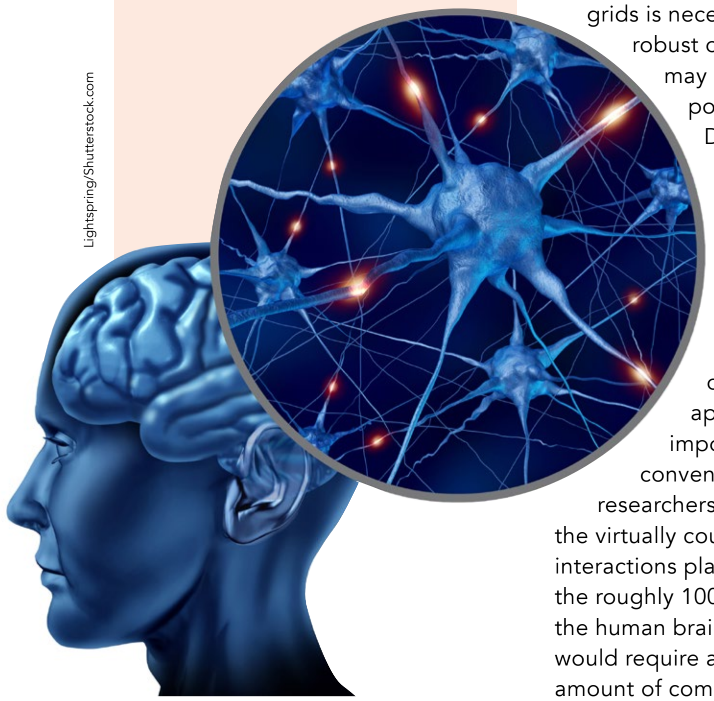
Modelling synchronisation in the brain and in nature

Many systems in both nature and technology are governed by intricate webs of interactions between oscillating objects. In some cases, these oscillations can become synchronised, giving rise to a wide variety of intriguing behaviours. Until now, however, these processes have widely been viewed as too complex to study using conventional models. In his research, Dr Jakub Sawicki at the Technical University of Berlin and the Potsdam Institute for Climate Impact Research has introduced novel approaches to analyse synchronisation in complex systems. His approach has led to new explanations of characteristic effects in two entirely different scenarios: neurons in the brain, and pipes in an organ.



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From dance routines to communication networks, the effect of synchronisation is a familiar, often critically important aspect of many of the systems we see around us. "Synchronisation is a state where parts of a system behave coherently and can have both constructive and destructive consequences for the system itself", Dr Sawicki explains. "It is a ubiquitous phenomenon, observed in different disciplines including physics, acoustics, neuroscience, and socioeconomic systems."

Through his research, Dr Sawicki explores how synchronisation phenomena can arise in complex systems – where many different components interact with each other across intricate networks of links. In many of these cases, synchronisation can be fundamental to the operation of everyday infrastructures. In others, however, it can also be incredibly damaging. "Synchronisation in power grids is necessary for a stable and robust operation, and failure may result in cascading power breakdown", Dr Sawicki continues. "On the other hand, synchronisation in the human brain can lead to Parkinson's disease and epilepsy."

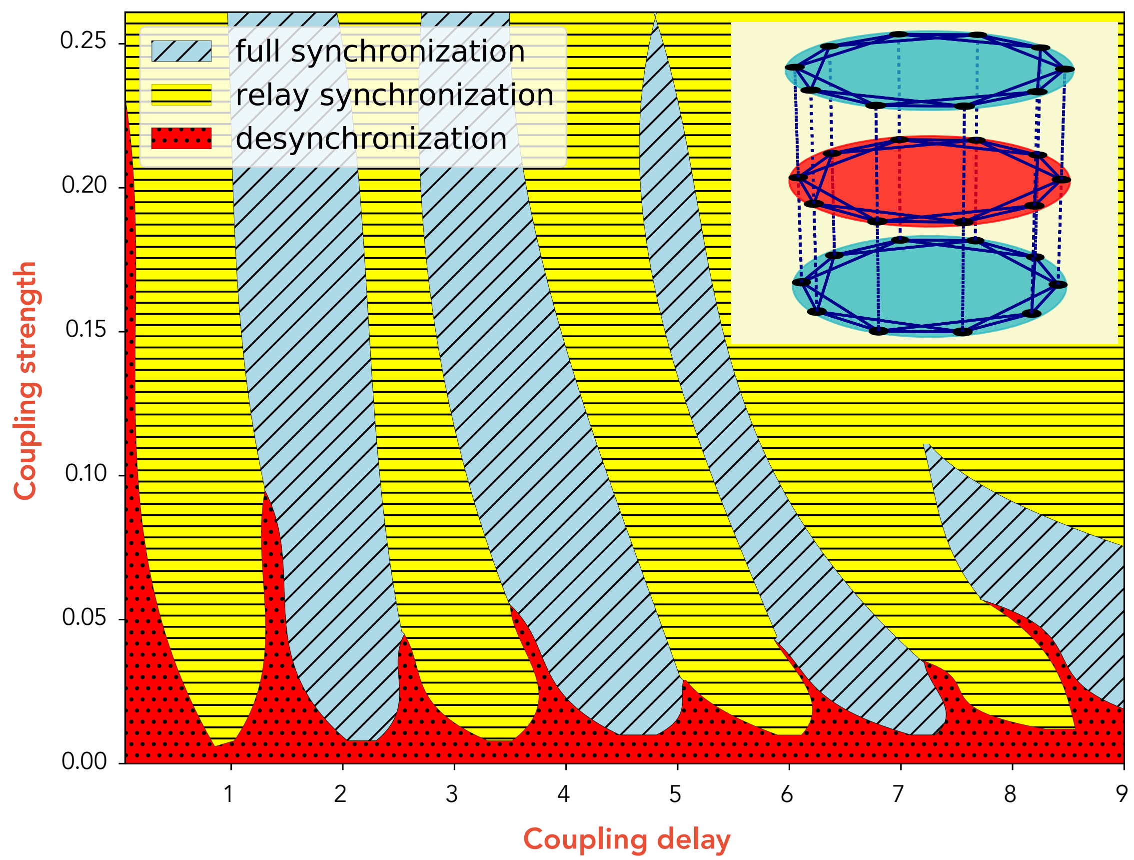
On the surface, each of these systems appears virtually impossible to study using conventional techniques. If researchers attempted to simulate the virtually countless numbers of interactions playing out between the roughly 100 billion neurons in the human brain, for example, they would require an unfathomable amount of computing power – putting such efforts entirely out of reach of present-day technologies.

So far, these challenges have widely prevented researchers from gaining useful insights into how synchronisation arises in complex systems, and how it evolves over time. Yet through his research, Dr Sawicki is developing advanced techniques to simulate these systems based on experimental data – crucially, without the need for vast amounts of computing power. Together with colleagues in Germany and the Czech Republic, he has now used these novel approaches to study synchronisation in two distinct scenarios.

MODELLING UNIHEMISPHERIC SLEEP

In the natural world, many animals are often in situations where sleep is not an option. While migrating birds need to travel across vast distances without ever landing for a rest, aquatic mammals must routinely come up to the surface to breathe, requiring them to maintain some degree of waking consciousness at all times. Through their evolution, these organisms have developed an ingenious solution to this problem. Their approach is based around the hemispheric structure of the brain – which divides it into two halves, each capable of operating independently of the other. When they need to rest, animals – including dolphins, seals, and swallows – will send one hemisphere of their brains into a deep sleep, while the other remains awake.

Named 'unihemispheric' sleep, Dr Sawicki proposes that this behaviour relies on synchronisation between the electrical signals fired by neurons in each hemisphere. Through a study published in 2019, his team produced a model based around experimental



Relay synchronisation 'tongues' in the parameter plane of inter-layer coupling strength and in-layer coupling delay.

data of structural connectivity, measured in the brains of healthy human subjects. From the data, they constructed networks of interactions between model neurons, which fired off realistic periodic signals, and were divided into two distinct, yet interacting hemispheres.

The results were promising. "The brain has a naturally hemispheric structure, which can be modelled in a 'multilayer' framework: two hemispheres with a coupling within and between them", Dr Sawicki describes. "Through computer simulations, I have shown for the first time that in certain cases, states of unihemispheric sleep can be obtained as a certain type of synchronisation pattern."

Here, the patterns appeared as time-varying asymmetric signals in the model brain; causing one hemisphere to be more active at a given time and allowing the other to sleep.

Furthermore, these synchronisation patterns could be enhanced by controlling the coupling strength between the two hemispheres. For the first time, the result clearly shows how the sophisticated sleeping patterns of many animals could have evolved. Moreover, for human brains the result can be used to explain the mechanism of the first-night effect, which describes troubled sleep in a novel environment.

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CHIMERA STATES IN THE BRAIN

In a more general picture, previous studies have shown that unihemispheric sleep could be connected to phenomena named 'chimera states'. These complex synchronised patterns feature a coexistence between 'coherent' states – electrical signals that can be described using mathematically well-defined patterns – and 'incoherent' states, which cannot be so clearly defined. In our own brains, this effect can be seen in 'first night syndrome' – the state in between waking and sleeping we often experience when spending the night in a new location. Yet in some rare cases, spontaneous synchronisation can have far more dangerous consequences, producing life-threatening epileptic seizures.

In a 2018 study, Dr Sawicki revealed how certain types of chimera states can emerge in 'triple layer' brain models, where different regions of the brain are connected via a 'relay' sandwiched between them. "A highlight of my research is the discovery of so-called 'double chimeras' in my simulations", he says. "Recent research in neuroscience indicates that many parts of the brain, including the thalamus, interneurons, and hippocampus, act as relays that connect two different regions. I have shown that previously

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The overall sound of church organs is deeply affected by synchronisation.

unexplained experiments on imperfect synchronisation in mice brains might be explained by my novel scenarios of chimera states."

Through a further study, published in 2020, Dr Sawicki and his colleagues also demonstrated the emergence of seizure-related chimera states in networks of neuronal oscillators. Their results have now brought about significant progress in neurologists' understanding of how epileptic seizures initiate and end, and how the many people who suffer from them could be better treated.

SYNCHRONISED WAVES IN MUSIC

Alongside his research, Dr Sawicki is also a professional organist, and no stranger to the ways in which synchronisation can affect the acoustic waves produced by musical instruments. In a church organ, for example, grand soundscapes are generated by the oscillations in large pipes, as pressurised air is driven through them. In some cases, the peaks and valleys in amplitude in the waves produced by different pipes can become in-phase synchronised; or, in the reverse case, they can become anti-phase synchronised. When this happens, interference between them can weaken their overall sound, which is highly undesired.

Strangely, recent experiments have shown that the inter-pipe interactions which generate these synchronisations depend strongly on the distance between them in a non-monotonic way. Due to this distance, the sound from one pipe needs time to reach another one. To provide a deeper understanding of the impact of such a delay time, Dr Sawicki and his team introduced a nonlinear model to give a detailed and complete analytic picture of both sound amplitudes and frequency. This detailed analysis has affirmed the existence of in- and anti-phase synchronisation in dependence on the delay time.

"In each case, the synchronisation frequency has a different value which perfectly agrees with my analytic calculations and the experimental data", describes Dr Sawicki. "Moreover, the results explain the surprising counter-intuitive dependence of synchronisation upon the distance between organ pipes. This dependence has been found experimentally, but has not been understood so far." As a result, the results provide a solution to a long-standing mystery among musicians and could help organ builders to re-arrange pipes to produce better sounds.

EXPANDING MODELS OF SYNCHRONISATION

Through the widely varied cases of synchronisation studied by Dr Sawicki and his colleagues, researchers are now gaining an increasingly sophisticated understanding of how large, complex systems behave. Already, their results have revealed numerous potential benefits to research in the fields of neuroscience and acoustics alike. In the future, similar simulation techniques could expand into even more diverse areas: from the efficient operation of electrical grids, which are becoming increasingly reliant on dispersed renewable power generation, to new techniques for managing a diverse and global economy.

Dr Sawicki and his colleagues demonstrated the emergence of seizure-related chimera states in networks of neuronal oscillators.

Behind the Research

Dr Jakub Sawicki

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Research Objectives

Dr Sawicki studies synchronisation phenomena in complex systems.

Detail

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Bio

Jakub Sawicki is a professional musician and physicist. His research is combining aspects of both fields. Apart from his position as organist at Berlin Cathedral, he teaches improvisation at University of Arts Berlin. His research interests include synchronisation phenomena in music, nonlinear delay differential equations, and modelling of neural dynamics.

Collaborators

Prof Eckehard Schöll

References

Gerster, M., Berner, R., Sawicki, J., Zakharova, A., Škoch, A., Hlinka, J., Lehnertz, K., & Schöll, E. (2020). FitzHugh–Nagumo oscillators on complex networks mimic epileptic-seizure-related synchronization phenomena. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 30(12), 123130. Available at: https://doi.org/10.1063/5.0021420

Ramlow, L., Sawicki, J., Zakharova, A., Hlinka, J., Claussen, J.C., & Schöll, E. (2019). Partial synchronization in empirical brain networks as a model for unihemispheric sleep. *Europhysics Letters*, 126(5), 50007. Available at: https://doi.org/10.1209/0295-5075/126/50007

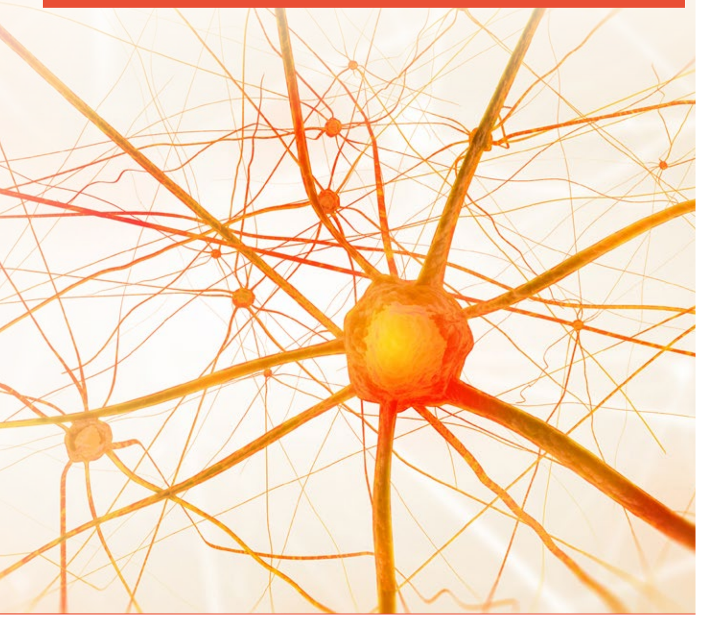
Sawicki, J., Omelchenko, I., Zakharova, A., & Schöll, E. (2018). Delay controls chimera relay synchronization in multiplex networks. *Physical Review E*, 98(6), 062224. Available at: https://doi.org/10.1103/PhysRevE.98.062224

Sawicki, J., Abel, M., & Schöll, E. (2018). Synchronization of organ pipes. *The European Physical Journal B*, 91(2), 1-9. Available at: https://doi.org/10.1140/epjb/e2017-80485-8

Personal Response

How could your dynamical approaches extend to other aspects of synchronisation?

" Synchronisation is a phenomenon that appears with a lot of facets in nature and technology, and has fascinated mankind for centuries. Studying synchronisation phenomena allows us to better understand highly complex systems such as real neural populations in the mammalian brain or smart networks of power grids. Furthermore, our findings may be useful in the study of novel concepts for encrypted and secure communication, where relay synchronisation of complex spatio-temporal patterns, for instance chimera states, can be employed. "



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