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Backstory

Physics of Brains

Franca Davenport,⁴ Martin J. Cann,² Stephen Smye,³ and Tom McLeish¹

The UK Physics of Life network brings together researchers from biological, biomedical, and physical sciences to develop novel insights on significant scientific questions. The network is chaired by Tom McLeish, Professor of Natural Philosophy in Department of Physics at the University of York. Professor Martin Cann Head of Department of Biosciences at Durham University and Stephen Smye, Professor in the School of Medicine at the University of Leeds, are co-chairs of the Physics of Life network. Franca Davenport is a science writer and communicator with a degree in experimental psychology.

Entitled Physics of Brains, the latest Physics of Life workshop brought together neuroscientists, experimental and biological psychologists, statistical physicists, neural computing experts, biophysicists, and neurologists to discuss the intricate machinery of the brain and how this maps onto the impressive functions it performs every day.

The workshop showcased novel research that is attempting to explain and understand some of the brain's phenomena through the use of tools such as statistical physics, precision scanning, and neural computing

Contributors to the Physics of Brains workshop



which have been valuable in simplifying and understanding a range of systems. By hosting this workshop, the network aimed to generate discussion around the value of these tools and provide insight into the biology of the brain whilst acknowledging its inherent complexity.

“Biology is under no need to be intelligible it just has to work and can stay as opaque as it likes Finding optimal representations of brain damage is going to be a central task – how to come up with a compact, succinct navigable representation of those brain patterns.” Professor Parashkev Nachev.

By drawing on the research, theories, and ideas presented in the workshop, this backstory has collected examples of how working across and between physics and life sciences have led to advances in understanding significant scientific challenges in this area.

CHALLENGES

Explaining the brain’s complex biological system

It would take an unfeasibly long time to sample all the states of a system consisting of a few thousand interconnected neurons, let alone a system comprising the 80 billion neurones in the human brain. Statistical physics was initially developed to describe the properties of large numbers of interacting particles and is now being applied to describe the interactions and emergent properties of large numbers of neurones.

One of the pioneers in this field is Bill Bialek from Princeton University who works at the biology and physics interface. Working with experimental neuroscientists, he has identified a probability distribution of the states of a neuronal network that agrees with data on neurones’ mean activity and the correlation between pairs of neurones (Bialek, 2020). The group has demonstrated that this dynamical model can predict correlations between triads of neurones and that correlation structure does not arise from the fields of the location-sensitive place cells that reside in the hippocampus but from collective activity.

Using electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI) recordings of brain activity, several researchers, including Daniel Baker from the University of York, have demonstrated the ability of a simple equation to reproduce and predict a range of binocular phenomena. This equation, initially developed by the physicist Erwin Schrödinger, can also explain how the brain combines signals from the ears and across space. Recently, Baker has proposed that the equation implements a Kalman filter, which down-weights noisier signals to achieve optimal combination of multiple inputs. Future work plans to extend the model’s application to signal combination not only from the visual cortex but also from subcortical pathways that determine automatic biological functions such as melatonin production or pupil size (Baker, 2020).

Scaling up dynamic models of neuronal interactions

If we build models on data from samples of hundreds of neurones, then a subsequent challenge arises: that of scaling up these models to represent larger and larger populations. Bialek’s work with data from the hippocampus has averaged over scales of increasingly large size to observe what happens to his model as it moves from the microscopic to macroscopic (Bialek, 2020). He suggests that typically it gets simpler, fitting nicely with the idea of a renormalization group approach that investigates the system’s changes when viewed at different scales.

“We’ve reached the state where we can no longer shrug and say ‘well it’s biology and it’s a bit of a mess’. It is possible to get to the point of real quantitative agreement between theory and data.” Professor Bill Bialek

By applying a coarse-graining method and using the strength of correlation as a surrogate for the physical neighborhood, his approach respects the critical fact that neurones interact over considerable distances. He scales out to “superneuronal” activity, averaging over groups of up to 256 neurones, and shows they have simple, orderly behaviors that are quantifiable and reproducible across different animals.

“We’ve reached the state where we can no longer shrug and say ‘well it’s biology and it’s a bit of a mess’. It is possible to get to the point of real quantitative agreement between theory and data.” Professor Bill Bialek

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Understanding how sensory visual and spatial information is encoded in the brain

Responding to stimuli requires organisms to encode information about the external world. The study of neural encoding characterizes the relationship between sensory stimuli and neural signals and is fundamental to understanding how the brain represents and processes information.

Using data from simultaneous recordings of 10,000s of neurones Kenneth Harris from UCL, together with other computational and visual neuroscientists, has investigated the encoding of natural images by large populations of neurones in the visual cortex. To study the mapping process from the retina's low dimensional stimulus space to the high dimensional space of the visual cortex, the group applied principle component analysis (Harris, 2020).

The analysis demonstrated that the populations were high dimensional and correlations obeyed an unexpected power-law relationship. The neurones were observed to behave like a random sample from a hypothetically infinite population. The encoding appears to balance two desirable properties: that of orthogonality to distinguish different stimuli and that of smoothness to recognize similar stimuli. Interestingly, it is this balance that artificial neural networks find so challenging to replicate completely.

Like Bialek, Harris believes there is real value in working from the data and parking the drive to formulate theory until justice has been done to the impressive wealth of experimental information accumulated in interdisciplinary groups around the world.

"It's important to let the data think for itself. Just as with string theory, we have to be careful in neuroscience that we don't fall into the trap that because the theories are so beautiful, we believe they have to be true." Professor Kenneth Harris.

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Focusing on the retina Thierry Mora from Ecole Normale Supérieure Paris has applied an artificial neural network that can learn a probability distribution over a set of inputs to represent the population coding of visual information by ganglion cells. By using hidden units, the model effectively describes collective activity and captures interactivity between neurones and stimulus response. Through his research Mora demonstrates the efficacy of the model with retinal data showing the importance of combining a bottom-up approach that proposes organization from efficient design principles with a top-down approach where local rules of interaction are learned from data using statistical physics (Mora, 2020).

As mentioned earlier in Bialek's research, place cells in the hippocampus are involved in processing spatial information: they become active when an animal enters a particular location in its environment. Models of continuous attractor networks are used to describe their dynamics where the peak of the attractor codes for the animal's position. When a new context or behavior arises, a familiar physical environment needs to be represented by a different attractor. Remi Monasson from ENS Paris is interested in this novelty-induced switch between a well-formed attractor to an unconsolidated attractor. Based on data from mice, he suggests the flip is triggered by a minimal increase in the membrane potential and the activity of dentate gyrus neurones. From this, he has derived a computational model to mimic the change in the place cells' activity in the hippocampus provoked by the burst of activity in the dentate gyrus and leading to the emergence of a new representation (Monasson, 2020).

"We should not be too fast to derive conclusions from this beautiful long-range order we see in experiments in the lab." Professor Alessandro Treves.

Remaining with spatial information processing, Alessandro Treves from SISSA Trieste is researching whether the beautiful example of order seen within the virtual 2D maps generated by grid cells in the medio-entorhinal cortex can also apply for space extending into three dimensions. He has investigated what happens to place fields when an animal moves on a sphere and his research has indicated that when grid cells interact, they become noisier and evolve into clusters with partial coherence with interacting grids. These findings suggest

that processing spatial information in natural environments may require a more complex and potentially ‘messier’ encoding process than is needed for experimental 2D environments (Treves, 2020).

Exploring the relationship between dynamic models and biological/molecular architecture

The integration of concepts from statistical physics with what happens biophysically in the membranes and ion channels of neurones is important to fully understand the dynamics of the brain. Fred Wolf from MPI Gottingen believes it is essential for constructing the next generation of dynamically realistic network models. He describes several biophysics explanations at the level of fine molecular architecture to explain neuronal networks’ properties and phenomena (Wolf, 2020). There is no absolute conclusion as to which might be correct but still, this two-way relationship between statistical physics and biology is providing essential insight into the link between molecular and network dynamics.

For models to provide a better understanding, they may not need to have a detailed biological equivalence yet they do need to consider what we know about the architecture. For example, the hidden units central to Moya’s retinal activity model encode different collective modes but do not correspond to a specific biological object.

“What many millions of neurones do in cognition and neural computation certainly depends on the finest detail of their molecular makeup.” Professor Fred Wolf.

The hierarchy inherent in a renormalization approach to scaling, as proposed by Bialek, appears to make intuitive sense in areas such as the retina and visual cortex. In these areas, there is a high level of architectural organization and signals from a primary layer are grouped to feed into the next layer. His coarse-graining approach on data from hippocampal neurones demonstrated that information (such as place cell activity) was preserved.

According to Bialek, coarse-graining can be considered as data compression whilst neuroscientist, Karl Friston from UCL, describes it as a way to ‘parcel the brain at different spatial scales’. A central question is what is ‘kept’ during this compression or parcelling. Bialek shows there is preservation of place cell information in a way that potentially indicates a type of “purification” process at scale as the trace of activity becomes more prominent after coarse-graining. This suggests the coarse-graining of activity could potentially lead to a coarse-grained representation of function.

“There are various ideas about this, but I think most work involves recovering conventional renormalisation group transformations from some information-theoretic principle. What would be exciting would be to show that something genuinely new and different can happen.” Professor Bill Bialek.

Visual neuroscience is particularly tractable to modeling and experimentation. Still, there is continuing debate about using such models on more complex functions such as social interaction where the relevant brain architecture or indeed function is not so clearly defined. However, as some contributors at the workshop pointed out, vision was not always as accessible to experiment and modeling as it currently is. Perhaps it will just be a matter of time before we can develop the right approach for these other brain functions.

“When we think about how a brain is generated in the first place, how it arises developmentally, it should be compressible.” Professor Parashkev Nachev.

NEXT BIG QUESTIONS

Do neural systems work at a critical point, and what do these critical points look like?

The theory that brain systems have evolved to work at a critical point to maximize information processing properties is popular. However, according to Viola Priesemann from the Max Planck Institute for Dynamics and Self-organization, the hypothesis is far from confirmed. Operating in a disordered state has its own advantages for the brain such as maximizing entropy, minimizing redundancy, and relating to efficient code (Priesemann, 2020).

To address these two plausible hypotheses of how the brain functions, Priesemann’s group have overcome a series of challenges. The most formidable being that of subsampling for which the group have derived a

subsampling-invariant estimator, an approach that they are also using to model disease propagation in the COVID-19 pandemic.

Having overcome these challenges, they found that in rat, cat and monkey cortices the neural networks operate in a space close to critical point, which is neither critical nor disordered. According to Priesemann, there are clear benefits of operating in such a regime where small changes in a control parameter allow rapid movement between states and the tuning of the computation needs of a network to task requirements.

Can there be an overarching theory of the brain? How can we converge models to produce a complete picture of the brain?

The Bayesian approach to brain function suggests a deep hidden structure behind our behavior. It proposes that the brain operates by continually making predictions about the world, then updating them based on what it senses. Karl Friston from UCL is interested in making the link between Bayesian probability and the ensemble dynamics proposed by statistical physics. His central proposition for this link is the “free-energy principle” which suggests brains seek to minimize the difference between the states we expect to be in and the states our senses tell us that we are (Friston, 2020).

“On the one hand, the brain seems to be in the game of optimising beliefs about how its sensations are caused while on the other hand our choices and decisions appear to be governed by value functions and reward. Are these formulations irreconcilable or is there some underlying imperative that renders perceptual inference and decision-making two sides of the same coin?” Professor Karl Friston.

He suggests a free-energy principle can model not only perception but how we make decisions, behave, and plan so that we choose policies or paths through the future in a way that optimizes expected free energy, or in statistical terms minimizes complexity whilst maximizing accuracy.

More of a unifying concept is Amanda Ellison’s proposal from Durham University that the rhythm of the frequency at which neurones communicate is central to understanding how the specialized areas of the brain work together and that synchronized rhythms regulate which neuronal networks and ensembles “talk” to each other (Ellison, 2020). EEG experiments have shown the subcortical thalamus is important in setting up the rhythm of firing rates during sleep, whilst thalamocortical dysrhythmia has been observed in a range of cognitive and psychiatric disorders. Ellison suggests that brain rhythms could hold the key to consciousness and suggest the thalamus and its spindle type waveforms could be the physiological gatekeeper between the preconscious and conscious.

“In quantum theory, a unifying description is that our reality is shaped by the question we ask of it. By minor extension, our reality is what we are conscious of but, until we ARE conscious, all possibilities are possible. Can we use a quantum theory approach to inform our gross thoughts on consciousness?” Professor Amanda Ellison.

How can we incorporate the complexities of the brain’s learning mechanisms into AI?

Several commercially available neuromorphic computing systems operate at a scale that can represent one million neurones (256 million connections) on one chip. David Halliday from the University of York focuses on fault-tolerant learning and self-repair performed by astrocyte regulation of neuronal activity (Halliday, 2020). With his group he has built a system that emulates this tripartite synapse and has demonstrated that, in the case of a lesion, the indirect astrocyte-mediated pathway can recover the information. This design can be extended to a quad-partite system and the design property can be verified using a simple robotic demonstrator that can learn in a robust way despite failures in synaptic pathways.

“We are working towards concepts that might be important in the next generation of neuromorphic computing systems.” Dr David Halliday.

Francesca Mastrogiuseppe from UCL is interested in modeling how neural circuits categorize stimuli according to abstract knowledge by associating this with sensory information (Mastrogiuseppe, 2020). These associations involve synaptic plasticity across multiple brain regions. As synapse activity is hard to measure, she uses a model that works with data on neuronal activity, proposing a machine learning hypothesis using gradient descent. This model can capture how individual neurones develop selectivity to abstract variables and how neuronal populations can become sensitive to similarity.

Can we address brain dysfunction when we don't fully understand function?

Research with fruit flies has become recognized as a valuable approach to study neurological diseases. Flies and humans have a common ancestor dating back to 600 million years ago and share a lot of brain machinery. Alex Wade from the University of York works with fruit flies as a means to understand neurological disease in humans and to test therapeutic approaches (Wade, 2020). He suggests that, for those diseases that arise from a genetic mechanism where all neurones are affected, the fly brain can provide a suitable parallel to the human brain.

“Conceptually, it may be easier to address some of the neurological diseases than it is to understand how a normal brain performs the function that they affect, for example, dementia and memory recall.” Professor Alex Wade

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Professor Alex Wade

Wade works with the visual correlates of Parkinson's as a form of marker for the disease and uses this to derive diagnostic tools. Interestingly perhaps this approach of identifying visual correlates of symptoms or behaviors could bypass the need to find a “primitive” for more complex behavior, which has been raised as a challenge to the application of models developed for the visual cortex to more complex social functions.

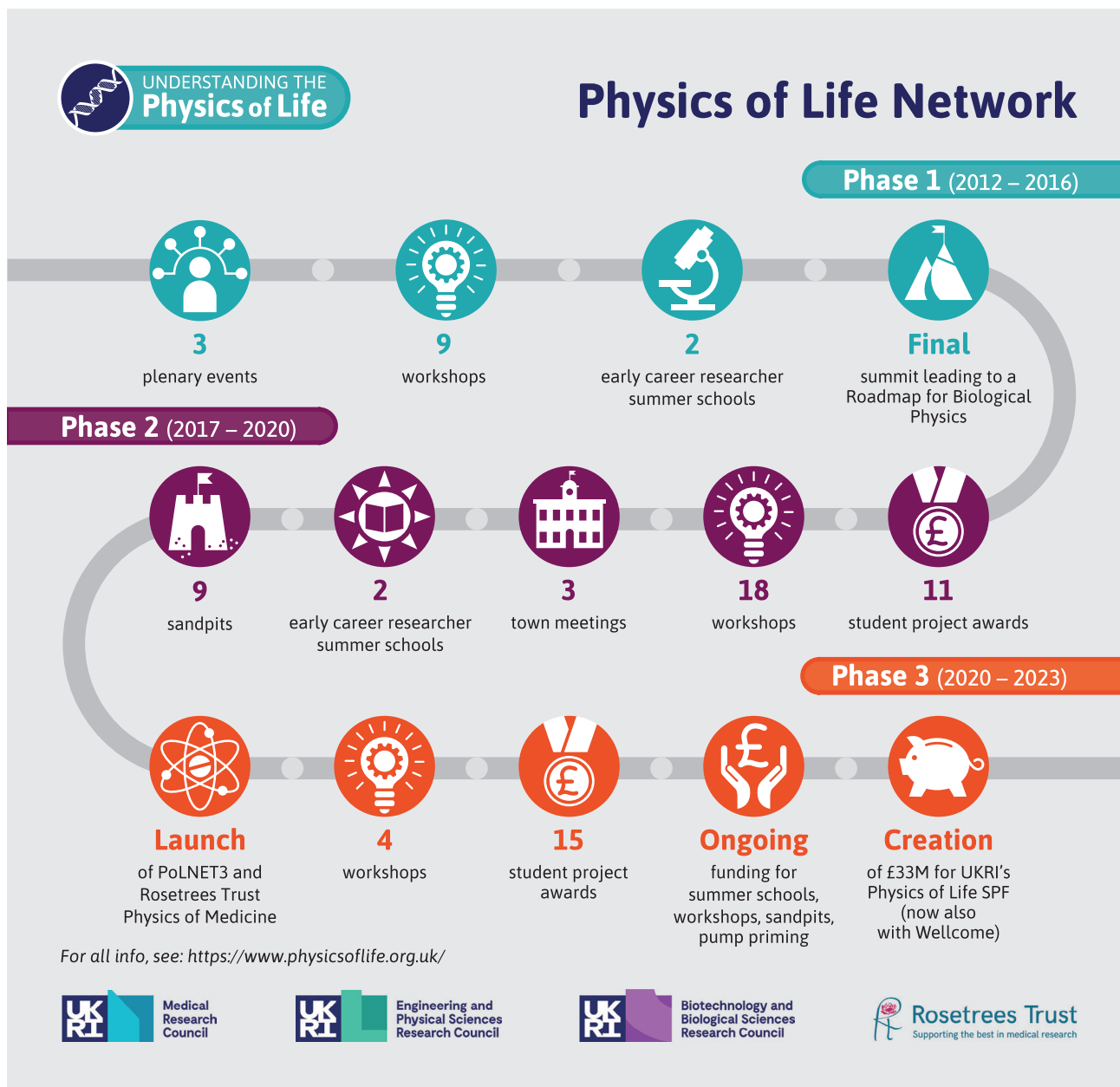
In the context of focal injury to the brain after stroke, there is striking diversity and consequent difficulty in predicting outcome. Using data on spatial patterns of stroke lesions, Parashkev Nachev from UCL has shown they are not random but have a structure with archetypal clusters of damage (Nachev, 2020). However, the ability to predict what happens to a patient remains relatively weak. Lesions involve a multiplicity of brain areas, and there is a need for complex models to allow flexibility to encompass a sizable causal field.

Whether from disease or damage, brain dysfunction differs in complexity. Nachev proposes there may be a need for a form of hierarchical representation for dysfunction where the detail of the representation can be adapted depending on data and the problem to be solved. Above all, he stresses, it needs to be patient-centered.

How unique is the human brain?

Despite its apparent complexity certain elements of the human brain are very similar to those of animals and seem to have remained relatively unchanged over time. Alex Wade's research using fruit flies to study neurological disease relies on the understanding that flies and humans had a common ancestor about 600 million years ago. Research suggests that the fundamental building blocks to complex systems may be comparable in different animals. Further investigation in this area may help reveal more about how architecture relates to function and why specific areas of the brain such as the modern mammalian hippocampus appear to have evolved quickly whilst other structures are more resistant to change.

In a similar vein, the overarching concepts and principles proposed by Friston and Ellison suggest that apparently complex brain functions such as decision-making and consciousness could be described by an approach that also describes less complex functions such as vision and sleep. Contributing to the discussion is the research by Halliday and Mastrogiuseppe which is demonstrating how learning and categorization can be modeled with computational approaches. As Nachev suggests it may be that rather than attempting to find a solution by trying to mimic or simplify biological complexity, we start with the problem and decide what level of complexity (or simplicity) we need for the job.



Initiatives of the Physics of Life Network.

INTERDISCIPLINARY COLLABORATION IN METHODS AND DATA COLLECTION

Data on neural structure, connectivity, and interactivity to provide insight into function

Hannah Smithson from Oxford University and her group at the Oxford Perception Lab have been using adaptive optics to collect detailed information on the retina's architectural and functional aspects (Smithson, 2020). They can successfully assess the number, density, and type of cones, and can stimulate single cones. By coupling adaptive optics with optical coherence tomography, they can extract 3D images through the nerve layer, allowing them to measure functional response in cone receptors. The hope is that they will be able to do this for other retinal cells, such as ganglion cells, to enable better insight into the functional hierarchy of the retina.

“High resolution *in vivo* retinal imaging is a potential tool for investigation of vision and principles of neural organisation more generally.” Professor Hannah Smithson.

Transcranial magnetic stimulation briefly and reversibly disrupts the activity of neurones by applying a magnetic coil above the brain area’s location. This stimulation provides more causal insight than the correlative information obtained from MRI and has better spatial specificity than EEG. In her work, Amanda Ellison demonstrates its use in investigating functional connectivity and identifying how specialist areas of the brain work together to perform tasks such as visual search and shape identification.

Capturing brain architecture at several scales

The imaging of *ex vivo* brains using ultra-high field MRI combined with light-sheet microscopy reveals an increasing amount of architectural detail of the brain at various levels. Using MRI scanners of 9.4 Tesla and 7 Tesla, Alard Roebroek and his team at Maastricht University are producing resolutions as small as 75 μm . Through combining MRI and light-sheet microscopy, they have achieved a valuable balance between field of view and resolution, taking a step closer toward multi-scale imaging where they can capture the cytoarchitecture of the cortex alongside single neuronal cell bodies in 3D (Roebroek, 2020).

“One of the characteristics of the human brain that is most challenging for imaging is the many scales at which it’s organised.” Professor Alard Roebroek.

De-isolating *in vitro* systems to become more like *in vivo* systems

Isolated *in vitro* neurones self-generate activity which is characterized by strong bursts and pauses. This is very different to the fluctuating spiking activity that is seen in *in vivo* neurones. By changing input strength, Viola Priesemann’s group has shown it may be possible to tune a network and in principle rescue these *in vitro* systems from their isolation to establish more *in vivo* like dynamics. This finding could be valuable experimentally, and work is underway on optogenetic approaches using light to control neurons that have been genetically modified to express light-sensitive ion channels. According to Fred Wolf, a next generation of *in vitro* models could be the way forward to allow better control and handling of data. He suggests that interfacing with a living *in vitro* neural network in this way will require the light to be sculpted to address individual neurones. This is challenging but could be overcome by combining holographic techniques with optogenetics.

How can these new data connect with theoretical approaches?

As new data captures more architectural detail of the brain and potentially bridges the different observational scales, researchers are considering how this information connects with or informs the dynamic models that are being built on recordings of neuronal populations. As mentioned, the hierarchical and nested structure observed in the organization of the retina is inherent in the renormalization grouping approach, but there are challenges about whether this relationship can occur for brain areas involved in more complex functions. The connection between dynamic model and brain architecture may not always be as clear as that seen in retina but it can perhaps be understood by taking a conceptual step back.

Friston suggests it may be valuable to use hierarchy as a framework to bring together the physics of structure and scale invariance with the empirical data that is being captured at different scales. So rather than a hierarchy of structure, there is a hierarchy of connectivity and of the passing of messages in the brain (which is implied by Bialek’s coarse-graining of correlation strength). This could potentially transcend scales and be taken right up from interpreting visual sensations at the retina to understanding complex functions, perhaps drawing on work around concepts such as canonical microcircuits which are well-defined, interconnected circuits of neurones that represent a replicable unit. There may be a broad array of these reusable microcircuits or primitives which can build up a functional network and allow for more complexity when working with less definable functions such as social interaction.

When considering this framework, Parashkev Nachev stresses the need to balance intelligibility with functionality in our approaches. A hierarchical representation can potentially make the brain understandable but it may not necessarily offer value in predicting what happens to a specific individual and what treatment

they may require. The approach needs theory to meet with data and clinical functionality, which is the very aim of these Physics of Life workshops.

Interestingly there is also discussion about the utility of more precise architectural data for models such as Nachev's. Alard Roebroek suggested that the sheer level of detail provided could actually be a "curse for dimensionality" because, providing this amount of detail exponentially increases the number of scans and subjects and example data points that are needed for meaningful analysis. Unless we can scale up the resources for data collection and examination it may be difficult to draw out clinical insights from scanning data despite the impressive organizational insight it provides.

POTENTIAL SOCIETAL IMPACTS

Personalized medicine and prescriptive models

With a better understanding of the brain and more data, we can refine personalized approaches that tailor medical decisions, practices, interventions, and/or products to the individual patient. Nachev's work with large data sets from stroke patients provides insight into the clustering of different groups of patients, but it is not yet delivering the necessary power to predict the outcome of brain damage for these groups. He calls for prescriptive rather than predictive models that can inform what interventions would be effective. To be prescriptive requires more of the right kind of data, alongside the computing resources to analyze them. Projects like the UK Biobank are a step toward this, but still, he argues, they are not at the scale needed to provide these new types of personalized approaches.

Insight into the impact of disease, damage, and therapy

According to Amanda Ellison, more in-depth knowledge of the rhythms of the brain provides insight into dysfunction and treatment. Thalamocortical dysrhythmia is seen in Parkinson's disease, chronic pain, migraine, OCD, and tinnitus, indicating that addressing this can lead to alleviation. The approach of ablating areas that send sleep-like rhythms has met with some success for dystonia and, by detecting the source of the dysrhythmic signal and inserting a pacemaker to entrain normal firing rates, deep brain stimulation is now a viable treatment candidate for many disabling disorders.

Work on the retina by Hannah Smithson using adaptive optics scanning laser ophthalmoscopy (AOSLO) has allowed detailed analysis of different cone segments. As it is often the outer segment that deteriorates in pathologies, ascertaining the presence of healthy inner segments is valuable to the application of rehabilitation techniques such as gene therapy. The AOSLO approach also allows the tracking of disease progression and can inform the setting up of protocols and endpoints to monitor treatment.

Investigating neurological disease in animal models that are not ethically restrained

Through EEG recordings of fruit flies genetically modified to develop Parkinson's disease, Alex Wade's group has demonstrated an increased excitation in their visual system, which is also observed in humans with the disease. Furthermore, they have shown that this excitation is brought back to normal levels when flies are fed on a kinase inhibitor which has been developed as a potential drug for this form of Parkinson's.

Using multivariate statistics on data collected at different light frequencies and intensities his group have developed a way to diagnose the fly's genotype based solely on its response in the visual system. Wade has applied this model in patients in Tunisia, where this genetic form of Parkinson's is more common, to demonstrate that the EEG recordings in visual cortex in response to contrast stimuli can distinguish these Parkinson's patients with 66% accuracy.

Fruit flies are not subject to ethical control and have a rapid reproductive cycle, helping to address an ongoing societal challenge of reducing animal research in this area.

Improving rehabilitation, learning, and educational approaches

New interdisciplinary models that represent how brain areas work can potentially provide insight into the brain's plasticity and how, after damage, certain brain functions can recover by recruiting other networks.

Amanda Ellison suggests that entraining neurones at an alpha frequency can improve sensory, motor, and cognitive functions, which can inform rehabilitation following injury. Some success of this approach has been shown in Alzheimer's not only in terms of primary functional loss but also in more complex social effects, such as altered sensitivity to loneliness.

Alongside this, the neuromorphic, computational, and machine learning models can provide insight into ways to improve cognitive performance by modeling how the brain performs resilient and complex learning.

GOVERNANCE

There is an ever-growing recognition of the value of interdisciplinary approaches by research and funding councils, nationally and internationally. To raise awareness and ensure interdisciplinary research (IDR) is effective and translative, advanced training is needed to enable upcoming generations of researchers to identify a substantial area of IDR and follow it through to impact. Many joint honors degrees do exist but, despite this landscape, the research itself still seems to silo.

A gap exists between discipline-based models of peer review and the evaluation methods needed to address the particular characteristics of IDR and its capacities to provide additional value to the research process. These problems are also borne out in the assessment of research by many publishers and journals and resurface, in turn, in research quality assessments. Interestingly in the UK Research Excellence Framework, the majority of impact case studies submitted involve IDR, indicating that there is an awareness of the impact this approach produces but yet uncertainty still surrounds its academic assessment.

One solution is establishing high-quality, interdisciplinary journals, alongside special issues in high-impact, single-discipline journals that focus on interdisciplinary research. Evaluation of IDR encounters difficulties when it is done using approaches based in single disciplines — it requires fresh criteria, developed within an interdisciplinary context. Without this, we run the risk of merely imposing the traditions and evaluation methods of individual disciplines and stifling the potential value gained in working outside of our specialisms. IDR should be about merging and learning from other disciplines and not about seeing a subject through a different lens.

Finally, establishing enduring connections between researchers, policymakers, clinical and industry practitioners and research charities can be crucial in growing interdisciplinary collaborations in this area. By bringing greater solution-focused thinking, these groups can remove the tendency to think in disciplinary silos and help tackle complex problems from a range of perspectives.

CONCLUDING REMARKS

Research into the brain is an area that continues to captivate a range of audiences and has the potential to yield clinical, computational, and evolutionary insights. There has been huge progress in understanding the brain's organization and functions and yet, as we make more discoveries and insights, it seems there is more to connect to grasp the full picture.

Research between physical sciences and biological sciences is allowing these moments of connected clarity to occur. By working with data rather than imposing theory, models and concepts are emerging that resonate across a multitude of discoveries, such as the notion of a hierarchy of connectivity and the formulation of processes which balance organization and chaos to deliver function and flexibility. Through IDR we are connecting concepts and models with data whilst checking our experimental approaches for limitations. Working across disciplines is also ensuring a strong link to our clinical understanding of the brain and providing the constant reminder that the value of our approaches is only apparent in the solutions they can provide to individuals and society.

As research continues to reveal the interconnected nature of the brain's structure and mechanisms, it seems pragmatic to approach it with interconnected research.

By providing discussion forums such as Physics of Brains we hope we can bring together different perspectives to interrogate this field and escape the blindspots that may reside in our isolated specialisms.

Recordings of the Physics of Brains workshop can be viewed here:

Day One 18 November 2021.

Day Two 19 November 2021.

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