in resting state, which is inhibited when an external task comes, and so the “deactivation” appears [26–28].

There are many networks organized by function connectivity in brain and it is called “Default Mode of Brain Function” [28], which indicates that brain is a highly organized system and keeps on activities of regulation constantly even in absence of external input. Among the numerous networks the default mode network aforementioned is a special one. The decrease of activity of these regions during goal-directed tasks aims at external stimulus suggests that there is going on some activities which have no relationship with instant environment during resting states. These activities may be correlated to the monitoring environment, self consciousness, collection of episodic memory and the maintenance of a waking state [28].

The default mode network is negatively correlated with the network participating in attention and working memory [32], and the cognitive load will modulate its intensity of activation, that is, the active level decreases with the increasing difficulty of tasks [33]. More evidence comes from the experiment in which the spontaneous low-frequency BOLD signals in the default mode network negatively correlated with the ones in posterior sensory regions of brain including visual, auditory and somatosensory cortices [34], which is consistent with the Fox’s conclusion completely [32], yet they both indicate the possible mutual repression between the default mode network and the regions responsible for the processing of external information.

The processing carried through in the default mode network is extensive. According to the contrast with the control condition, the numerous experiments indicate the possible function of the regions of default mode network consisting of the processing of episodic memory [35], self-referential cognition [36], emotion [37], the sense of agency, the first-person perspective [38,39] and the maintenance of

awareness state [27]. Due to the complexity of the cognitive processing, there is no “task” whose activated map can “copy” these regions, therefore there is no direct evidence for the exact function of the default mode network, yet the stability of this network indicates the commonness over these complex cognitive processings. Based on the evidence at the present time that these regions are far from the relatively primary sensory motor cortex, and that their activities are always inhibited by the external stimulus–response tasks, we infer that they carry out the processing of internal signals irrelevant to the instant external world.

In conclusion, the brain is not a system that responds to external stimulus merely. The default mode network implies the process ignored by the global workspace and the global neuronal workspace hypothesis, that is the information processing is irrelevant to the instant environment such as memory, inner speech, and plan for future.

3. An extended theory of global workspace of consciousness—The division of labor for internal–external information processing

The global neuronal workspace and the default mode network are the two sides of one coin, a uniform system of conscious activity in brain. The global workspace and the global neuronal workspace can explain the instances of awareness when individuals face external stimulus. When individuals are not devoted to the external stimulus–response tasks, the default mode network is active and the energy consumption of these regions is highest in the brain [40], or else their activities decrease and the distribution of them is close to (or overlap in some instance) the areas where abound in workspace neurons suggested by Dehaene [2]. Although there has no consistent evidence about the neural correlates of consciousness [41], the overlap of their core regions indicates the close relationship between the default mode network and the global workspace. Dehaene and Baars have noticed this fact, but they have not given more explanation of their function besides the maintenance of waking state [42] and awareness [25].

Here we integrate the default mode network into the global workspace theory and put forward an extended theory of global workspace of consciousness. The following is the main point of this extended theory.

3.1. The division of labor for internal–external information processing

Though the past attention research concentrated on the processing of the external information mostly, the internal information can be the objects of attention too. The “internal information” refers to the mental representation irrelevant to the instant external environment. Attention resource can be segregated into internal-devoted and external-devoted. When internal-devoted, the content of conscious center is the information representations from memory which have no direct relationship with instant

external environment and the planning or imagination based on them; when external-devoted, the content of conscious center is the representation of the instant environment.

The global workspace and the default mode network are two states of one uniform system about conscious activity in brain, and their difference lies in the direction of attention resource devotion. The extended theory of global workspace of consciousness can accommodate these two states. When attention resource is devoted to the instant external stimulus of environment, the global workspace is occupied by the representation of external stimulus; when the external environment becomes more and more stable and there is no requirement of attention resource for external world, the content bursting into the global workspace is the representations from memory and the manipulation based on them. Because of the limited capacity of the global workspace, it switches between the two states when an individual is awake. As we are absorbed in the external task, we will feel “losing our self”; as we concentrate on our own internal mental states such as rumination, we will feel just like the external world disappears.

3.2. The two states of the uniform system of conscious activity and its meanings

We call the two states of the uniform system of conscious activity as a “stable state” and a “sub-stable state”, respectively. The stable state is responsible for the internal-devoted attention resource. There were studies which found that the state of mind-wandering is correlated with the activities of the default mode network [43], and the contents of mind-wandering come from the information irrelevant to the instant external environment mostly [44], including episodic memory, semantic memory and problem-solving [44,45]. When individuals carry out the internal information processing mentioned above, the regions of the default mode network were activated individually [46–50], which indicates the relationship between the cognitive activities during resting state and the internal information processing.

Conscious activity will leave “stable state” for activated “sub-stable state” when attention resource is external-devoted [51], and then the content of global workspace is the representation of the external stimulus. We always drop into mind wandering constantly and need mental effort to process the external tasks, which suggests the brain’s activities have the tendency of coming back to “stable state” from “sub-stable state”.

There are plenty of unconscious activities carried out in brain [3]. At the time of the processing of instant external stimulus, a great deal of unconscious activities are going on to re-processing of the past representation and the consolidation of memory, and those who win the competition and reach the threshold of awareness come into the global workspace and consume attention resource. This kind of activities and the mass unconscious processing behind them

meet the individuals' needs for processing past information, estimating the coming events, and dealing with the changes of environment better. On this meaning, the brain is a "Bayesian inference engine" and its function is to get the best estimation of the future [28].

3.3. The self-organized brain and the extended global workspace

The extended theory of global workspace of consciousness emphasizes that there are two states under the uniform system of conscious activities. Consistent with the global neuronal workspace hypothesis, no matter the stable state or the sub-stable state, the general mechanism of consciousness is the dynamic neuronal activity pattern of the global workspace. But the extended theory of global workspace covers more wide fields. The high correlation among the spontaneous activities of regions in the default mode network indicates that the brain has the ability of "each attending to its own duties" by the self-organized spontaneous activities of neurons. The deactivation of the default mode network when brain processes instant external stimulus represents the commonness of these cerebral regions, that is the internal-devotion of attention resource. Other analogous self-organized attributes are verified in several brain networks [28,52]. It is these self-organized attributes that guarantee the division of labor for internal-external information processing.

We propose that the default mode network is one part of the global workspace. The experimental facts that the default mode network is inhibited during the external task [53] accord with the limited capacity of global workspace. The facts that the representation of external environment becomes superficial and task performance decreases along with mind-wandering indicate that internal and external information processing compete for common resource of attention [54].

Similar to the external information processing, the internal information processing can come into global workspace and have access to consciousness only if it reaches the threshold. The internal information processing during resting state comes from the competition among the unconscious modules and is influenced by the shaping of unconscious context. Some internal information that is relevant to the personal goal can come into the global workspace easier, and thus becomes the content of mind-wandering [54]. The general mechanism about awareness of internal and external information is the reason that why the regions of the default mode network and the ones relevant to consciousness of external stimuli are overlap.

4. Conclusion and the prospect

The default mode network hypothesis and the global neuronal workspace theory are the hot topics of the research in cognitive neuroscience. The former reflects the cognitive activity of brain irrelevant to the instant external

environment, and the latter offers the possible mechanism about consciousness of external stimulus. Here we integrate the default mode network into the global workspace, and put forward the extended theory about the global workspace of consciousness. We propose that the brain is not a system that only responds to external stimulus. It has its own organized mechanism which guarantees the division of labor for internal-external information processing, and behind it is a general mechanism for the uniform system of consciousness—the global workspace. The system has two states: when default mode network is active, the brain comes into the stable state which corresponds to the internal information processing; when the global workspace is occupied by the representation of external stimulus, the brain comes into the sub-stable state. But this theory needs to be verified by experiments.

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