A NOVEL PROCEDURE FOR THE ASSESSMENT OF MULTIDIMENSIONAL BRAIN ACTIVITIES

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The brain activity displays hidden functional dimensions, apart from the conventionally assessed three spatial ones (plus time). This finding, corroborated by a long sequence of recent experimental observations, requires novel methodological devices in order to provide a mathematical treatment for such elusive nervous extra-dimensions. Here we describe a novel, simple approach that makes feasible to extract hidden multidimensional information from real neurodata series, in order to detect, assess and quantify a fourth spatial dimension of cortical activity. Also, our technique might stand for the first step towards an artificial nervous network equipped with four spatial dimensions, instead of the classical three.

KEYWORDS: central nervous system; Hall effect; oscillations; fourth dimension; EEG

The brain activity might take place in dimensions higher than the classical three spatial dimensions plus time. Many recent papers point towards this hypothesis. To make an example, it has been shown that the brain might react to stimuli by building a tower of temporary multidimensional blocks, starting with mono-dimensional rods, then bi-dimensional planks, three-dimensional cubes and more complex multidimensional geometries (Reimann et al., 2017). Tozzi and Peters (2016) detected a spatial fourth dimension in the brain that follows donut-like trajectories, whose otherwise undetectable movements may be recognized by peculiar hints endowed in three-dimensional (plus time) human neurodata. In touch with these claims, also the color's perceptual space, correlated with the three cone absorption spectra, is believed to occur in dimensions higher than the three spatial dimensions-plus time (Victor et al., 2017). Mazzucato et al. (2016) demonstrated that external stimuli are able to reduce the dimensionality of cortical activity: the more the network's ensemble size grows, the more neurons are recruited, the more the dimensions. In particular, they showed, in touch also with Peters et al. (2017), that the default mode network displays higher dimensionality, compared with other brain networks.
The issue of the multidimensional brain is an exciting field of research, potentially able to provide integrative insights into nervous organization and pathology. It is easy to foresee that the hidden dimensions of the brain will play a role in the assessment of psychiatric disorders. However, a problem arises: how to experimentally cope and assess such elusive multidimensional activities? The recent appearance of datasets encompassing thousands of features has led to the development of novel tools, such as feature selection, able to model the underlying high-dimensional settings of data generation (Garcia et al., 2018). However, despite feature selection's techniques allow the reduction of the data dimensionality and improve algorithms' performance (Dmochowski et al., 2017), the huge volumes of data make the learning tasks more computationally demanding than ever. When dealing with a very large number of more and more complex features, learning algorithms' performance degenerates, so that speed and efficiency of the algorithms decline in accordance with size. Indeed, the most used algorithms were developed when dataset sizes were much smaller, and nowadays they are not able to cope with emerging Big Data problems. Therefore, novel tools are required in order to assess and quantify such multidimensional issues related to nervous activities. Here we describe a novel tool that is able, starting from simple traces detected through easily available neurotechniques (such as EEG and fMRI), to detect the fourth spatial dimension of the brain.

MATERIALS AND METHODS: A NOVEL TOOL FROM THEORETICAL PHYSICS

Here we ask: is it feasible to assess and quantify how brain oscillations generate nervous multidimensional activity? More specifically, is it feasible to build a real or an artificial neural network able to simulate the otherwise undetectable fourth spatial dimension of the brain? The answer might be affirmative. Indeed, recent experimental findings describe a technique that might throw an operational bridge between theoretical physics and biophysical neuronal activity. At first, we need to take into account the "Hall effect" (Hall, 1879): when a magnetic field is applied perpendicularly to an electric current flowing in a conductor, it occurs the production of a voltage difference, transverse to the electric current. In simpler words, a magnetic field with the proper angulation is able to curve an electric ray. A similar process, called "quantum Hall effect" occurs in other contexts (Novoselov et al., 2007). An electric charge sandwiched between two surfaces behaves like a two-dimensional material. When this material is cooled down to near absolute-zero temperature and subjected to a strong magnetic field, the amount that it can conduct becomes "quantized", leading to the so-called quantum Hall effect. It has been suggested that this puzzling phenomenon is easily explained, if we take into account that it occurs in four, instead of the canonical three, spatial dimensions (Zhang and Hu 2001; Kraus et al., 2013; Zilberberg et al., 2018). In touch with the latter claim, Lohse et al. (2018) found a (relatively) simple way to probe four-dimensional quantum physical phenomena, starting from a simple artificial, two-dimensional dynamic system. They found that the light flowing through the two-dimensional device behaves exactly according to the predictions of the four-dimensional quantum Hall effect. In other words, the Authors provided a two-dimensional waveguide equipped with complex patterns that act as a manifestation of higher-dimensional coordinates. In operational terms, Lohse et al. (2018) built a 2D lattice consisting of superlattices along the x and y axes. Each superlattice is achieved by superimposing two standing waves of different wavelength (**Figure 1A**). Then, a third wave is introduced along the x direction: this operation corresponds to tilting the long lattice along the one-dimensional path along the axis x, carefully choosing the proper inclination (**Figure 1B**). In their skillful account, Lohse et al. (2018) and Zilberberg et al. (2018) provided all the measurements (wavelengths, angles, equations) required in order to detect the 4D quantum Hall effect. They demonstrated that their procedure allows the achievement of dynamics along the axis y that are equivalent to movements in four spatial dimensions. Indeed, they attained two different responses: a linear one (two-dimensional) along the axis x and a nonlinear one (four-dimensional) along the axis y (**Figure 1C**).

In sum, the Authors provided a relatively simple approach that describes peculiar quantum dynamics is terms of pure oscillations. In our proof of concept study, we ask: could such procedure be transferred, with the due corrections, to the neuroscientific field? Or put simply: might the peculiar conformation of the waves located in the above-mentioned lattice stand for nervous oscillations of different frequency, able to intersect one each other in order to build a spatial four-dimensional where brain activities might take place?

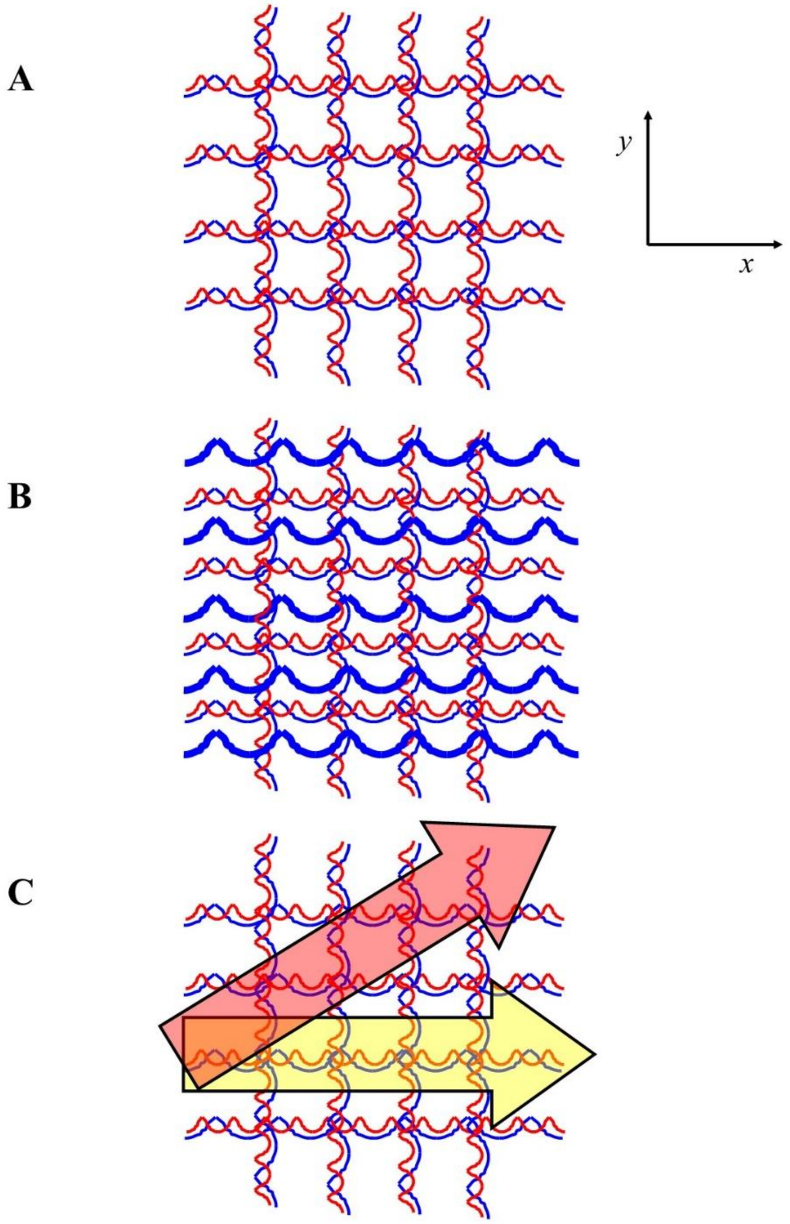

Figure. 4D physical activities on a 2D superlattice, according to Lohse et al. (2018). **Figure A** depicts a topological lattice equipped with two waves of different wavelength (red and blue thin lines). **Figure B**: another wave (blue thick line) with the proper wavelength and angulation (not shown here) is superimposed to the lattice along the direction x. Note that, in the experimental assessment of Lohse et al. (2018), the proper angulation of the third wave is achieved by tilting the lattice. **Figure C**: the superimposition of the three waves gives rise to two different motions: a linear one along the axis x (yellow arrow), and a nonlinear one along the axis y (red arrow).

RESULTS: THE FEASIBLE PROCEDURE IN NEUROSCIENCE

In the previous paragraph, we showed how Lohse et al.'s (2018) approach holds true for the assessment of peculiar multidimensional issues occurring in the field of quantum dynamics. Here we show how, with the proper amendments, their "four-dimensional-building apparatus" could be used also to assess and quantify the presence of a further spatial dimension in the brain. The waves required to build the lattice might stand for well-known nervous electric oscillations, detected in vivo through different neurotechniques such as EEG and fMRI. The superimposition of real neural waves of different wavelengths might produce the required superlattice illustrated in **Figure 1A**. Further, when the functional

reticulum is crossed by other brain waves of different frequency (**Figure 1B**), both (two-dimensional) linear and (four-dimensional) nonlinear nervous dynamics might be achieved. Therefore, our theoretical aim is to transfer the framework of the quantum Hall effects provided by Lohse et al. (2018) to the realm of neuroscience, in order to: a) describe the real multidimensional brain dynamics and b) demonstrate the feasibility of a synthetic nervous network equipped with four spatial dimensions (plus time), instead of the classical three (plus time).
How to locate the above-mentioned lattice, when we take into account in vivo, experimentally detected brain oscillations? We stated that a superlattice is achieved by superimposing two standing waves of different wavelength: **Figure 2** describes the required electrical nervous oscillations, extracted from EEG traces. In this case, the two required waves might stand for brain oscillations of different frequency, e.g., to make just a theoretical example, the beta and delta oscillations detected through EEG techniques (**Figure 2A**). The EEG trace displays, in awake subjects during mental activity, a predominant, diffused beta rhythm, that might stand for one of the two main components of the lattice. The beta oscillations can be superimposed with other oscillations with lower frequencies, say the delta ones, in order to achieve the required two-dimensional lattice. Now we need the third wave. To make an example, when, during awake and rest, the alpha rhythm starts to develop from the rostral areas, this might mean that a further oscillation is superimposed to the lattice, giving rise to our required third wave (**Figure 2C**). The superimposition of this latter wave gives rise to two different motions: a linear one along the axis x, and a nonlinear one along the axis y (**Figure 2D**). The oscillatory response along the y axis can be quantified and assessed: it stands for the component that displays the fourth spatial dimension of the brain electric activity.

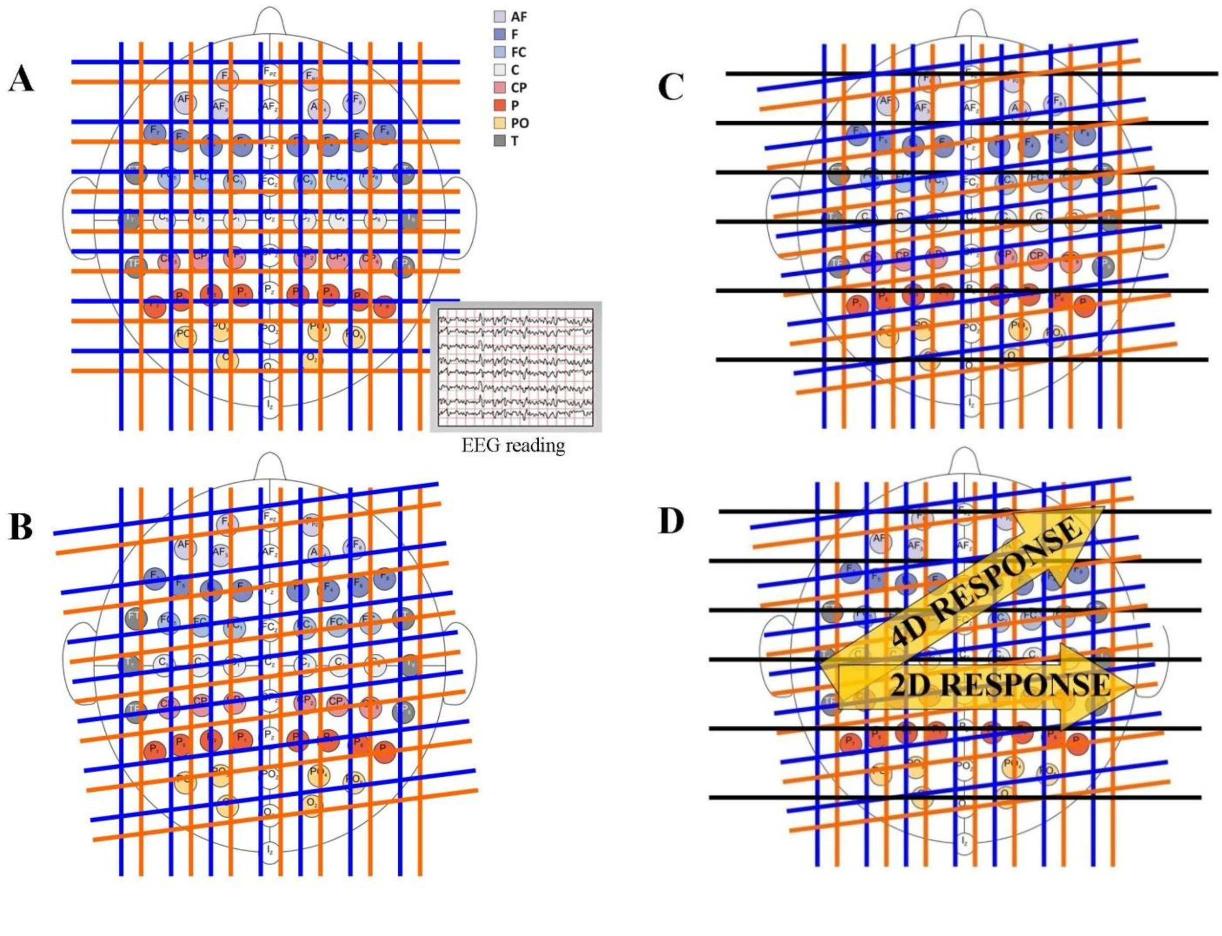

Figure 2. Procedure for the detection of a spatial four-dimensional activities, starting from brain oscillations extracted by EEG traces. **Figure A**: a two-dimensional reconstruction of EEG with mountages is superimposed with the real brain electric oscillations, arranged into a two-dimensional reticulum. The red and blue lines stand for different brain frequencies detected by EEG. In **Figure 2B**, a proper tilting is imposed to the two-dimensional reticulum. In **Figure C**, a third wave (black lines) standing for a further oscillation is superimposed to the reticulum along the axis x. **Figure D**: the superposition and interactions among the three oscillations give rise to two different oscillations along the axis x and y, standing respectively for a two- and a four-dimensional response. Note that the axes x and y can be arranged according to different orientations of the two-dimensional EEG reconstruction. Modified from Grabner and De Smedt (2012).

CONCLUSIONS

Working on a properly manipulated two-dimensional lattice, it is feasible to achieve a transverse oscillation which stands for the whole system's four-dimensional component. Here we showed how it is feasible to superimpose two-dimensionally arranged brain oscillations, in order to check for the presence of a four-dimensional transverse oscillation.

Recent claims suggest that this multidimensional brain framework, based on Lohse et al.'s (2018) account and on superimposed nervous oscillation that interact one each other, can be theoretically achieved. Indeed, Axelrod et al. (2017) showed that several cognitive processes functioned simultaneously during self-generated mental activity, so that internally directed experience may be achieved by pooling over multiple cognitive processes. The achievement of a four-dimensional neural manifold (starting just from lower-dimensional waves) gives us the opportunity to formulate empirically testable hypotheses. We provide here just a theoretical example. During visual perception, gamma waves convey the feed-forward message from primary sensory areas, while beta waves the feed-back message from higher associative areas: the frontal areas and, possibly, the posterior parietal areas. Indeed, Akrami et al. (2018) reported that the posterior parietal cortex is a central component in the processing of sensory-stimulus history and might encompass the subject's previous motor experience. The interaction among such different waves might produce a more efficient functional dimension, i.e., a higher dimensional phase space where mental operations might take place. Another possibility is to use transcranial stimulation's external waves that intersect the brain tissue with a proper angulation, in order to restore the physiological four-dimensional functional space that might be disrupted during diseases, such as, e.g., seizures. The last, but not the least, different nervous activities (such as mind-wandering, higher cognitive activities and task-related responses) might exhibit different four-dimensional components, that, once detected, could be experimentally assessed and quantified.

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