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Spatiotemporal neuroscience – what is it and why we need it

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Abstract

The excellent commentaries to our target paper hint upon three main issues, (i) spatiotemporal neuroscience; (ii) neuro-mental relationship; and (iii) mind, brain, and world relationship. (i) We therefore discuss briefly the history of Spatiotemporal Neuroscience. Distinguishing it from Cognitive Neuroscience and related branches (like Affective, Social, etc. Neuroscience), Spatiotemporal Neuroscience can be characterized by focus on brain activity (rather than brain function), spatiotemporal relationship (rather than input-cognition-output relationship), and structure (rather than stimuli/contents). (ii) Taken in this sense, Spatiotemporal Neuroscience allows one to conceive the neuro-mental relationship in dynamic spatiotemporal terms that complement and extend (rather than contradict) their cognitive characterization. (iii) Finally, more philosophical issues like the need to dissolve the mind-body problem (and replace it by the world-brain relation) and the question for different levels of time including their nestedness are discussed.

Spatiotemporal Neuroscience I – from history to present

What is Spatiotemporal Neuroscience? In order to understand the novelty of the concept of Spatiotemporal Neuroscience (STN), let us go first back briefly into the history of neuroscience. At the turn of the 19–20th century, the investigation of the brain focused on sensory and motor function, as for instance by Charles Sherrington. He and others investigated the relationship between sensory input and motor output. This input-output view of the brain was

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complemented by behaviorism, which viewed behavior as conditioned reaction of the organism and its brain and in the process rejected mental features and consciousness from the scientific agenda, developing a form of "psychophobia" that blocked important areas of research for decades (Evers, [10]).

The input-output view of the brain as a stimulus-response organ dominated in the first half of the 20th century, while in the second half of 20th century it gave way to the cognitive view of the brain. The development of cognitive science, including the delineation of various cognitive functions like attention, memory, etc., led to a shift in the view of the brain at that time: cognitive functions could no longer be explained by mere input-output relationship or a conditioned reaction of the brain.

Complementing input and output, a third layer was introduced, a cognitive layer that mediates between sensory input and motor output layer. That is, for instance, neuroanatomically reflected in the distinction between lower-order regions like input-based sensory and output-based motor cortex on the one hand and higher-order cognitive regions like default-mode network, fronto-parietal network etc. on the other. The predominant sensory and motor neuroscience in the first half of the 20th century thus gave way to Cognitive Neuroscience in the second half of the 20th century, which still dominates also in our time at the beginning of the 21st century [41].

Despite its introduction of an additional, cognitive layer, Cognitive Neuroscience nevertheless shares some similarity with the preceding input-output view of the brain. Like the input-output view, Cognitive Neuroscience focuses on how the brain processes stimuli and their respective cognitive contents. These are no longer restricted to sensory input and motor output but include additional cognitive processing of those very same sensory inputs and their information including their transformation into a motor output. The brain is thus still very much conceived as input-output device albeit with a cognitive layer sandwiched in between.

The view of the brain as input-cognition-output device is contested in STN. STN does not conceive the brain as mere input-cognition-output and information processing device. The focus is no longer on processing of stimuli and their respective contents: both the contents of internal cognition, like mind wandering [6], self-referential processing [43], and mental time travel or episodic simulation [48], and external perception and cognition are de-emphasized. Instead, the focus now shifts away from stimuli, content, and information (regardless of whether internal or external) to the brain itself, that is, its own dynamics. The early sensory-motor and current cognitive views of the brain are now complemented and, as we suppose, integrated within the larger framework of a dynamic view of the brain, i.e., STN.

Fingelkurts and Fingelkurts are right. The dynamic view of the brain as core of STN has historical predecessors. They go back to Freeman, as they point out, and their own approach to brain and consciousness in terms of Operational Architectonic is indeed a beautiful example of a dynamic spatiotemporal view of the brain – they can be termed 'spatiotemporal neuroscientists'.

It shall be noted, however, that the history of a dynamic view of the brain can be traced even further back to the beginning of the 20th century. Among Graham, Lashley, and others (see Raichle [44], [45], [46]), Hans Berger, the inventor of the EEG already stated in 1929 the following as recounted by [46]: "Since the introduction of electroencephalography (EEG) in humans by Hans Berger in 1929 [4] (for an English translation of this important work see [11]), it has been clear that ongoing spontaneous electrical activity is a prominent feature of the brain of every species in which it has been studied including humans.

In referring to the spontaneous activity in the human EEG, Berger rhetorically asked [4, pp. 562–563] 'Is it possible to demonstrate the influence of intellectual work upon the human electroencephalogram, insofar as it has been reported here?' He concluded that: 'Of course, one should not at first entertain too high hopes with regard to this, because mental work, as I explained elsewhere, adds only a small increment to the cortical work which is going on continuously and not only in the waking state'. Consistent with Berger's prediction it has subsequently been shown that extensive averaging of the EEG is necessary to attenuate if not eliminate this seemingly random, ongoing activity in order to see event-related potentials (ERPs)". (Raichle [46]).

Spatiotemporal Neuroscience II – dynamic vs cognitive view of the brain

Spatiotemporal Neuroscience aims to provide a more systematic framework for a view of the brain that first and foremost focuses on the brain's activity itself, rather than primarily its function. While the shift from brain function to brain activity may sound trivial to many in Cognitive Neuroscience, it is not. The traditional presupposition is that brain activity is identical to brain function, with both standing in more or less a one-to-one relationship such that changes in the one are manifest in changes in the respective other. That, however, is contested in STN. STN focuses mainly on the spatiotemporal dynamics of brain activity which spans across wider range than the one related to brain

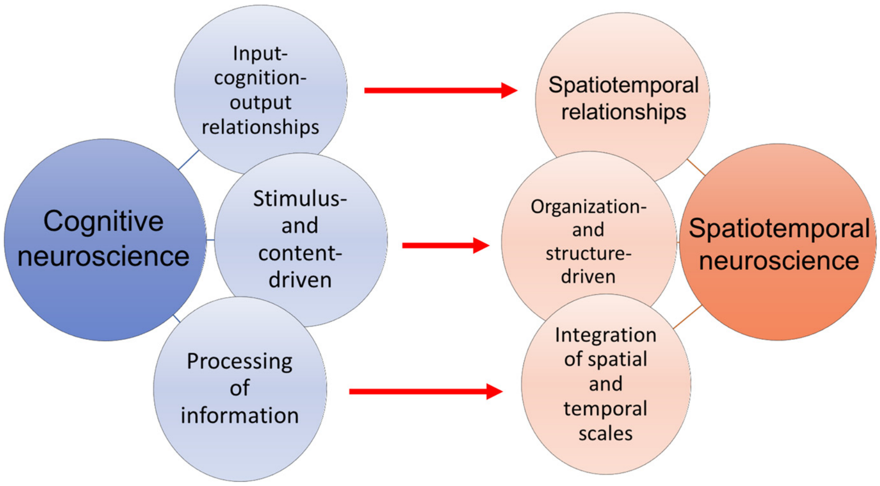

Fig. 1. From cognitive neuroscience to spatiotemporal neuroscience.

function: brain activity may be present without any brain function – for instance, the case in the example of anesthesia raised by Huang.

The shift from cognition to temporo-spatial dynamics carries three important consequences for the view of the brain. *First*, the focus on input-cognition-output relationships is replaced by spatiotemporal relationships as they can be measured by various measures like entropy, scale-free activity, etc. – these are highlighted in our target paper.

Secondly, the view of the brain as information processing device is replaced by its characterization as enabling space-time transformation: information processing is no longer regarded as primary purpose of the brain's activity, as it is replaced by the brain's capacity to transform and integrate different temporal and spatial scales of brain, body, and environment. One example of that is consciousness that may consist in exactly that, the transformation of different temporo-spatial relations into mental features – this is well compatible with the leading theories of consciousness like the Global Neuronal Workspace Theory [7,8], the Integrated Information Theory (IIT) [53], and especially the Temporo-spatial Theory of consciousness (TTC) [34,23,24].

Thirdly, the focus on stimuli and content (both internal and external) themselves in the brain's neural activity is shifted to spatiotemporal form, organization, or structure of neural (and also psychological and mental) activity like network relationships (rather than single networks) [20], shape of power spectrum across different frequencies (rather than the absolute power of each frequency) [14,15], global-to-local activity [62,63] – these were exactly the kind of measures we discussed in our target paper (Fig. 1).

How does such view of the brain in terms of spatiotemporal relationships, space-time constitution, and spatiotemporal structure stands in relation to the cognitive view of the brain? Spatiotemporal Neuroscience does not see itself in competition to Cognitive Neuroscience. Instead, STN aims to provide a broader and more comprehensive framework for Cognitive Neuroscience such that the latter can better explain and account for the various cognitive functions and especially mental features like self, consciousness, and psychiatric disorders (as in the examples of our target paper). This raises the question, how the dynamic features of the brain can be linked to its cognitive functions – how can Spatiotemporal Neuroscience be linked to Cognitive Neuroscience? That will be addressed in the next sections.

Neuro-mental relationship I – repertoire of dynamical spatiotemporal measures

There are various obstacles in establishing neuro-mental relationship in terms of dynamic spatiotemporal features. Several commentators emphasize the need for additional dynamic measures. For instance, **Kiran Reddy** suggests including the fractal dimension. We agree: the power-law exponent (discussed in our paper) is related to the fractal dimension for many processes [9]. It is prudent to point out here that estimates of fractal properties in electrophysiology can be confounded by non-fractal processes, such as cortical oscillations [5]. New computational methods to separate these processes allow for more accurate estimates of fractal properties [54]. These methods have only recently begun to see wider use, revealing differential roles for fractal and oscillatory processes in pre- poststimulus interaction [56], cognitive processing speed [39], differential relations to the fMRI signal [55], and alterations in psychiatric disorders

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such as schizophrenia [38]. In our view, the different temporal properties of fractal and oscillatory processes may result in a different relationship to mental features: however, this remains unclear at this point, and should be the topic of future research.

Vidal et al. mention the role of the brain's global activity. Global activity is often measured in terms of the global signal (GS) in especially fMRI where it is, however, often regressed out as it is seen as mere confounder and noise [42,21]. However, recent data show that the GS contains important information as it (i) exhibits specific topographical distribution in both rest and task states [63,60], (ii) dynamic pattern of co-activation with different networks [17,63], (iii) is strongly reduced during the absence of consciousness [52]; and (v) shows abnormal pattern in psychiatric disorders like schizophrenia [59,60], bipolar disorder [62], and major depressive disorder [47]. Hence, we fully agree with Vidal et al. that the brain's global activity is highly relevant and should be considered. What remains open is the exact relationship of global to local activity which, reframed in the spatiotemporal context, can be conceived as relationship between larger and smaller spatial scales. Moreover, how such global-to-local scale transformation accounts for neuro-mental transformation remains unclear, and should be the subject of further research.

Atasoy suggests including cross-frequency coupling as one important measure into our repertoire of spatiotemporal measures. Again, we agree. Cross-frequency coupling in the infraslow frequency (0.01 to 0.1 Hz), as measured with fMRI, has been shown to strongly modulate the interaction of pre- and post-stimulus activity: the more cross-frequency coupling, the more non-additive (and thus non-linear) the pre-post-stimulus interaction [15]. Since we assume that the degree of non-additivity during pre-poststimulus interaction is central for the processed stimuli and their respective contents to become conscious [34], cross-frequency coupling may be highly relevant in dynamic-mental relationship. Moreover, the degree of cross-frequency coupling is also related to the degree of scale-free activity [15,13,12] – this link cross-frequency coupling directly to the dynamic of brain activity.

Yet another example of the relevance of cross-frequency coupling is provided by [57]. She investigated resting state in EEG and observed that cross-frequency coupling (as operationalized by the modulation index) is related to inter-individual variation in the degree of self-consciousness: the stronger the phase-amplitude coupling between different frequencies, the higher the degree of private self-consciousness. This suggests that our sense of self is based on temporal integration, thus further supporting an intrinsically temporospatial view of self [28,29]. More generally, it points out the potential relevance of cross-frequency coupling and its connection between different scales for neuro-mental transformation.

Neuro-mental relationship II – spatiotemporal investigation of mental features

In his very elegant and thoughtful commentary, **Nakao** proposes three ways how cognitive functions can be linked to dynamic features. Slightly rephrased and put in a nutshell, he proposes three strategies like (i) *application* of dynamic measures to the psychological level with dynamic measurement of cognitive functions, (ii) spatiotemporal *re-definition* of cognitive and mental features; (iii) *explication* of a deeper spatiotemporal layer complementing the more surface cognitive layer as he shows impressively by his own example of agency.

We agree with Nakao in that all three strategies may be worth pursuing in parallel. Moreover, it may also depend upon the target phenomenon. Although mostly in single or only a few studies, all three strategies can be found in the current literature. (i) *application:* One can apply dynamic features like entropy, scale-free activity, etc, to cognitive or behavioral parameters as has, for instance, been done in the case of movement [40,49]. Even the self that, on the psychological level, has been operationalized and measured in the dynamic terms of scale-free activity [58].

(ii) *re-definition:* Affective, cognitive, and motor symptoms in, for instance, depression or bipolar disorder have been re-defined in spatiotemporal terms as based on spatiotemporal abnormalities in the brain's spontaneous activity [25,62,20]. (iii) *explication:* the self has been associated with a deeper spatiotemporal layer [26] featured by, for instance, temporal continuity [28,29]; this is based on empirical findings showing that self-consciousness is related to long-range-temporal correlation (LRTC) in resting state activity [14,57] including its alterations in schizophrenia [38].

Neuro-mental relationship III – Inverted U-shape relationship between dynamic measures and mental features

Huang points out the issue that even in the absence of consciousness, we can still find dynamic features of brain activity as in anesthesia. He is right. However, the presence of dynamic features as such cannot be equated with the presence of mental features. The data clearly show (as in our target article) that different degrees of dynamic features like scale-free activity or entropy are related to different degrees of mental features like consciousness or self.

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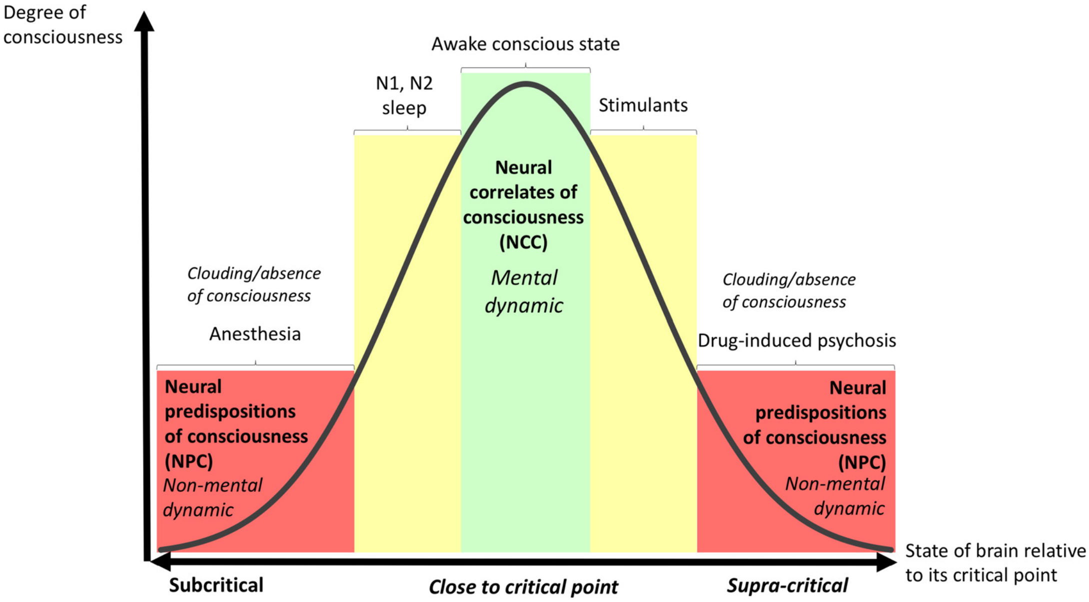

Fig. 2. Mental and non-mental dynamics.

Moreover, going to the more extreme ranges on our inverted U-shape curves of neuro-mental relationship, we can see that here different degrees of neuronal dynamic are no longer related to corresponding changes in mental features (see also [37]). Hence, the relationship of brain dynamic and mental features is not linear, amounting to one-to-one correspondence. Instead, it is non-linear, entailing an inverted U-shape relationship (see [37]).

Accordingly, mental features are not an all-or-nothing phenomenon; instead, the dynamic-mental relationship can rather be characterized by 'more-or-less' and, even more important, 'more is not always better' (reflecting the rejection of a linear neuro-mental relationship). What the data as recounted in this target article, and also in another recent paper [37] tell us, is that both too high and too low degrees of specific dynamic measures impede the manifestation of mental features: average is good, extremes are bad. The neuro-mental relationship thus does not follow a linear course but is non-linear amounting to an inverted U-shape.

Applied to the case by Huang: there are non-mental dynamical features. They operate in the extreme degrees of dynamic measures like scale-free activity, entropy, etc. At the same time, there are mental dynamical features – they, as we postulated on the basis of an inverted U-shape relationship, result from brain activity that operates in the medium or average ranges of dynamic measures. Hence, despite being extraordinary for us, mental features are, conceived in a dynamic systems context, rather dynamic averages as dynamic extremes would abolish them.

We need to distinguish between different degrees of dynamic features on the one hand and the absence or presence of dynamic features on the other. Taking the power-law exponent as an example: if basic shape of the brain's power spectrum with its steep slope from slow to faster frequencies remains absent and is, for instance, completely flat, then perhaps consciousness will be altogether impossible (see [61] as well as [16] for empirical support). In such brain without a power-law relationship between frequencies, the basic dynamical feature remains absent. This basic shape may then reflect a necessary condition of consciousness; that is, a neural predisposition of consciousness (NPC; [33,23,24,34]). In contrast, if this basic shape is present, its degree of steepness may determine the actual level of consciousness, i.e., its degree – the slope as measured by the power-law exponent, [61] is then a sufficient neural condition, that is, a neural correlate of consciousness (NCC) [36] (Fig. 2).

Neuro-mental relationship IV – Nesting of different levels of spatiotemporal scales

Tagliazucchi raises an important question how the seemingly non-dynamical representation of mental features stands in relationship to the dynamic representation of the brain's activity. This is an excellent question which, if unaddressed, may put into doubt the whole idea of STN.

Without being able to go into detail, we suggest that Spatiotemporal Neuroscience no longer presupposes any form of representation (in whatever way this multiplex term can and has been understood). There is not a specific cognitive content which is shuttled back and forth between regions and subject to various processes and operations. Rather than re-presenting, the brain takes part in an ongoing construction and reconstruction of contents, in such a way that neural dynamics may not correspond directly to our intuitive, cognitive distinctions and conceptualizations, and cannot be said to "represent" them.

This very process of construction is dynamic and thereby temporo-spatial. These renders superfluous any kind of non-dynamical re-presentation of the mental feature in question – the mental feature is by itself dynamical. However, and that is the point Tagliazucchi is hinting upon, it seems as if the mental feature itself is non-dynamical rather than dynamical. If so, one would need to raise the question how a dynamical feature like brain activity can be transformed into a non-dynamical feature as in mental features. We argue that it only seems to be that mental features are non-dynamical; in truth they may be dynamical. The illusion of mental features being non-dynamical stems from the fact that mental features operate on a small time scale like my fleeting qualia of my perception of the table which makes it hard for us to perceive and recognize their deeper dynamic nature. We thus tend to detach mental features from their deeper underlying spatiotemporal dynamic and then conceive them as re-presentations of events and objects rather than as their dynamic spatiotemporal constructions – we will come back to that point further down.

Specifically, we assume time (and space) to be constructed in different scales, small and long, with all different scales being nested (like the different Russian dolls) within each other. What looks non-dynamical and thus non-spatiotemporal to Tagliazucchi may turn out to be an abstraction: a mental feature may be characterized by an extremely short and restricted spatiotemporal scale which, if abstracted and thereby detached from its underlying longer and more extended scale may seem to be non-dynamic and thus a re-presentation of an event or object. This is like taking one smaller Russian doll out and consider it in isolation from all the others (and, even worse, forgetting that any of the others were ever present).

If, in contrast, one conceives the spatiotemporal scale of mental features in the larger context of other spatiotemporal scales, one can take into view their nestedness. In this view, mental features are nothing but a small Russian doll that is nested within the longer and more extended scales of the brain's spontaneous activity (which, by itself, is nested within the yet much larger spatiotemporal scales of body and world).

Accordingly, what Tagliazucchi describes as non-dynamic representation may turn out to be a small-scale construction, i.e., mental features, of an underlying larger-scale construction mechanism, i.e., brain dynamic and ultimately body and world dynamic. This shifts the question. Instead of explaining the relationship of non-dynamical and dynamical, as in Tagliazzuchi, we now need to account for the relationship between different spatiotemporal scales, i.e., levels of time [32]. This, in a first step, can be done by for instance recruiting mathematical tools like category theory that allows formalizing relationships between different temporo-spatial scales [36].

Brain, mind, and world I: undermining and dissolving the mind-body problem

The suggestion of temporo-spatial dynamic as "common currency" of neuronal and mental states raises not only empirical issues as discussed above also various conceptual issues. This has been pointed out by **Friston, Tagliazucchi, Huang, and Atasoy**. Roughly, as we see it, these fall into two categories, relationship of brain and mind as well as relationship of brain and world. Let us start with mind-brain relationship.

Friston states that there is no causal relationship between neuronal and mental features – there is conjugation rather than causality. That conjugation can be expressed and formalized by two forms of information geometry, mental and physical-thermodynamic which roughly capture internal and external features. He then shows (and also in other papers) how the Markov blankets allow for differentiating internal and external spheres including their different information geometries.

He summarizes his view beautifully in the title of his excellent contribution, "Dynamics versus Dualism". What does dualism mean here? His biological elaboration of the neuro-mental relation in terms of information geometry and Markov Blankets carries a deeper hidden conceptual message. By showing how internal and external spheres and their respective information geometries result from one and the same underlying dynamic process, he eradicates the conceptual possibility of dualism. Note that we here do not mean actual dualism but possible dualism, as philosophers would say. By tracing internal mental and external neuronal spheres to one and the same underlying constitutional process, dualism is not even a possibility, let alone actually realized.

While this may sound trivial, it carries major conceptual implications. If dualism is impossible, its underlying question becomes meaningless by itself. To understand the implications of that we first need to understand how the presupposition of possible dualism shapes our current philosophical questions. The possibility of dualism presupposes possible distinction of mind and brain, hence if that distinction is impossible, so is dualism and, for the sake of the matter, any other possible dualistic mind-brain theory whether as a version of supervenience, panpsychism, eliminativism, etc.

Thus Friston's shift from dualism to dynamics has consequences for a deep philosophical issue. The dualistic version of the question underlying the mind-body problem: "what is the relationship between mind and brain?" is rendered meaningless. And an answer to a meaningless question (including identity theory or functionalism with multiple realizability, as raised by **Tagliazzuchi**) also becomes meaningless. In other words, Tagilazzuchi aims to provide an answer to a question we no longer presuppose.

We, in contrast, question the question itself and discard it as meaningless which, in turn, renders any subsequent answer equally meaningless. Therefore, we suggest that the characterization of our view as either identity theory or functionalism is not valid. Taken together, we complement Friston's shift from dualism to dynamic by its conceptual elaboration pointing out its far-reaching implications for the philosophical landscape, i.e., unravelling meaningless questions like the one for the relationship between brain and mind [30].

Brain, mind, and world II: from universality to world-brain similarity

Friston describes how the internal-external distinction differentiates within the biological world itself. If so, one would expect that those features that characterize the brain's dynamic are shared with the world. In other terms, dynamic features suggested in Spatiotemporal Neuroscience should also occur in the world independent of the brain – they should thus be universal as it is nicely hinted upon by **Atasoy** especially with regard to the harmonic modes. We fully agree.

Consider scale-free activity. Scale-free activity describes long-range temporal correlation (LRTC) which have been investigated in the brain and related to perception, cognition, consciousness, and self [22,13,12,18,19,14,61,51,50,57]. Most interestingly, scale-free activity with LRTC is a ubiquitous phenomenon prevalent throughout nature as initially explored in sand dunes [2,3,1] and later in various other domains of nature and life like seismic waves and stock markets [13].

The universal nature of dynamical features like scale-free activity points to a yet deeper philosophical issue. Traditionally, the brain is regarded as special when compared to other organs and the rest of the world – that has historically been manifest in philosophical discussion of the specialness of mind and resurfaces nowadays in the tacit assumption of the specialness of brain. By denoting the brain as special, one distinguishes it from other organs and the world: what makes the brain special that it can yield something as special as mental features like consciousness? The emphasis is here thus on world-brain distinction. This, obviously, renders impossible to take into view that what brain and world share, i.e., world-brain similarity.

However, the assumption of such world-brain similarity is strongly supported on empirical grounds when hinting upon the universal nature of dynamic features as they seem to be shared by both world and brain. If now those very same dynamic features are also central in constituting mental features, neither brain (and its neuronal features) nor mental features may then be endowed with the kind of specialness we currently attribute to them.

Brain, mind, and world III: from levels of time to temporo-spatial nestedness and alignment

The assumption of world-brain similarity opens, for instance, a novel view on the puzzle of inner and outer time that **Huang** points out in his nice commentary. What is inner time and what is outer time? This, as Huang correctly points out, goes back to Kant who first introduces this distinction. We need to revisit this distinction though. There is subjective time and that is manifest in our experience or perception of our own inner time as well as in our perception of time in the outer world. Both perception of inner and outer time may for instance neuronally be related to neuronal variability in different regions of the brain like motor and sensory cortices, as we could show in a recent study [35].

Inner and outer time, conceived in such way, may thus be two distinct facets of time consciousness. Both inner and outer time are thus dependent upon us and our brain. One can thus say that inner and outer time on the mental level are two distinct manifestations of the brain's dynamic and its own time, i.e., 'brain time'. That needs to be complemented by the time in the world itself which remains independent of us, that is, our consciousness and our brain – one can thus speak of 'world time'.

One may now complain about an unjustified amplification of the concept of time: inner and outer time, brain time, and world time, to name just a few. Following Leibniz and the ancient Chinese philosopher Zhuangzi, we speak of levels of time [32]. These levels of time can be characterized by different scales; world time has a much longer and

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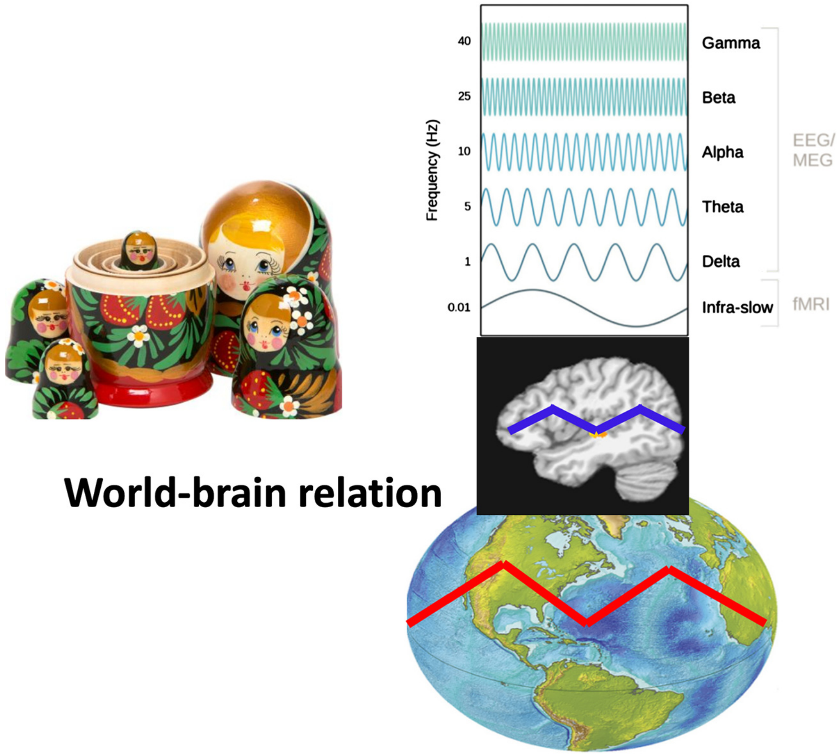

Fig. 3. Temporo-spatial nestedness and world-brain relation.

more extended time scale than brain time. We consider these different levels and scales of time as nested within each other, like the smaller Russian doll is nested within the next larger one – temporo-spatial nestedness in both world [30] and within the brain itself [34].

Given the fact that the different levels of time occur all within one and the same world, that is, the world we live in (the natural world in the terms of philosophers), the different levels must ultimately refer to the existence and reality of one and the same time, i.e., world time. We consequently suggest that time is manifest in different scales, short and long, which operate in different contexts like the world itself, brain, consciousness, cognition, etc… Time thus does not operate within the brain itself independent of the world. Instead, world-time operates through its different levels including brain thereby establishing what was recently described as world-brain relation [27,30] (Fig. 3).

The world-brain relation is essentially dynamic and therefore temporal and spatial as it relates the different spatiotemporal scales of world and brain with each other. Tentatively, we suppose that such spatiotemporal relation of world and brain is central for consciousness: the better the brain is temporally and spatially aligned to and thus integrated within the world, the more likely mental features like self and consciousness can be yielded – we thus speak of temporo-spatial alignment of the brain to the world [34,30,31]. Consider music: the better we are in synchronization with the rhythm of the music, the better we can dance, and the better our consciousness of the music. Why, after all, should our brain be different from us?

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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