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Review

Is temporo-spatial dynamics the "common currency" of brain and mind? In Quest of "Spatiotemporal Neuroscience"

Georg Northoff [a,b,c,*], Soren Wainio-Theberge [b], Kathinka Evers [c]

[a] *Mental Health Center, Zhejiang University School of Medicine, Hangzhou, Zhejiang, China*
[b] *Mind, Brain Imaging and Neuroethics, Institute of Mental Health Research, University of Ottawa, Ottawa, Canada*
[c] *Centre for Research Ethics & Bioethics, University of Uppsala, Uppsala, Sweden*

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Abstract

Neuroscience has made considerable progress in unraveling the neural correlates of mental phenomena like self, consciousness, and perception. However, the "common currency" shared between neuronal and mental activity, brain and mind, remains yet unclear. In this article, we propose that the dynamics of time and space provides a "common currency" that connects neuronal and mental features. Time and space are here understood in a dynamic context (as in contemporary physics): that is, in terms of the way the brain's spontaneous activity constructs its spatial and temporal relationships, for instance in terms of functional connectivity and different frequencies of fluctuations. Recruiting recent empirical evidence, we show that the different ways in which the spontaneous activity constructs its "inner time and space" are manifested in distinct mental features. Specifically, we demonstrate how spatiotemporal mechanisms like spatiotemporal repertoire, integration, and speed yield mental features like consciousness, self, and time speed perception. The focus on the brain's spatiotemporal mechanisms entails what we describe as "Spatiotemporal Neuroscience". Spatiotemporal Neuroscience conceives neuronal activity in terms of its temporo-spatial dynamics rather than its various functions (e.g., cognitive, affective, social, etc.) as in other branches of neuroscience (as distinguished from Cognitive, Affective, Cultural, Social, etc. Neuroscience). That allows Spatiotemporal Neuroscience to take into view the so-called 'spatio-temporality' of mental features including their non-causal, intrinsic and transformative relationship with neuronal features. In conclusion, Spatiotemporal Neuroscience opens the door to investigate and ultimately reveal the brain's own temporo-spatial dynamics as the hitherto missing "common currency" of neuronal and mental features.

Keywords: Time and space; Physics; Neuroscience; Mental features; "Common currency"; Dynamics

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[*] Corresponding author at: Mental Health Centre/7th Hospital, Zhejiang University School of Medicine, Hangzhou, Tianmu Road 305, Hangzhou, Zhejiang Province, 310013, China; Mind, Brain Imaging and Neuroethics, Institute of Mental Health Research, Royal Ottawa Healthcare Group and University of Ottawa, 1145 Carling Avenue, Room 6467, Ottawa, ON K1Z 7K4, Canada.

E-mail address: georg.northoff@theroyal.ca (G. Northoff).

URL: http://www.georgnorthoff.com (G. Northoff).

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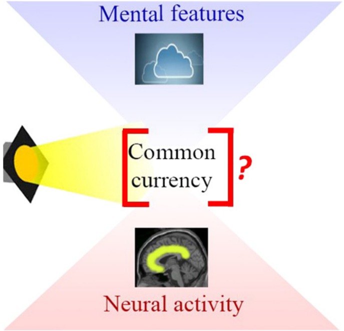

Fig. 1a. Missing "common currency" of neuronal and mental features. The figure highlights that we are currently missing those features that are shared and thus provide the "common currency" between neuronal and mental features.

1. Introduction

1.1. From neuronal to mental features – hypothesis of "common currency"

How can the brain bring forth the various mental features that characterize our experience? Recent investigations have demonstrated regions, networks, and/or frequencies involved in mental features like self [1], [2], [3], [4], [5], [6], [7], consciousness [8] [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], mind wandering [20], episodic simulation [21], empathy [22], [23], free will [24], and emotion [25], [26].

Various mechanisms like integration [16], higher-order cognitive functions [27], predictive coding [28], [29], [30], non-linearity and criticality [31], [32], [33], operational space-time [34], [35], and global neuronal workspace [36], [8], [9] have been put forward as underlying substrates of mental features (as well as several others not mentioned here). However, it remains difficult to demonstrate these mechanisms empirically, and all remain controversial.

The question of the connecting mechanism focuses more on an underlying commonly shared feature than on the differences between neuronal and mental features. Any connection of neuronal into mental features must presuppose some deeper underlying shared feature, a so-called "common currency".

What exactly is meant by "common currency"? Consider economic trade by way of analogy. Global trading between different countries is possible only on the basis of a shared currency, a "common currency" like the US dollar in our days. Imagine, if we could only observe the global trading without knowing that the US dollar (or any other currency, for that matter) provides the "common currency". We would then be puzzled about the sheer amount of trading between the different countries and wonder why and how they can be so closely connected and exchange so freely their goods.

Our little example of lacking knowledge about the "common currency" in global trading describes well the current situation in neuroscience. Having moved beyond our neuroscientific predecessors by having developed novel technical tools like brain imaging, we can now observe that neuronal and mental features are closely connected with and dependent upon each other. However, despite all this progress, we do not yet know why and how they are so closely connected with each other – their "common currency" still remains elusive to us. The quest for that very same "common currency" is the main focus in the present paper (see Fig. 1a).

The quest and assumption of a "common currency" can be conceived an empirical hypothesis about the relationship between neuronal and mental features, that is, those mechanisms that allow for neuronal activity to transform into mental features. Focusing on the brain itself and how its mechanisms transform neuronal into mental activity, the "common currency" is an explicitly empirical hypothesis that connects neuroscience to contemporary physics with especially the latter's view of time and space (see below) (rather than being an ontological assumption about the relationship between brain and mind as discussed in philosophy [37].

Taken in such empirical way, the "common currency" hypothesis must be distinguished from other neuroscientific hypotheses about neuro-mental relationship that focus on information [16], cognition [8], [9], embodiment [38], and predictive coding/free energy [30]. We will demonstrate in the last part of our paper on "Spatiotemporal Neuroscience" that the "common currency" hypothesis is not incompatible with these approaches as it provides an answer to the recent quest of a broader and unifying framework [18].

1.2. Main and specific aims – "common currency" and "Spatiotemporal Neuroscience"

We propose that the dynamics of time and space (see below for their determination) provides the "common currency" of neuronal and mental features. This converges well with the growing recognition in neuroscience of the central importance of time and space as the most basic and fundamental structures of the brain [39], [40], [41] and [42], [3], [37], [43], [44], [45], [46], [47], [48]. For instance, [43] write at the end of their recent paper in the journal "Science": "the terms 'space' and 'time', as well as other mental constructs will be part of research for years to come" (see also a recent special issue on "Time in the brain" in a merged edition of Trends in Cognitive Science and Trends in Neuroscience [46].

We here go beyond these approaches by extending the importance of time and space beyond the brain itself to their central role in yielding mental features. Specifically, our aim is to show how the dynamics of time and space, as understood in contemporary physics as distinguished from classical physics, can connect and provide the "common currency" of neuronal and mental features. Discussing recent empirical evidence from different examples like consciousness, self, and psychiatric disorders, we suggest that the dynamics of the brain's own "inner time and space" (see below) provides the "common currency" of neuronal and mental features.

The overall or main aim of our paper consists in discussing the "common currency" of neuronal and mental features. We propose that the dynamics of the brain's time and space, i.e., temporo-spatial dynamics, provides the currently missing link between neuronal and mental features, i.e. their "common currency". The specific aims are threefold.

First, we aim to compare different concepts of time and space as presupposed in classical and contemporary physics – this leads us to compare what can be described as "container vs constructions views" of time and space. We then characterize the brain in terms of the "construction view" of time and space when featuring its temporo-spatial dynamics, that is, here termed its "inner time and space". This is the focus of the first part.

Secondly, we will discuss various examples including altered consciousness, self, and psychiatric disorders, to illustrate how different mechanisms within the brain's time and space dynamics lead to different mental features. These so-called 'temporo-spatial mechanisms' provide the hitherto missing link as the "common currency" of neuronal and mental features. That is the focus in the second part which can be considered the core of our paper.

Thirdly, we introduce the concept of "Spatiotemporal Neuroscience" that focuses on the dynamics of the brain's time and space and how that relates to mental features including their own space and time, or "spatiotemporality". The determination of the brain's neuronal activity by its temporo-spatial dynamics (rather than by specific functions) distinguishes Spatiotemporal Neuroscience from other branches of neuroscience (Cognitive, Affective, Cultural, Social, etc.) that characterize neuronal activity by specific functions. We conclude that we require Spatiotemporal Neuroscience to unravel the dynamics of the brain's time and space as "common currency" of neuronal and mental features. This will be discussed in the third part of our paper.

2. Part I: time and space in physics – dynamics of the brain

2.1. Dynamics in physics – "container view" vs "construction view" of time and space

In physics, the concepts of time and space can be understood in multiple ways. Classical physics (Newton, Kepler, Galileo, etc.) views time and space more or less as "container" or "theater" within which events or objects like the brain are contained and located at specific points in time and space ("events occur in time", "the world is in space", "the brain is in time and space"). This amounts to what is described as "container view" of time and space [49], 2-3.

Serving as mere container, time and space remain independent of and outside the objects or events, they contain. As such, time and space themselves are here understood in an absolute way. Time and space are then considered separate properties or substances – this leads to what is described as "substantivalism" of time and space in philosophy [49], 2-3.

The container view of time and space carries major implications for how we conceive of the brain. Framed within such a container view, the brain is supposed to be "located" within absolute time and space like some kind of event or object. There is no intrinsic relation of the brain to its container, i.e. time and space. Instead, the brain only provides the neural basis for the perceptual and cognitive functions that allows us to perceive and cognize specific points in time and space within that very same container of absolute time and space. Neuroscience has indeed been extremely

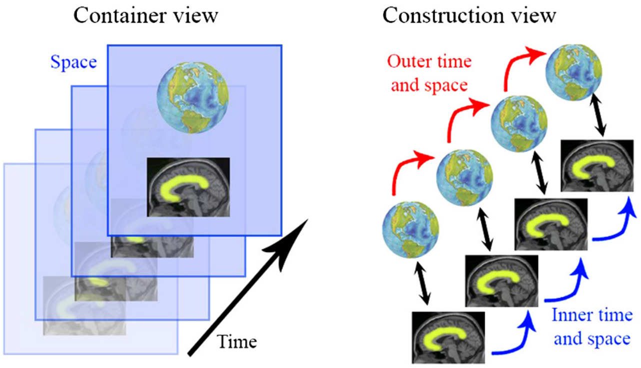

Fig. 1b. “Container view” (left; container = blue frame) and “construction view” (right; construction = arrows) of time and space in brain and world. The left part of the figure illustrated the “container view” where space (blue frame) and time (black arrow) are conceived as container as being outside and thus extrinsic to brain and world. The right part illustrates the construction view where both world and brain possess, i.e., construct, their own time and space. This is manifest in the world’s outer time and space (relative to us as humans, the world’s time and space is described as “outer”) and the brain’s inner time and space (as the brain’s time and space is part of us, we describe it as “inner”).

successful in revealing the regions, networks, and frequencies mediating our perception and cognition of time and space, or “absolute time and space” ([43], [46]; see Fig. 1b left panel).

However, neither the “container view” nor the “substantivalism” of time and space are upheld in modern contemporary physics [50], [51]. Here time and space are no longer viewed as entities that, as containers, are separate and distinguished from the events or objects which they supposedly contain. Instead, time and space supposedly consist in the continuous construction of spatiotemporal relations between the different objects or events. This amounts to a “construction view” of time and space that, as the construction concerns spatiotemporal relations, entails what philosophers describe as “relationism” [49], 2-3.

Historically, the “construction view” with “relationism” of time and space can be traced to philosophers like Leibniz, Bergson, Husserl, Heidegger, and Whitehead (in the western tradition) as well as to Zhuangzi and others (in the Chinese tradition) [52], [41] and [42], [53] and [54], [37]. The “construction view” conceives time and space in terms of relations between events or objects. Importantly, these spatiotemporal relations are part of the events or objects themselves. This is to be distinguished from the “container view” that only conceives points in time and space rather than spatiotemporal relation which, moreover, are not part of the events or objects themselves (see Fig. 1b right panel).

2.2. *Dynamics of brain I – construction of its own inner time and space*

The container view conceives the brain as part of the events and objects included and contained within absolute time and space. The brain is here only located and contained within time and space but does not exhibit its own time and space. That changes once one conceives the brain within the framework of the construction view of time. The brain can now be characterized by the continuous construction of spatiotemporal relations – these are described by the spatiotemporal dynamics of the brain’s spontaneous activity, here termed the brain’s “inner time and space” [3], [37] which resembles what [44] describe as the brain’s “operational time-space”. In contrast, the spatiotemporal dynamics of the world, independent of the brain’s activity, is termed “outer time and space”.

Let us briefly illustrate the dynamics of the brain’s “inner time and space”. The brain constructs these dynamics in terms of different frequencies with oscillations and fluctuations [55] that show a specific temporal structure with long range temporal correlations (LRTC) and scale-free activity [56], [57].

As they connect different points in time by operating across different temporal scales, LRTC can be conceived as example of temporal relation. Specifically, LRTCs and scale-free activity reflect the relationship between different frequencies and thus model different points in time relative to each other – they thus can be conceived as an operational index of relational time that signifies the brain’s “inner time”. The data now suggest that these operational indices of the brain’s inner time are central in mediating mental features like self and consciousness as well as in psychiatric disorders – this will be illustrated in the next part of this paper.

The assumption of the brain’s inner space and time takes also centre stage in formulations of neuronal dynamics, like the free energy principle. This follows because the variational free energy is defined in terms of a generative model

– and the generative model can include beliefs about states of the world in the future; particularly the states caused by our own actions [58]. This leads to the notion of *deep temporal models* that possess a necessary *temporal thickness* or depth [59]. It has been argued that a necessary characteristic of generative models that support consciousness and intentionality is precisely their capacity to model time into the future [2]. Put simply, if we, as on the basis of our brain's spontaneous activity, did not entertain a private, inner space and time, we would never be able to plan or anticipate anything.

2.3. Dynamics of brain II – from physics to neuroscience

Finally, we shall emphasize that the "construction view" and its implicit emphasis on relations between events that define the brain's neural activity as construction of spatiotemporal dynamics is well compatible with physics. Nearly all of physics, ranging from gauge theories (e.g., general relativity) to quantum mechanics can be reduced to a Langevin formulation of spatiotemporal dynamics [60]. Mathematically, this implies that the rate of change of any state is some function of that state, plus some random fluctuation:

$$\hat{x} = f(x) + \omega$$

This equation underpins quantum mechanics (via the Schrödinger wave equation [61], statistical mechanics (via the Fokker Planck equation and associated ensemble dynamics) [62], [63], right through to classical mechanics (when the amplitude of random fluctuations tends to zero). Crucially, on the current view, the very structure of this equation speaks to a *relational* perspective in space and time. This is because the rate of change of a state with time, in its state space, depends upon the location within state space.

Accordingly, the distinction between inner and outer time and space that also features the brain's intrinsic dynamics underwrites the fundamental dynamics upon which all of contemporary physics is based. We will now see that very same fundamental dynamics as being also present in the brain's construction of its own spatiotemporal dynamics is central for connecting neuronal and mental features thus providing their hitherto missing "common currency".

3. Part II: spatiotemporal mechanisms as "common currency" of neuronal and mental features

3.1. Spatiotemporal repertoire as "common currency" of brain and consciousness

3.1.1. From the spontaneous activity's entropy and complexity to consciousness

The brain's spontaneous activity exhibits an elaborate temporal and spatial structure with various networks organized in a certain way like a small-world [64], [48], [41] and [42], and [65], [66]. Importantly, this spatiotemporal structure is not static but dynamic as it constantly changes its configurations, [67] therefore speak of a "dynamic repertoire" that describes the range or number of different configurations the spontaneous activity's spatiotemporal structure can take on. Since such a dynamic repertoire reflects the range of spatiotemporal configurations, we speak of "spatiotemporal repertoire" [48].

Let us illustrate the notion of spatiotemporal repertoire by Deco's comparison of the brain's spontaneous activity to a tennis player [68]. Awaiting the service of her/his opponent, the tennis player makes various moves around the baseline of his field to put her/himself in optimal position once the opponent's service actually arrives. By moving back and forth in various ways (before the service), the tennis player constructs a virtual spatiotemporal structure along various dynamic trajectories – the more varied her/his spatiotemporal repertoire and trajectories, the more likely she/he will be able to properly respond to the opponent's service.

How then can we measure the spontaneous activity's spatiotemporal repertoire? First and foremost, one can measure entropy, ex. Shannon entropy, which describes the degree of order or disorder in a time series: the more uniform the probability distribution of the time series, the higher the degree of entropy and thus the larger the spatiotemporal repertoire [69]. If, in contrast, the probability of one particular value is much higher than the others, one will measure a low entropy – the spontaneous activity exhibits then a high degree of order with a rather limited spatiotemporal repertoire.

Another measure of the spontaneous activity's spatiotemporal repertoire is complexity. Roughly, complexity, as indexed by Lempel-Zev complexity (LZC), describes the number of unique patterns in the time series: the higher the

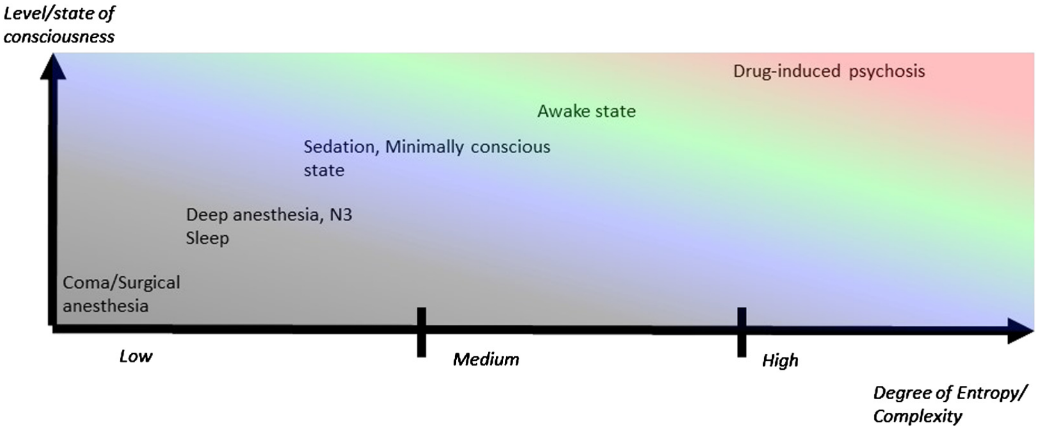

Fig. 2a. Degrees of entropy and complexity (x-axis) in states with different levels/states of consciousness (y-axis). The figure summarizes the empirical data by showing how different degrees of entropy (x-axis) are related to different level/states of consciousness (y-axis) in different conditions.

number of unique patterns one requires to account for the whole time series, the higher the LZC, and thus the higher the complexity with a larger spatiotemporal repertoire [69].

Entropy and complexity of the brain's spontaneous activity are reduced in states where the contents of consciousness become sparse [70], [71], [72]. If the contents and consciousness are lost completely, entropy and complexity, i.e., LZC (or its perturbational variant; [72] of the spontaneous activity break down [72], [73], [74], [75], [76], [77], [78], [79], [80].

How about the opposite case where the contents are increased showing abnormal richness as in drug-induced psychosis? Interestingly, investigations in drug-induced psychosis demonstrated increased degrees of entropy and/or complexity in the spontaneous activity during different psychedelic drugs like ketamine, LSD, psilocybin, and ayahuasca [81], [82], [83], [84], [77]. Importantly, the degree of entropy correlates with the intensity of psychedelic experience: the higher the degree of entropy, i.e., disorder, the more intense the psychedelic experience with increased "richness" of contents [83], [40], [81], [85] (see Fig. 2a).

3.1.2. Spatiotemporal repertoire – "common currency" of brain and consciousness

The data now suggest that the spatiotemporal repertoire of the brain's spontaneous activity is directly related to consciousness: higher degrees of spatiotemporal repertoire lead to increased numbers of contents in consciousness There thus seems to be direct relationship between the spontaneous activity's spatiotemporal structure, here indexed by order and complexity, and particular mental features of consciousness. This suggests that the neuro-mental relationship is essentially spatiotemporal.

This spatiotemporal nature of the neuro-mental relationship is more explicated in what [86], [85] suggests as 'entropic brain' hypothesis. He proposes that three main features of consciousness like (i) the richness of conscious experience, (ii) its information content, and (iii) subjective uncertainty are related to entropy on the neuronal level: the subjective uncertainty is maximized, and when neural content is completely random, the link or correspondence to mental representations of specific objects and situations does not matter anymore (as it may, for instance, be the case in extreme states of drug-induced psychosis).

Following the entropic brain hypotheses, the degree of entropy on the neuronal level of the brain translates into corresponding degrees of richness, information, and uncertainty on the mental level of consciousness. Higher degrees of entropy or disorder in the brain's spontaneous and task-evoked activity allow for richer conscious experience, more information content, and higher degrees of uncertainty: the higher the degree of the spontaneous activity's entropy, the higher the number of contents ('content-richness') with higher information and unpredictability ('subjective uncertainty') in consciousness [86], [85].

Extending this hypothesis, one may want to assume that spatiotemporal order, i.e. entropy, and complexity, i.e. LZC, are manifest on both neuronal and mental level. On the neuronal level, spatiotemporal order and complexity concern the spatiotemporal pattern of neuronal activity, i.e., the degree to which it repeats or is different over time.

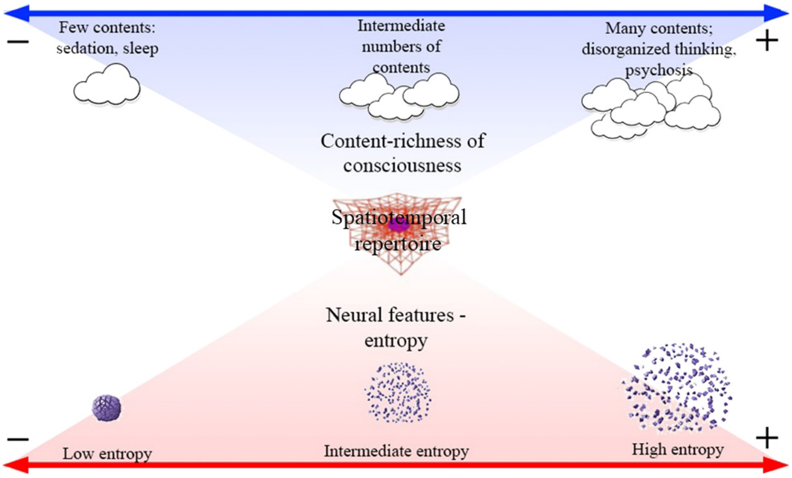

Fig. 2b. Spatiotemporal repertoire as "common currency" of the neuronal activity's entropy (lower level) and the contents of consciousness (upper level). The figure shows our hypothesis that the spatiotemporal repertoire provides the "common currency" of neural activity and the contents of consciousness. The spatiotemporal repertoire can be measured by entropy on the neuronal level (lower part) and the number of contents on the mental level of consciousness (upper part).

On the mental level, spatiotemporal order and complexity may refer to the number of different contents and their information across time and space: higher number of contents and information across (subjective) time and space leads to a higher degree of spatiotemporal entropy and complexity on the mental level of consciousness (see Fig. 2b).

Future studies are warranted to measure entropy and complexity (LZC) not only on the neuronal level but also on the mental level of consciousness, that is, the degree of spatiotemporal order and complexity of the contents of consciousness. One would expect direct correspondence of both "neuronal and mental entropy/complexity" and, even stronger, that "neuronal repertoire" transforms "mental repertoire". If so, spatiotemporal order and complexity can indeed be seen as "common currency" of the brain's neuronal activity and the mental features of consciousness. Consciousness would then ultimately have spatiotemporal (rather than primarily cognitive) basis as postulated in the recently suggested temporo-spatial theory of consciousness (TTC) [48], [87], [41] and [42].

4. Spatiotemporal integration as "common currency" of brain and self

4.1. Spontaneous brain activity and its spatiotemporal integration

Our sense of self is a central feature of our inner mental life which is neurally mediated by specific regions. When asking participants to judge trait adjectives (own vs. other) or other stimuli (like auto- vs. heterobiographical events, or own vs. other names), the resulting task-evoked activity strongly recruits regions in the middle of the brain, the so-called cortical midline structure (CMS) [88], [89], [90], [1], [91], [92]. It shall be noted though, that the CMS are not specific to the self as they have been implicated in other internal processes like emotion regulation, mind wandering, and social interaction [93], [20], [94], [95], [96].

Task-evoked activity, specifically in CMS during self-reference, strongly overlaps with resting state activity in the default-mode network (DMN), notably in the medial prefrontal cortex (including both ventral and dorsomedial prefrontal cortex; VMPFC and DMPFC) [97], [98], [99], [100], [101]. In particular, the level or amplitude of task-evoked activity during self-referential stimuli (like the own name or trait adjectives applying to the respective person) does not differ or deviate much, if at all, from the level of the ongoing spontaneous activity in these regions. Therefore, we speak of "rest-self overlap" [102], [3] that describes the convergence or overlap between self-related task-evoked and spontaneous activity in specifically CMS.

What are the neural mechanisms underlying the rest-self overlap? One hallmark of the brain's spontaneous activity consists in the fact that it can integrate neural activity over longer stretches of time. Integration means here that neuronal activities at different discrete points in time and space (as we observe it from the outside of the brain) are related and processed in dependence on each other: while different neuronal activities can be "located" at different

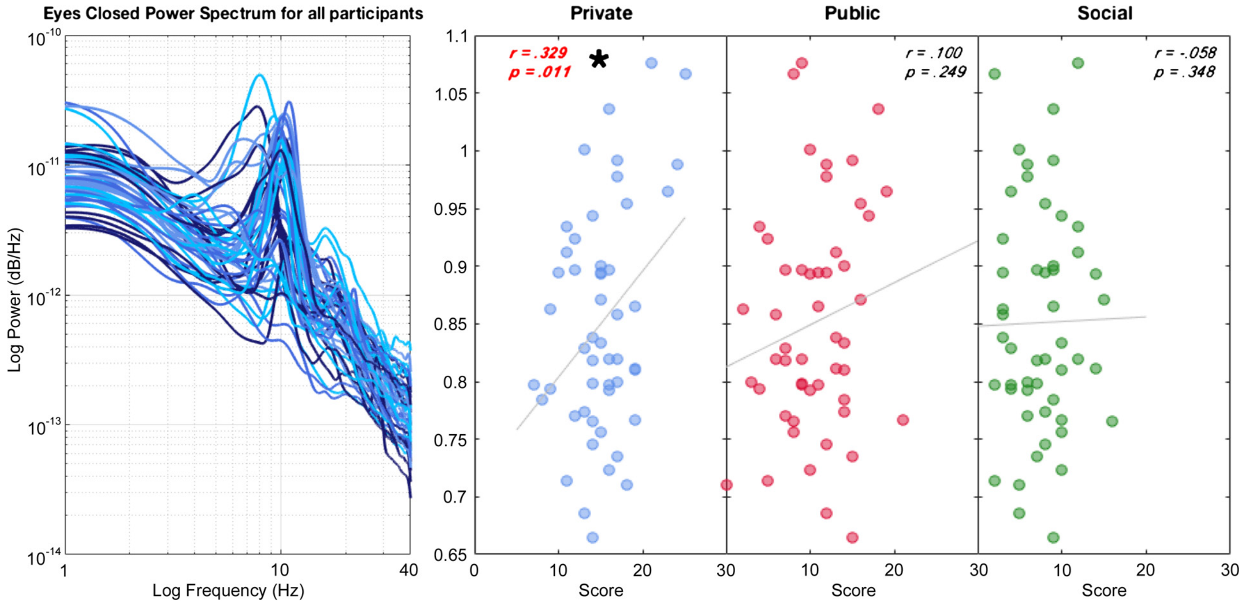

Fig. 3a. Power spectrum (in EEG; basis for power law exponent/PLE) (left) and correlation of PLE (y-axis) with private, public, and social self-consciousness (x-axis) (right). The figure shows the subjects; (each line is one subject) power spectrum (resting state EEG) on the left (x-axis log frequency, y-axis log power). The right part shows the correlation of the self-consciousness (y-axis) with the PLE of the resting state (x-axis) for private self-consciousness, public self-consciousness, and social self-consciousness.

discrete points in time and space (as we observe it from the outside of the brain), they are nevertheless "lumped" and processed together.

There are various measures of such spatiotemporal integration. On the spatial side, functional connectivity, measuring the degree of synchronization of the time series' of different regions, is one such measure of spatial integration. Temporal integration can be measured in various ways. One measure of temporal integration is scale-free or scale-invariant activity [103], [57], [104]. Scale-free activity can be expressed in the frequency domain by the relationship $P \propto 1/f^{\beta}$ where P is power, f is frequency, and β is called the power-law exponent (PLE; [105]. Scaling properties can also be measured in the time domain with detrended fluctuation analysis (DFA), which measures the power-law scaling of variance as a function of the size of the window it is calculated over [56]; [106]; [103]; [57]; [107], [108].

Both PLE and DFA imply a scale-free, or "fractal" time series, meaning that the time series is qualitatively similar no matter the scale it is observed at. For such a process, patterns at smaller scales are contained within patterns at larger scales – indeed, such scale-free processes are typically in this nested, recursive way, as in the classic Koch snowflake or Cantor set. For this reason, we can conceive of these measures as measures of temporal "nestedness": the faster frequencies and their power are contained and thus nested within the stronger power of the slower frequencies.

In addition to PLE and DFA, one can also measure the auto-correlation of the time-series, i.e., the extent to which neighboring points in the time series are correlated – this amounts to what is described as auto-correlation window (ACW; [109], [110], [111]). Since it measures the correlation of different time points, the ACW can be conceived as measure of temporal continuity [112]. Finally, [57] also measured the degree of cross-frequency coupling (CFC), which describes the coupling of the slower frequency's phase to the faster frequency's amplitude [57], [104]. The CFC thus reflects the degree to which different frequencies are coupled, or what we term temporal coupling (see Figs. 3a and 3b).

Taken together, all measures mentioned here, PLE, DFA, ACW, and CFC allow for measuring different facets of temporal integration of neuronal activity over longer stretches of time. These facets of temporal integration include temporal nestedness (PLE, DFA), temporal continuity (ACW), and temporal coupling (CFC).

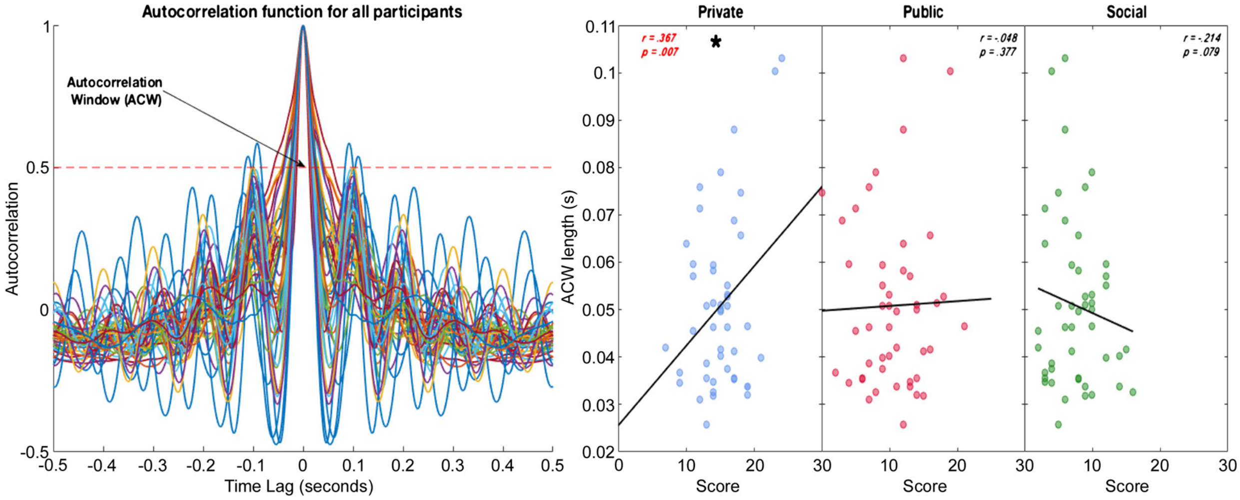

Fig. 3b. Autocorrelation window (ACW) (in EEG) (left) and correlation of ACW (y-axis) with private, public, and social self-consciousness (x-axis) (right). The figure shows subjects' autocorrelation windows (resting state EEG) on the left (x-axis time lag, y-axis autocorrelation). The right part shows the correlation of the self-consciousness (y-axis) with the autocorrelation window of the resting state (x-axis) for private self-consciousness, public self-consciousness, and social self-consciousness.

4.2. Spatiotemporal integration as "common currency" of brain and (sense of) self

How does the spatiotemporal integration of the brain's spontaneous activity, as measured by PLE/DFA, ACW, and CFC, relate to the sense of self? Given the above-mentioned rest-self overlap, one would expect that these measures of the spontaneous activity's spatiotemporal integration are directly related to self. This is exactly what we observed in recent studies using both fMRI and EEG where we therefore measured individual differences in subjects' sense of self with a scale that includes three dimensions: private, public and social [113], [112].

In both fMRI [113] and EEG [112], we showed that individual differences in self-experience, as measured with the self-consciousness scale, were related to individual differences in the CMS of the spontaneous activity's PLE/DFA, ACW and CFC: the higher the degree of self-consciousness, the higher the degree of LRTC and CFC as indexed by higher values in PLE/DFA, ACW and CFC. Most notably, these correlations only hold for private self-consciousness but not for the other subdimensions of the self-consciousness scale, e.g., public ("how much are your thoughts concerned with other people?") and social ("Are you afraid when speaking in front of crowds?") self-consciousness. In contrast, the private self-consciousness subscore measures the tendency to focus on the own self and its inner thoughts as in introspection rather than on other persons.

Together, these data suggest that the spontaneous activity's degree of spatiotemporal integration including spatiotemporal nestedness, continuity, and coupling is directly related to the sense of self on the mental level, as indexed by the private self-consciousness scale. This raises the question whether the spatiotemporal integration on the neuronal level corresponds to and surfaces in analogous spatiotemporal integration on the mental level of the self. One would, for instance, expect that the degree of spatiotemporal continuity of neuronal activity across different points in time, as measured by the ACW, surfaces in analogous integration of different points in time on the psychological level of self.

Psychologically, the self has been associated with integration, as in the integrative self model of Sui [114], [5]. Specifically, the self supposedly integrates different functions like emotions [115], reward [116], decision making [117], [118], perception [119], and action [120]. Given the primary temporal nature of spatiotemporal integration, one would now assume that the integrative function of the self on the psychological level may mainly operate by integrating the different points in time associated with the different functions (e.g., affective, cognitive, sensory, motor, etc.) pointed out above.

For instance, perception, action, emotions, and reward all show different time scales, e.g., slower or faster, which may be linked and thus integrated by the self through its temporal continuity across their different points in time. The data show that the sense of self is associated with strong power in slower time scales entailing long cycle durations. These long cycle durations, in turn, are ideal to integrate and embed shorter time scales as associated with, for instance,

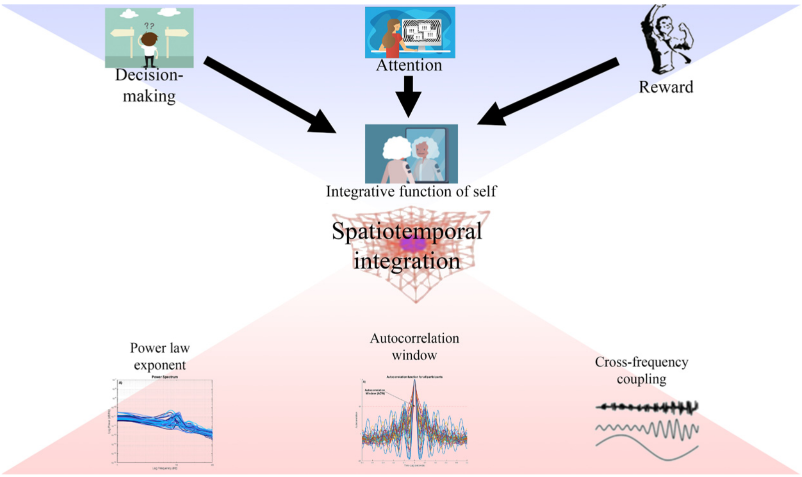

Fig. 3c. Spatiotemporal integration as "common currency" of the spontaneous activity's temporal structure (lower level) and the integrative function of self (upper level). The figure shows our hypothesis that the spatiotemporal integration provides the "common currency" of neural activity and the integrative function of self. The spatiotemporal integration can be measured by PLE and ACW on the neuronal level (lower part) and the degree to which the self integrates different cognitive functions like attention, decision making, etc. (upper part).

sensory or cognitive functions – the latter will subsequently be integrated and embedded within the former. The exact mechanisms of such temporal integration remain unclear though. One possible mechanism could consist in cross-frequency coupling with the phase of the slower frequency (related to the sense of self) coupling to the amplitude of the faster frequency (as mediating the cognitive or sensory functions).

One would thus expect that the degree of spatiotemporal integration on the neuronal level can predict the degree of the self and its temporal integration across different points in time on the psychological level. Spatiotemporal continuity and, more generally, spatiotemporal integration would then be manifest on both neuronal and mental level and thus provide the "common currency" of both. In short, spatiotemporal integration may be the "common currency" of brain and self (see Fig. 3c).

5. Speed as "common currency" of brain and time perception

5.1. Depression and mania – abnormal inner and outer time speed perception

We so far demonstrated that spatiotemporal repertoire provides the "common currency" of brain and (contents of) consciousness, while spatiotemporal integration connects brain and self. Yet another mental feature is our perception of time speed. You may sit in a meeting which lasts for 2 hours. However, you felt and perceived the duration of the meeting much longer, perhaps around 3 hours, as you were completely bored and not at all interested. There is thus a discrepancy between the objective duration of the meeting and your subjective perception – the meeting was subjectively much longer than it objectively took place.

One extreme example of such objective-subjective discrepancy can be found in psychiatric disorders most notably in depression and mania as in bipolar disorder. Bipolar disorder is a psychiatric disorder that can be characterized by extreme mood fluctuations as in depression and mania with both showing abnormal experience of time and space.

Depressed bipolar patients are known to suffer from an experience of abnormal slowness in their inner time perception – they have the feeling that "nothing changes" and that time "stands still" [121]. Their "inner time speed" is thus extremely slow as indexed by lack of perceived change, while "outer time speed" of events in the world is perceived as too fast. For instance, one depressed patient told me that she did not speak at all because she subjectively perceived her mother to speak extremely fast – although, objectively, she knew that this was not the case. Manic patients, in contrast, show the opposite pattern. They perceive the outer time speed in the world as too slow, while their inner time speed is much faster.

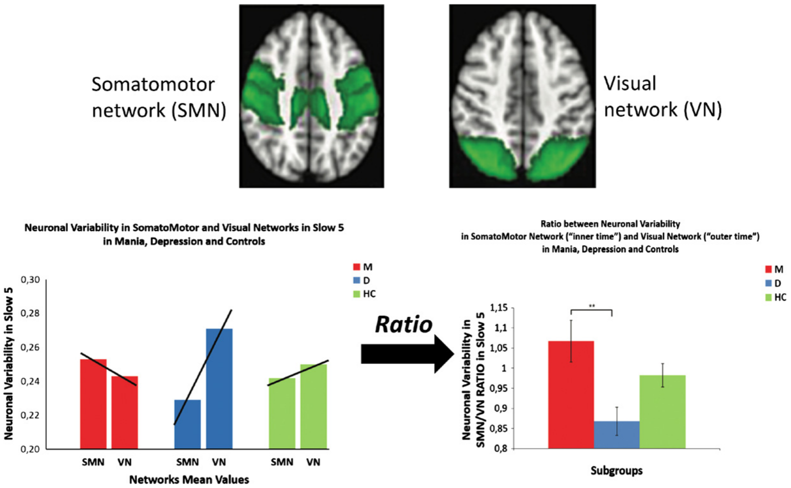

Fig. 4a. Somatomotor (SMN) and visual (VN) networks (upper) and their neural variability in mania (M) (red), depression (D), and healthy controls (HC) (green) in SMN and VN (lower left) and the ratios between VN and SMN (lower right). The upper part shows the anatomic characterization of the visual network (VN) and somatomotor network (SMN). The lower left part shows the degree of neural variability in SMN and VN in mania (red bars), depression (blue bars), and healthy subjects (green bars). The lower right part shows the ratios in neural variability between SMN and VN in mania (red bars), depression (blue bars), and healthy subjects (green bars).

5.2. Speed as "common currency" of brain and (inner and outer) time perception

One may now raise the question of how we can relate these abnormalities in time speed perception to the dynamics of time in the brain's spontaneous activity. The time speed of neuronal activity can be operationalized by neuronal variability (defined here as standard deviation, or SD) that describes the degree to which the signal changes over time. If the SD is high, the fluctuations in neuronal activity are large, and the signal changes more from time point to time point; if, in contrast, the signal does not change much, the SD is low, indexing slow neuronal speed [121]. In short, we take neural variability as a proxy of neural "speed".

Moreover, given the distinction between inner and outer time perception on the mental level, we, analogously, may want to distinguish between inner and outer time speed on the neuronal level. The sensorimotor network (SMN) has been associated with the perception of ones' own inner time speed (see [121] for details). In contrast, we assumed that the primary sensory networks like the visual network (VN) may be linked to the processing of outer time speed as it is here where the external sensory stimuli first (neglecting subcortical regions for simplicity) contact with the brain. We thus conceived SD in SMN and VN as spatiotemporal proxies of inner and outer time speed on the neuronal level.

Following the abnormal temporality on the mental level, one would expect in depressed patients abnormally low SD in the SMN ("slow inner time") and abnormally high SD in the VN ("fast outer time"). In contrast, manic subjects exhibiting the reverse mental pattern with fast inner time and slow outer time may show the opposite neuronal pattern, with high SD in the SMN and low SD in the VN. This is exactly what our results demonstrated, showing opposite disbalance in SD between the SMN and VN in depressed and manic BD patients – this corresponded well to the desynchronization between inner and outer time speed on the mental level. Healthy (and euthymic) subjects show more balanced in SD between SMN and VN which, on the mental level, indicates synchronization between inner and outer time speed perception (see [121] for details) (see Fig. 4a).

Taken together, the empirical data from bipolar disorder suggest that time speed connects neuronal and mental levels. Time speed is manifest in the degree of change on the neuronal level, as measured by neuronal variability in different networks like SMN and SN. At the same time, speed surfaces on the mental level in our perception of inner and outer time speed. Speed may thus provide a "common currency" of neuronal and mental activity across time (see Fig. 4b).

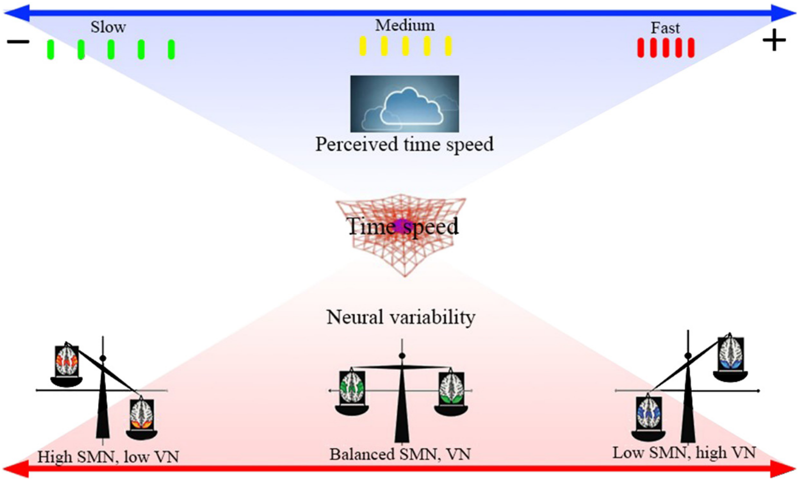

Fig. 4b. Time speed as "common currency" between the brain's neural variability in distinct networks (SMN, VN) (lower level) and the perceived time speed (upper level). The figure shows our hypothesis that time speed provides the "common currency" of neural activity and the integrative function of self. Time speed can be measured by neural variability on the neuronal level (lower part) and the perceived time speed on the mental level (upper part).

6. Part III: spatiotemporal neuroscience – a spatiotemporal approach to the neuro-mental relationship

We here focused on the dynamics of time and space in the brain's activity and how that connects neuronal and mental features. Specifically, we demonstrated how the brain's activity constructs its own dynamics of time and space (its so-called inner time and space), indexed by different spatiotemporal features like spatiotemporal repertoire, spatiotemporal integration, spatiotemporal speed. Most importantly, based on empirical findings, we showed how these three spatiotemporal mechanisms correspond to distinct mental features, e.g., contents of consciousness, sense of self, and inner and outer time speed perception.

Together, we suggest a spatiotemporal approach to the brain which amounts to what we describe as "Spatiotemporal Neuroscience". As in its name, Spatiotemporal Neuroscience conceives the brain in terms of its temporo-spatial dynamics rather than in terms of specific functions like cognitive, affective, social, cultural, etc. Taken in this sense, we deem Spatiotemporal Neuroscience essential to understand and reveal neuro-mental relationship.

We characterize Spatiotemporal Neuroscience by four main features: (i) dynamic- and rest-based approach to neural and mental features; (ii) spatiotemporal rather than cognitive characterization of mental features in terms of 'spatio-temporality'; (iii) transformative rather than causal relation between neuronal and mental features; and (iv) characterization of neuronal and mental features as conjugate pairs and derivatives of their underlying temporo-spatial dynamics. In the following we shall briefly explicate these three core features of Spatiotemporal Neuroscience (see Fig. 5a).

6.1. Brain – dynamics vs functions and rest vs. task

Neuroscience conceives the brain and its neural activity predominantly in terms of functions like cognitive, affective, social, sensory, motor, cultural, vegetative, and behavioral functions. This has led to the development of different branches of neuroscience including Affective Neuroscience [122], Cognitive Neuroscience [123], Vegetative neuroscience [124], Social Neuroscience [125], and Cultural Neuroscience [126], [127].

The basic (sometimes hidden or implicit) presupposition shared by the various branches of neuroscience is that the brain's neural activity is determined by specific functions (e.g., sensory, motor, affective, etc.). For instance, a region like the fusiform face area is defined by its function of processing faces, while a particular frequency like theta is characterized by a specific cognitive process, that is, memory [128].

Both spatial and temporal features of the brain's activity are here thus characterized by their function – function determines activity including its spatial (like FFA) and temporal (like theta) features. The temporal and spatial features of the brain's neural activity are here thus completely determined by their function. Methodologically, this

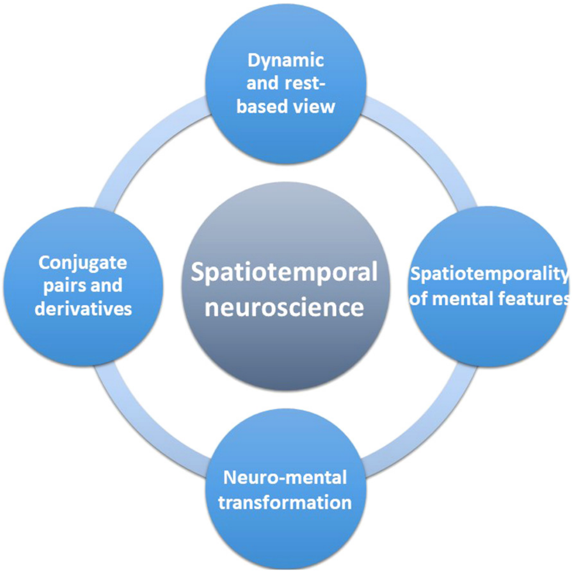

Fig. 5a. Characterization of Spatiotemporal Neuroscience. The figure depicts central features of Spatiotemporal Neuroscience which distinguishes it from other branches of neuroscience like Cognitive, Affective, Social, and Cultural Neuroscience.

function-based view naturally requires a focus on the brain's stimulus-induced or task-evoked activity: to investigate the relation of neural activity to function, we need to apply specific stimuli or tasks to probe its function. The function-based approach to the brain thus goes methodologically hand-in-hand with what we describe as 'task-based approach' in current neuroscience. The function- and task-based view of the brain is somewhat limited, however, in investigating mental features. This, as we assume, is based on both temporal and spatial differences. Let us start with the temporal differences.

Mental features cannot be limited to the short and often discrete moments in time and space as functions and their underlying task-evoked or stimulus-induced activity. Even though the contents of our consciousness may change and thus be discontinuous, consciousness itself nevertheless remains more or less continuous over time. The time scales mental features are thus distinct from those of affective, cognitive, etc. function and their respective neural activity. That is one reason why the function- and task-based view of the brain as characterized by short time scales may be insufficient to account for the much longer more continuous time scales of mental features.

In addition to these temporal differences, there are also spatial differences concerning their recruitment of regions in the brain. Various studies demonstrated that cognitive functions like attention, semantic processing, and working memory remain insufficient to account for the basic features of our mental like consciousness (especially its phenomenal components, e.g., [129], [130], [16] and self [3], [38]). The main finding in these studies is that the regions related to the different cognitive functions simply do not overlap with those implicated in consciousness. Hence, in addition to the stated temporal differences, there also seem to be spatial differences on the neuronal level. Together, the temporal and spatial differences between cognitive functions and mental features make it even more pressing to search for alternative ways of relating neuronal and mental features, i.e., neuro-mental relationship.

Based on our examples presented above and others, we propose that the dynamic- and rest-based view of the brain may provide a promising option. Specifically, we discussed above three spatiotemporal mechanisms, namely spatiotemporal repertoire, integration, and speed, which may underlie some of these more basic phenomenal features of mental life. In our view, we therefore define the brain by its spatiotemporal mechanisms rather than neuro-cognitive, -affective, -social, etc. mechanisms that underlie their respective functions. The function-based view is here thus replaced by what we describe as 'dynamic-based view' of the brain.

The dynamic-based view of the brain also shifts the focus away from the stimulus-induced or task-evoked activity to its own spontaneous activity, the so-called resting state activity [131]. As explicated above, the spontaneous activity constructs its own inner time and space resulting in spatiotemporal dynamics. The primary focus is then on the

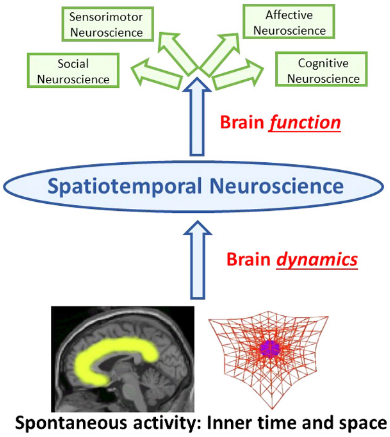

Fig. 5b. Spatiotemporal Neuroscience – dynamics- and rest-based. The figure shows how Spatiotemporal Neuroscience, as featured by dynamics and spontaneous activity (lower and middle part), is related to and, specifically, provides the basis and ground for other branches of neuroscience that focus more on function and task-evoked activity (upper part).

spontaneous activity's temporo-spatial dynamics and how they modulate and shape subsequent stimulus-induced or task-evoked activity, so-called rest-stimulus interaction [132], [133].

Taken together, Spatiotemporal Neuroscience conceives the brain in terms of dynamics rather than function. Methodologically, that entails a shift in focus from stimulus-induced or task-evoked activity to the brain's spontaneous activity, the resting state, and how that constructs the brain's inner time and space – the task-based view is thus replaced by a rest-based view. Together, dynamic- and rest-based views shift the focus away from the brain's various functions towards its "inner time and space" as defining feature of Spatiotemporal Neuroscience.

Note that, we do not consider Spatiotemporal Neuroscience to stand in contradiction to and/or be mutually exclusive with the other branches of neuroscience. Instead, we assume that by focusing on the brain's temporo-spatial dynamics and its spontaneous activity, Spatiotemporal Neuroscience provides a larger more comprehensive and eventually unifying framework as it provides the spatiotemporal and dynamical basis that underlies the various functions, e.g., cognitive, affective, sensory, motor, etc. (see Fig. 5b).

6.2. *Mental features – dynamics- and rest-based approach*

The function- and task-based view of the brain is also applied to mental features. For instance, the current neuroscientific theories of consciousness search for a specific function that defines consciousness. The Integrated Information Theory (IIT) defines consciousness in terms of a specific function that allows for integration, i.e., integrated information [16]. Analogously, the Global Neuronal Workspace Theory (GNWT) conceives consciousness in terms of an access function, that is, access to cognitive functions and their global workspace [8], [9]. This amounts to what we describe as 'functional approach' to mental features.

Either function, integrated information and access to the global workspace, is then, in a second step, related to specific regions and their activity in the brain which are probed by investigating stimulus-induced or task-evoked activity (when comparing unconscious vs conscious stimuli/tasks or states during stimulation/task). Both IIT and GNWT thus presuppose a function- and task-based view of the brain. Such function- and task-based view of the brain is also presupposed in the case of other mental features like self when the self is conceived as integrative function [114] and associated with specific networks in the brain [5].

As demonstrated in our three examples, such 'functional approach' to mental features is no longer presupposed in the spatiotemporal approach to mental features. Instead of specific functions, the brain's own spatiotemporal mechanisms and their dynamics are here the starting point as they are supposed to provide the connection to mental features, i.e., their "common currency". This presupposes dynamics-based rather than function-based view of the brain. Moreover, as we showed in all three mental features discussed above, i.e. consciousness, self, and time speed perception, the spontaneous activity and, more specifically, its dynamics, plays a central role in yielding the respective mental features. Methodologically, the task-based view is here thus replaced by a rest-based view of the brain.

Together, Spatiotemporal Neuroscience suggests a dynamic- and rest-based approach to mental features. That puts the hitherto dominating function- and task-based approach in a wider context as it allows to unravel the dynamical and thus temporo-spatial mechanisms that underlie functions like integration and access to the global workspace as defining features of consciousness and self. We therefore do not consider Spatiotemporal Neuroscience to stand in contradiction to the other branches of neuroscience. Instead, Spatiotemporal Neuroscience provides a larger, more comprehensive, unifying framework that allows for taking into view a more intimate relationship between neuronal and mental features.

6.3. Mental features – 'spatio-temporality' as 'subjective' time and space

Spatiotemporal neuroscience defines the brain's neural activity in terms of its construction of "inner time and space". If that very same inner time and space is supposed to provide the bridge and thus "common currency" to mental features, one would expect the latter to show somewhat corresponding spatial and temporal features. Such spatiotemporal view of mental features seems to stand in contradiction to their traditional characterization in philosophy. The early philosopher Rene Descartes could not "localize" mental features like self and consciousness in the "absolute time and space" of the body and the physical world, presupposing classical physics with a "container view" of time and space. He therefore assumed a separate atemporal and aspatial entity, the mind, as distinguished from the body, to which mental features could be attributed. This laid the foundation for his mind-body dualism [134], [130], [37].

However, as in contemporary physics the container view of time and space has been replaced by the construction view, the Cartesian view of mental features as atemporal and aspatial has also been abandoned since and revised by subsequent philosophers. For instance, William James presupposed consciousness as temporal when he spoke of a "stream of consciousness" [135], [136]. Similarly, the philosopher Edmund Husserl spoke of "inner time consciousness" [137]. Analogously, our experience or sense of self is also strongly temporal as characterized by "self-continuity" [138], [4].

Taken together, mental features are no longer conceived as a-temporal and a-spatial in current philosophy. That distinguishes these approaches from older traditions in philosophy that contrast the subjective nature of mental features with objective time and space in physics. Instead, mental features are now supposed to be spatial and temporal albeit in a subjective sense focusing on the experience of time and space in first-person perspective (as distinguished from their observation in third-person perspective). Such subjective experience of time and space in first-person perspective is described as 'spatio-temporality' [139], [121]. In short, spatio-temporality describes time and space in subjective (rather than objective) terms.

The subjective nature of 'spatiotemporality' implies that time and space in mental features are described in a virtual way as they cannot be observed from the outside in terms of discrete points in time and space (as in the container view of time and space). Instead of discrete points in time and space, spatio-temporality can be characterized by the subjective experience of relation between discrete points in time and space, as, for instance, in the "stream of consciousness" and the continuity of self. Time and space, as presupposed in spatio-temporality, are thus determined in a relational way and thus in exactly the same way as in the construction view of time and space in contemporary physics.

Taken together, time and space are defined in a relational way in both the construction view in temporary physics and spatio-temporality in contemporary philosophy. Next, we showed that the construction view of time and space also applies to the brain and, more specifically, how the spontaneous activity constructs its own inner time and space. That, in turn, leads us to assume that the brain's construction of its relational "inner time and space" is transformed into and thus manifest in the "spatio-temporality" of mental features.

In conclusion, both spontaneous activity and mental features share one and the same concept of relational time and space, or temporo-spatial dynamics. Due to their shared temporo-spatial dynamics, one can hypothesize that neural dynamics are mental dynamics – temporo-spatial dynamics thus provides the "common currency" of neuronal and mental features.

Such a spatiotemporal approach has been recently developed for different mental features like consciousness in the "Temporo-spatial theory of consciousness" (TTC) [48], [87], [130], [37], spontaneous thought or mind wandering as reflected in the "Spatiotemporal theory of task-unrelated thought" (STTT) [37], and the "baseline model of self" as featured by its spatiotemporal characterization [3], [4], [113], [112]. Moreover, "Spatiotemporal Psychopathology"

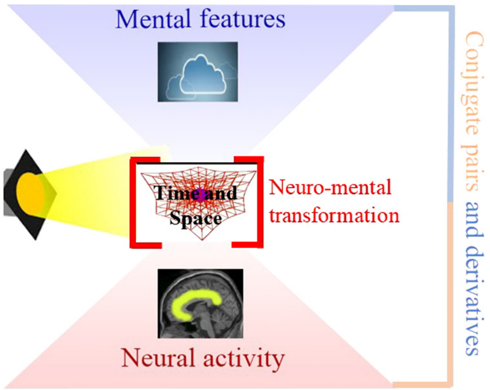

Fig. 5c. Temporo-spatial view of neuro-mental transformation. The figure schematically illustrates how temporo-spatial dynamics is essential for transforming neural activity (lower part) into mental features (upper part). Importantly, temporo-spatial dynamics is manifest in the spontaneous activity's neuronal dynamics (as it can be measured with complexity, entropy, scale-free activity, etc.) as well as in mental features where it has been described as 'spatio-temporality'. Taken in such sense, both neuronal and mental features can be conceived as conjugate pairs and derivatives of the more basic underlying temporo-spatial dynamics (right vertical part).

conceives psychiatric symptoms in spatiotemporal terms [53] and [54], [4], [37], [45]. Finally, such a spatiotemporal approach also provides the bridge for linking the neuroscientific empirical investigation of mental features with more philosophical or ontological issues about consciousness [41] and [42], [3], [37] and mind-body problem [3], [37]. That, for instance, leads one to reformulate consciousness in spatiotemporal terms and the mind-body problem as world-brain problem [130], [3], [37].

6.4. Neuro-mental relationship – transformation vs causality

Defining mental features by specific functions, the current approaches assume causal relation between the respectively underlying neuronal activity and the respective mental features. This is especially obvious in the Integration Information Theory (IIT) that assumes integration on the neural level to cause consciousness [16]. Similarly, neural activity in dorsolateral prefrontal cortex, providing supposedly access to global cognition, stands in a causal relation to consciousness as postulated in the GNWT [8], [9]. The relationship between neuronal and mental features is here thus defined by causality, here termed 'neuro-mental causality'. The assumption of a causal relationship implies that the neural activity and mental activity are distinct entities – otherwise, a causal relationship would be nonsensical.

Such neuro-mental causality is no longer presupposed in the case of Spatiotemporal Neuroscience and its approach to mental features. Mental features are here supposed to reflect the dynamics of time and space itself rather than a specific function like integration or access. In short, neural dynamics are mental dynamics. No causal relationship is thus necessary anymore to connect neuronal and mental features – the dynamics of time and space provides an intrinsic and non-causal neuro-mental relationship. Neuro-mental transformation is an intrinsic (rather than extrinsic) feature of spatiotemporal mechanism and, more generally, the brain's temporo-spatial dynamics. No additional extrinsic ingredient (like a specific function as integration or access) is needed besides temporo-spatial dynamics and its spatiotemporal mechanism to allow for neuro-mental transformation. The intrinsic nature of distinguishes neuro-mental transformation from neuro-mental causality where both neural and mental features remain extrinsic to each other (as otherwise the assumption of causality would not be necessary at all) (see Fig. 5c).

Presupposing such intrinsic relationship, neuronal and mental features can be conceived as features of one and the same underlying characteristics, that is, temporo-spatial dynamics. This marks temporo-spatial dynamics as "common currency" of neuronal and mental features. This can be compared to the two perspectives on one and the same train in the following quote: "The internal perspective can be likened to the perspective of a passenger inside a moving train, whereas the external perspective can be likened to the perspective of one observing the moving train from a distance" [140].

The data suggest that such neuro-mental transformation is based on specific spatiotemporal mechanisms and, importantly, the degree to which they are expressed. For instance, stronger degrees of spatiotemporal repertoire, as measured by entropy, lead to higher number of contents in consciousness, i.e., extended consciousness. While a more restricted spatiotemporal repertoire reduces the contents of consciousness as in sedation and, even stronger, disorders of consciousness (see above). Neuro-mental transformation may thus be a function of the degree to which the respectively underlying spatiotemporal mechanism is expressed.

7. Conclusion

The connection between neuronal and mental states and, more generally, the link between brain and mind is one of the great remaining mysteries of nature. Specifically, the "common currency" connecting neuronal and mental states remains unclear. We have here suggested the dynamics of time and space as the yet unclear connection or "common currency" of brain and mind.

Presupposing a "construction view" of time and space, as in contemporary physics, we focused on various spatiotemporal mechanisms how the brain constructs its "inner time and space". We highlighted three such spatiotemporal mechanisms: repertoire, integration, and speed. The empirical evidence strongly suggests that these mechanisms allow the transformation of neuronal activity into mental features like consciousness, self, and time speed perception.

The spatiotemporal characterization requires a "spatiotemporal approach" to brain and mind, for which reason we speak of "Spatiotemporal Neuroscience". Spatiotemporal Neuroscience defines the brain's neuronal activity in terms of its temporo-spatial dynamics rather than by functions (cognitive, social, sensory, motor, affective, etc.). The spatiotemporal or dynamics-based approach to the brain allows Spatiotemporal Neuroscience to link the brain's temporo-spatial dynamics to the temporo-spatial dynamics of mental features. Temporo-spatial dynamics are thus shared by both neuronal and mental features for which reason they provide their "common currency": in short, neural dynamics are mental dynamics. This entails a transformative, intrinsic, and non-causal relationship of neuronal and mental features – neuro-mental transformation replaces neuro-mental causality.

In conclusion, we propose a novel empirical view of neuro-mental and, more generally, mind-brain relationship. Neuronal and mental features are here conceived as derivatives and conjugate pairs of a commonly shared underlying feature, temporospatial dynamics, which provides their "common currency". Importantly, our Spatiotemporal Neuroscience approach aligns neuroscience, in its search for the neural basis of mental features with contemporary physics as hallmarked by its construction view of time and space. Such alignment with physics, in turn, opens novel doors and methodological tools to investigate the neuro-mental relationship in neuroscience.

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