Title: Uncovering the spatiotemporal scales of common neuro-mental constructs

Subtitle: Comment on “Is temporo-spatial dynamics the ‘common currency’ of brain and mind? In Quest of ‘Spatiotemporal Neuroscience’” Georg Northoff et al.

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Among the oldest and most elusive questions in philosophy is the so-called mind-body problem[1,2]. Until recently, the concept of mind was considered to be non-scientific and remained outside the scope of science, but over the last few decades neuroscientists have become more and more interested in understanding the relationship between the psychological contents of the human mind and brain activity[3]. With the development of novel technical and analytical tools, neuroscience has started to identify incipient correlates of subjective mental phenomena at a neural level, for example identifying the brain states underlying wakefulness and various sleep stages – and the transitions between them[4]. However, a precise understanding of the mechanisms behind deeper constructs linking mind and body is still missing, as suggested by the interrogative title of the review "Is temporo-spatial dynamics the 'common currency' of brain and mind? In Quest of 'Spatiotemporal Neuroscience'".

In this review, the authors put forward the interesting hypothesis that the mental life and neural activity are two manifestations of the same phenomenon; in stark contrast with other theories that define mental features as being specific functions of the brain[5]. This change of perspective implies that the mental features can no longer be understood as a by-product of any underlying neural activity, but rather as being the same entity. The neuro-mental relationship is governed by a transformation between neural and mental space. Crucially, because this transformation is done at once on the whole system, what matters is not the state of one of its parts, but how they relate to each other within the system.

In our opinion, in the review the authors have underlined a fundamental question of how best to make progress in understanding and revealing the neural correlates of complex mental constructs such as self, consciousness or free will: when and where do we have to look for them? Such high-level psychological experiences are likely to be found at the global, integrative level; in the global brain dynamics resulting from the temporally evolving patterns of interaction between different brain areas. The authors discuss recent empirical evidence in favour of this perspective, showing how different features of the brain's spatiotemporal organization can be linked with three specific mental experiences: consciousness, the self and time speed perception. For instance, their Figure 2 illustrates how the richness of the brain's spatiotemporal repertoire could reflect different states of consciousness. The ongoing spontaneous activity of the brain shapes an inner time and space, which could account for the richness of conscious experience rather than being a simple one-to-one map of outer reality, opening up the possibility of

subjective experience, learning, and free will. When mental representations are too constrained by the physical environment conscious experience ceases to exist and when they are totally independent from it, the subject can become detached from reality, for example in cases of psychosis. Optimal levels of intrinsic fluctuations allow for conscious integration of information, yielding adaptability, functionality and responsiveness to the challenges posed by the external reality. This is supported by accounts suggesting that a notion of 'levels of consciousness' is an over simplified description of what is a much more complex phenomenon unfolding in a multidimensional space[6,7].

The global approach in the study of the brain has to be seen as a complementary perspective to the localist one. While a localist approach has been remarkably successful in elucidating specific psychological functions (for example cognitive, affective, sensory and motor functions), the global, network perspective has the power to potentially reveal the neural underpinning of much more global integrative functions such as personality, a sense of self and perhaps even consciousness. These global constructs transcend and integrate specific functions, providing a certain degree of continuity and unity across time. These phenomenal constructs are likely to be affected at longer time scales by every single experience of the subject. In support of this view are the changes in personality that gradually arise in some patients over the course of the first 18 months after limb amputation[8] or the progressive psychological adjustment associated with the process of trauma[9,10]. None of these have been explained by merely localist approaches.

If indeed the spatiotemporal structure defines the neuro-mental relationship, the fundamental question to correctly focus the problem is to precisely determine the relevant temporal and spatial *scales* of the global patterns of activity[11–13]. Indeed, different phenomena are best characterized by diverse spatial scales and evolve over the course of different temporal scales[14]. And rather than merely relying on correlations, whole-brain modelling of brain activity can provide a natural framework to disentangle the different scales that are at stake in the brain activity[15,16]. In such models, the global spatiotemporal dynamics result from the mutual interactions of local node dynamics coupled through a structural connectivity matrix. Typically, these models include global parameters that are kept constant and optimized to reproduce the patterns encountered over the course of hundreds of seconds. However, with longer recordings and higher computational power, additional differential equations could be introduced to describe the evolution of these parameters over the course of longer time scales. We believe that the statistical

description of the non-stationarity of these parameters could be used as a "second-order" characterisation of a brain/mental state.

The review by Northoff et al. is well timed and offers the reader a general perspective of how recent developments in neuroscience have provided new information to better defining the intriguing mind-body problem from a scientific perspective. Through reviewing the recent evidence, the authors have made a commendable effort to bridge the gap between philosophical and scientific inquiry and set up an interesting starting point to make further progress in our understanding of the neuro-mental relationship in the coming years.

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