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Review article

How do the brain's time and space mediate consciousness and its different dimensions? Temporo-spatial theory of consciousness (TTC)

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ABSTRACT

Time and space are the basic building blocks of nature. As a unique existent in nature, our brain exists in time and takes up space. The brain's activity itself also constitutes and spreads in its own (intrinsic) time and space that is crucial for consciousness. Consciousness is a complex phenomenon including different dimensions: level/state, content/form, phenomenal aspects, and cognitive features. We propose a Temporo-spatial Theory of Consciousness (TTC) focusing primarily on the temporal and spatial features of the brain activity. We postulate four different neuronal mechanisms accounting for the different dimensions of consciousness: (i) "temporo-spatial nestedness" of the spontaneous activity accounts for the level/state of consciousness as neural predisposition of consciousness (NPC); (ii) "temporo-spatial alignment" of the pre-stimulus activity accounts for the content/form of consciousness as neural prerequisite of consciousness (preNCC); (iii) "temporo-spatial expansion" of early stimulus-induced activity accounts for phenomenal consciousness as neural correlates of consciousness (NCC); (iv) "temporo-spatial globalization" of late stimulus-induced activity accounts for the cognitive features of consciousness as neural consequence of consciousness (NCCcon).

1. Introduction

1.1. General background

Consciousness is a complex phenomenon that includes different dimensions. The initial characterization of consciousness by contents (Crick and Koch, 2003; Koch, 2004) has been complemented by the level or state of consciousness (Bachmann and Hudetz, 2014; Koch et al., 2016; Laureys, 2005). Recently, additional dimensions have been suggested. One such dimension is the distinction between phenomenal/experiential and cognitive aspects of consciousness (Cerullo et al., 2015; Northoff, 2014). Another dimension was introduced with the form (or structure) of consciousness (Northoff, 2013, 2014). The form of consciousness pertains to the grouping and ultimately the organization of different contents, which, neuronally, is supposedly associated with the spontaneous activity and its spatiotemporal structure. The exact neuronal mechanisms underlying the different dimensions of consciousness, e.g. level/state, content/form, phenomenal/experiential, cognitive/reporting, including their relationships remain an open question.

Many studies in especially healthy subjects sought to associate consciousness with stimulus-induced or task-evoked brain activity. Specifically, the stimulus-induced or task-evoked activity refers to those neural activity changes that are related to and sufficient for the contents of consciousness (Koch et al., 2016) therefore speak of content-neural correlates of consciousness (NCC). Temporally, content-NCC is associated with event-related potentials such as the N100 and P300 (Bachmann and Hudetz, 2014; Dehaene and Changeux, 2011; Koch

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Consciousness Dimensions	Level/State	Content/Form	Phenomenology /Experience	Cognitive Processing /Reporting
Experimental testing	Task-free/resting-state paradigms	Pre-stimulus paradigms	Post-stimulus no-report paradigms	Post-stimulus report paradigms
Types of brain's neural activity	Spontaneous activity	Pre-stimulus activity	Early stimulus-induced activity	Late stimulus-induced activity
Temporo-spatial features	Infra-slow fluctuations Temporal correlations Cross-frequency coupling Small-worldness Dynamic repertoire	Non-linear interaction between pre- and post- stimulus-evoked activity Phase-preference	P50 and N100 Posterior cortical hot zones Sensory areas Cortical midline regions	Gamma activity P3b wave Prefrontal-parietal recruitment loops
Neuronal mechanisms	Temporo-spatial nestedness ⇨	Temporo-spatial alignment ⇨	Temporo-spatial expansion ⇨	Temporo-spatial globalization
Terminology	Neural predisposition of consciousness (NPC) ⇨	Neural prerequisite of consciousness (preNCC) ⇨	Neural correlates of consciousness (NCC) ⇨	Neural consequence of consciousness (NCCcon)

Fig. 1. Four Temporo-Spatial Mechanisms Account for Four Dimensions of Consciousness.

et al., 2016). Spatially, stimulus-induced or task-evoked activity in higher-order brain regions like prefrontal cortex and posterior cortical "hot zones" may be the NCC for mediating conscious content (Dehaene et al., 2014; Dehaene and Changeux, 2011; Koch et al., 2016).

More recently, different components of stimulus-induced activity have been identified including the distinction between early and late stimulus-induced activity, as well as the interaction between pre-and post-stimulus activity. Early stimulus-induced activity, as tested for in so-called no-report paradigms may be related to the phenomenal features of consciousness (e.g. experience), while late stimulus-induced activity is supposedly more related to its cognitive components (e.g. reporting and awareness of contents) (Koch et al., 2016; Lamme, 2010; Northoff, 2014; Tononi et al., 2016; Tsuchiya et al., 2015). While on the other end, prior to stimulus onset, several studies demonstrated that the level of pre-stimulus spontaneous activity impacts both stimulus-induced activity and the respectively associated content of consciousness (Boly et al., 2007; Hesselmann et al., 2008; Mathewson et al., 2009; Ploner et al., 2010; Qin et al., 2016; Sadaghiani et al., 2015, 2010, 2009; Schölvinck et al., 2012; van Dijk et al., 2008; Yu et al., 2015). The relevance of pre-stimulus activity level suggests a central role of the brain's spontaneous activity for consciousness. This is also supported by other studies in subjects with altered state of consciousness, such as unresponsive wakefulness state (UWRS), sleep, and anesthesia; these subjects showed major changes in the brain's spontaneous activity (Bayne et al., 2016).

Why and how are these different forms of neural activity (i.e. spontaneous, pre-stimulus, early, and late stimulus-induced activity) related to consciousness and its different dimensions? To date, this has not yet been thoroughly examined. We here suppose that these different forms of neural activity reflect different ways of how the brain constructs its own inner time and space, i.e. its intrinsic time and space (see below for definition). This amounts to what we describe as "Temporo-spatial Theory of Consciousness (TTC)".

1.2. Aim and overview

Time and space are the central and most basic building blocks of nature. Time and space can be constructed in different ways. While the different ways of constructing time and space have been extensively investigated in physics, their relevance for the brain's neural activity and, even more importantly, consciousness remains largely unknown though. Current neuroscientific views focus mainly on information, behavioral, affective, or cognitive features of brain and consciousness, e.g. Information Integration Theory/IIT (Tononi et al., 2016), or cognitive, e.g. Global Neuronal Workspace Theory/GNWS (Dehaene et al., 2014; Dehaene and Changeux, 2011), or Predictive Coding (Friston, 2010; Hohwy, 2016; Seth and Friston, 2016). While these views presuppose and implicitly touch upon the brain's own time and space, they do not consider time and space themselves – central dimensions of the brain's neural activity – in an explicit way, that is, how the brain itself constructs time and space in its neural activity.

Given that (i) time and space are most basic features of nature and (ii) that the brain itself is part of nature, we here consider the brain and its neural activity in explicitly temporal and spatial terms. In other words, we conceive the brain's different forms of neural activity (spontaneous, pre-stimulus, early and late stimulus-induced activity) in primarily temporo-spatial terms rather than informational, behavioral, cognitive or affective terms. This, as we postulate, is central for understanding how the brain can generate consciousness with its different dimensions. In this sense, consciousness can be understood as a temporo-spatial phenomenon of the brain's neural activity.

The main and overarching aim of this review is to provide a unified hypothesis that directly links and thus integrates the different forms of neural activity with the different dimensions of consciousness. Such integrative coherent framework is suggested to consist in temporal and spatial features of the brain's neural activity (across its different kinds). Based on various lines of empirical evidence, here we postulate the four dimensions of consciousness (level/state, content/form, phenomenal/experience, cognitive/reporting) are mediated by four corresponding temporo-spatial neuronal mechanisms: (i) the neuronal mechanism of "temporo-spatial nestedness" accounts for the level or state of consciousness; (ii) the neuronal mechanism of "temporo-spatial alignment" accounts for selecting the content and constituting the form of consciousness; (iii) the neuronal mechanism of "temporo-spatial expansion" accounts for the phenomenal dimension of consciousness, e.g. experience with qualia; (iv) the neuronal mechanism of "temporo-spatial globalization" accounts for the cognitive dimension of consciousness, e.g. the reporting of its contents (see a summary in Fig. 1). The TTC is primarily a neuroscientific theory of brain and consciousness, which may carry major philosophical implications in terms of a novel view of consciousness, and a paradigm shift from mind-body problem to world-brain problem (Northoff, 2016, 2017).

1.3. Definition of the brain's time and space

What do we mean by the terms "time" and "space"? One would argue that the brain's neural activity is by default temporal and spatial. This makes any account of consciousness and its different dimensions in