CHAOTIC MINDS

CHAOTIC MINDS

THE INTERPLAY BETWEEN NEURONS

DANIEL DURSTEWITZ & ANDREAS MEYER-LINDENBERG

When you feel a cold breeze on your face, smell fresh coffee, or hear a baby crying, your mind takes in this sensory information and compares it against your memory. Together with how you feel inside – maybe you are tired, thirsty, or irritable – you use this information to inform an appropriate response. Brains are, in essence, information processing systems. As they both store memories and take in information, it makes sense for us to compare our brains to computers. However, the way information is processed in your nervous system is fundamentally different to how your personal computer works.

PROF. DR. DANIEL DURSTEWITZ is a researcher at the Mannheim Central Institute of Mental Health (ZI) with a focus on the neuronal foundations of higher cognitive skills and their dysfunction in psychiatric conditions. He has been heading the Computational Neuroscience group since 2008, and in 2011 became a Heisenberg Professor of Theoretical Neurosciences at Heidelberg University and the ZI. In addition, he has served as coordinator of the Bernstein Center for Computational Neuroscience Heidelberg-Mannheim since 2010. Dr. Durstewitz studied psychology and computer science in Berlin and earned his PhD at Bochum University. He worked two years at the Computational Neurobiology Lab of the Salk Institute for Biological Studies in La Jolla (USA) before setting up his own junior research group for "Computational Neuroscience" within the DFG's Emmy Noether program at Bochum University in 2000. The years 2005 to 2008 saw him doing research as a Reader at the Centre for Theoretical and Computational Neuroscience of Plymouth University, England.

Contact: daniel.durstewitz@zi-mannheim.de

PROF. DR. ANDREAS MEYER-LINDENBERG has held the chair of Psychiatry and Psychotherapy at the Medical Faculty Mannheim of Heidelberg University since 2007. In the same year, he became chairman of the board of the Mannheim Central Institute of Mental Health (ZI) and Medical Director of the Clinic for Psychiatry and Psychotherapy at the ZI. After completing his studies of medicine and earning his PhD in Bonn,he worked at the LVR Hospital in Bonn before transferring to Giessen University Hospital in 1994. 1997 marked the beginning of a 10-year stay at the National Institute of Mental Health in Bethesda, USA. During this time, he also earned his teaching credentials at Giessen University (1999). Dr. Meyer-Lindenberg's research focuses on the neural mechanisms of schizophrenia and depression, imaging technology in genetics, social neurosciences and new therapeutic methods for psychiatric conditions.

Contact: a.meyer-lindenberg@zi-mannheim.de

O

On the face of it, your brain shares many characteristics with computers. Both are information processing devices, using electricity to transmit signals. Like computers, brains perform computations on their inputs and seem to rely on different memory storage systems, with limited capacity, for short-term or long-term use. But that, perhaps, is where the similarities come to an end. A standard computer has distinct hardware components – for instance for storing information or processing it – and responds to commands in a sequential manner. Neurons, on the other hand, work together in a highly distributed, parallel way to produce memories, make decisions, or process sensory information, and do this on many different levels of physical organisation.

Every cell in our nervous system consists of a complex machinery of molecules and genes that translate incoming chemical signals into adaptive changes. Each cell, in turn, is wired into intricately branching networks from which it receives, and to which it sends electrical signals, known as 'action potentials', via several thousand synaptic contacts. These networks form brain areas with different roles, that themselves link up in densely interconnected 'super-networks', enabling your brain to function in the way it does. Thus, at various scales – from molecules to individual cells and synapses, to local networks and brain systems – computations are carried out in the nervous system through interactions among millions to billions of processing units, without any true hierarchical ordering among them.

Your brain is also very distinct from the everyday computer in that computational algorithms in your nervous system are directly translated into hardware changes. Whenever you learn something new, this ultimately results in changes to your brain. Neurons receive electrical inputs from other cells mainly through tree-like morphological structures called dendrites, and send out information to other cells via their axons. The dendrite has branches with thousands of contact sites called spines on which the synapses from other neurons terminate. When a synapse is stimulated in certain ways, and depending on the state of the neuron, these spines literally alter their physical shape (sometimes within minutes) and thus weaken or strengthen the link between the neuron and the other cell. Almost everything we do alters connections between brain cells – learning and memory crucially depend on it – and software changes are, so to speak, directly burnt into the hardware of the nervous system.

Again, this happens at different levels of organisation – cell morphology and anatomical layout often directly reflect essential computational demands, and studies have revealed examples of dendritic trees that have been tailored towards processing specific types of sensory input. Understanding this further could, in turn, have important implications for our understanding of the structure of the brain and how it changes in response to environmental impacts that may affect our emotions, memories, or way we make decisions.

These and many other examples of differences between the way the brain and computers process and handle information, explain why the language theoretical neuroscientists use to describe computational processes in the brain is very different from the formal programming languages used in computer science. In essence, neural networks are complex, self-organising, highly nonlinear, dynamical systems with emergent computational properties.

Mathematically speaking

The language that has most frequently been employed by theoretical neuroscientists to describe processes in the brain comes from a branch of mathematics termed 'nonlinear dynamics'. Nonlinear dynamics deals with systems that are represented mathematically by a set of nonlinear differential equations. These equations describe the evolution of a set of variables in space and time, like the firing rates of a set of neurons or their membrane potentials. The behaviour of dynamical systems can best be illustrated by the concept of a 'state space' – an abstract space representing all possible states a dynamical system could be in. In a complete state space, a point within this space uniquely identifies the current state of the whole system, while the set of differential equations gives a vector at each point that determines its future state, that is where and how fast it will move next. Along this vector field, the state of the system follows a unique path through the space – known as its trajectory – until it may eventually converge toward some bounded, spatially confined region of the space that is a geometrically defined limited subset of all the states the system theoretically could be in. These regions of convergence are called 'attractors', and they come in many different geometrical shapes and dimensions.

In many cases, the attractors may be simple geometrical objects like single points or closed orbits (loops through the state space that start and end at the same point) that give rise to completely regular behaviour, such as oscillations. In other cases, however, they may be complicated fractional geometrical objects that densely fill some region of state space within which attracted trajectories cycle forever without ever precisely repeating their path. This will give rise to irregular, never-repeating behaviour in the system that nevertheless is purely deterministic – it is not caused by any random component, but can be fully described by a completely deterministic set of

ZI: Weltweit anerkanntes Zentrum moderner Psychiatrie

Das Zentralinstitut für Seelische Gesundheit (ZI) in Mannheim verknüpft Krankenversorgung, Forschung und Lehre im Bereich psychischer Störungen. Mit dieser Zielsetzung wurde es im April 1975 als Landesstiftung des öffentlichen Rechts mit Mitteln des Bundes, des Landes Baden-Württemberg und der VolkswagenStiftung errichtet. In seinen vier Kliniken werden jährlich etwa dreitausend psychisch kranke Menschen aller Altersstufen mit modernsten Therapiemethoden stationär behandelt. Gleichzeitig ist das ZI ein weltweit anerkanntes Zentrum innovativer Psychiatrieforschung und pflegt zahlreiche wissenschaftliche Kooperationen mit nationalen und internationalen Einrichtungen.

Die Forschung am ZI hat es sich zur Aufgabe gemacht, neue Behandlungsmöglichkeiten für psychische Erkrankungen zu entwickeln und vorhandene Therapien zu verbessern. Vorrangiges Ziel ist es, psychotherapeutische und pharmakologische Wirkmechanismen zu identifizieren, zu etablieren und schließlich zu personalisieren. Die Forschung basiert dabei auf einem translationalen Konzept: Zum einen zielen die Wissenschaftler darauf ab, neurobiologische Mechanismen im menschlichen Gehirn zu entschlüsseln, zum anderen untersuchen sie, inwiefern psychische Störungen auch aus einer Wechselwirkung von psychosozialen und verhaltensbiologischen Prozessen heraus entstehen.

Das ZI vertritt an der Medizinischen Fakultät Mannheim der Universität Heidelberg Lehre und Forschung in den Fächern Psychiatrie, Kinder- und Jugendpsychiatrie, Psychosomatische Medizin sowie Suchtforschung. Seine vier Klinikdirektoren sind an der Universität Heidelberg zugleich Lehrstuhlinhaber ihres Fachs. Geleitet wird das ZI von Prof. Dr. Andreas Meyer-Lindenberg, Vorstandsvorsitzender sowie Ärztlicher Direktor der Klinik für Psychiatrie und Psychotherapie. Prof. Dr. Daniel Durstewitz leitet am ZI das Bernstein Center Heidelberg-Mannheim für Computationale Neurowissenschaften sowie die Arbeitsgruppe Computationale Neurowissenschaften.

www.zi-mannheim.de

differential equations. This phenomenon has been termed 'deterministic chaos', and when we refer to chaos in this article, this is precisely what we mean.

Determining chaos in the brain

What might be interesting about deterministic chaos in the context of neural systems? As the brain is a nonlinear dynamical system, a common line of thinking in theoretical neuroscience is that these dynamical properties, like the specific flow of trajectories and the geometrical objects which govern them, implement computational processes. For instance, convergence towards an attractor from an initial state could reflect the process of memory retrieval and pattern completion, while transitions among different attractor states may result in sequences of cognitive events or motor actions. In fact, artificial pattern recognition and memory devices, as well as adaptive motor pattern generators in robots, have been constructed on this basis. However, these are usually attractors with regular dynamics, raising questions as to whether deterministic chaos itself is also computationally beneficial in some way, or whether it is just an inevitable consequence of the brain being a highly nonlinear, diverse and complex dynamical system.

Since the days of the great British mathematician Alan Turing, physicists and computer scientists have been interested in exploring alternative concepts of computation. This is particularly so for emergent computations that

Computational Processes in the Brain

The way information is processed in our nervous system is fundamentally different to how a personal computer works. Neural networks are:

Complex

They consist of intricate networks of billions of interacting units governed by billions of positive and negative feedback loops.

Self-organising

No programmer, software engineer, world-class teacher, central executive or homunculus is needed – they adapt to environmental challenges largely through intrinsic and local mechanisms.

Highly nonlinear

Many processes in the brain do not change gradually and steadily with, for instance, changes in the input, but may exhibit rather abrupt twists and turns. For example, synaptic inputs to a neuron may give rise to brief 'explosive' pulse-like electrical events, so-called 'action potentials', that are used to communicate with other neurons and form the basis of the neural code.

Dynamical

Their states and properties evolve over time. Although the basic currency of neural information exchanges.

"Neural networks are in essence complex, self-organising, highly nonlinear, dynamical systems with emergent computational properties."

can be performed by large, interactive and self-organising collections of simple processing elements. These are systems that can be naturally described by sets of differential equations, and hence are subject to the kinds of dynamic phenomena described above. With advances in dynamical and complex systems theory, there came a realisation that the computational capabilities of such systems may depend on the type of dynamic regime which dominates.

If the system behaves in a very orderly way, it may only faithfully follow the input without performing any interesting computations on it. If, on the other hand, the system is in a highly chaotic state, it will quickly forget about any inputs – even initial states that are very similar to begin with will quickly diverge from each other. Such systems are highly sensitive even to very small input variations, a phenomenon sometimes referred to as the 'butterfly effect' in popular science literature. They will not produce any consistent or reproducible behaviour if there is even the slightest bit of noise – in essence, they will behave quasi-randomly. It turns out that there is an interesting intermediate state, a kind of optimal balance between order and disorder called the 'edge of chaos', where the dynamic hovers at the transition from complex yet regular, to chaotic dynamics.

On the edge of chaos?

On their transition towards a state of chaos, dynamical systems often undergo a series of changes, where they become increasingly complex in both space and time. However, they will still remain regular until they finally hit the boundary of true chaos. At the edge of chaos, the optimal balance between 'order' and 'chaos' is reached. Here, the complexity of the system dynamics is enough to allow for interesting computations, yet not so high as to lead to an exponentially fast loss of information. Such characteristics can be found in diverse physical systems such as sand avalanches, or forest fires.

Systems on the edge of chaos often possess what are known as 'long memory' properties – they can retain their input information, in principle, for an indefinite time. This is reflected in power law distributions of events generated by the system and the so-called 'scalar property' that comes with them, which loosely states that event relations are preserved at many different temporal or spatial scales. Power law distributions and the scalar property have often been observed in neural systems and, indeed, the large-scale wiring of the human brain may have characteristics that support 'edge of chaos' dynamics. Thus, it has been argued by some that neural systems thrive by entering a regime that is on the edge of chaos, as this is computationally optimal for information processing purposes.

"The properties and diversity of neurons and synapses quickly lead to a highly chaotic system that is far beyond the edge of chaos."

However, while in theory this hypothesis represents an important contribution to the field, it is not clear how well it applies to dynamics in the brain in reality. Theoretical and empirical studies have shown that the highly nonlinear biophysical properties of neurons and synapses, as well as their large diversity, quickly lead to highly chaotic system dynamics that are far beyond the edge of chaos. Moreover, empirical observations of power law-like distributions are relatively unspecific and may be attributable to a range of different phenomena. Recent electrophysiological observations in the living brain support the idea that jittering, adding, or deleting even a single action potential within a large network will lead to rapid changes in subsequent action potential times across the network. Moreover, there are many sources of intrinsic noise in the nervous system – for instance, neocortical synapses are surprisingly unreliable, with transmitter release probabilities usually below thirty percent.

Chaos ≠ randomness

This creates an apparent paradox: How could a system as divergent and chaotic as the brain carry out any sensible computations? Indeed, given what we have considered so far, one might expect the brain to quickly lose this information about the inputs and behave quasi-randomly. While this remains a puzzle for scientists, some important ideas have been put forward that are allowing us to think about this question in new ways.

One of these ideas is that chaos has a number of important differences to complete randomness: it is still purely deterministic, despite its trajectories diverging exponentially fast – theoretically speaking it is still possible to infer future states from the present. This is different from a purely random process, where successive measurements in time are independent and the best guess for the future is simply taking the average across the observed time series. Even in a highly chaotic system, successive observations are still correlated, only that they decay exponentially fast and are easily obscured by noise, while in a purely random process there are no correlations to begin with.

More importantly, chaotic attractors are still spatially bounded geometrical objects, meaning that data points cannot just be from anywhere in state space – they come from a spatially confined set. Moreover, different attractor states in the system will form mutually exclusive sets, with noise potentially inducing spontaneous transitions among these. As a consequence, the activity dynamics of the system may best be described by a probability distribution that will be far from uniform: it will have many local peaks and troughs, implying that some states and some transitions between states are far more likely than others.

“How could a system as divergent and chaotic as the brain carry out any sensible computations?”

DAS WECHSELSPIEL DER NEURONEN

CHAOTIC MINDS

DANIEL DURSTEWITZ & ANDREAS MEYER-LINDENBERG

Die primäre Aufgabe des Gehirns ist die Verarbeitung von Informationen. Es nimmt Reize aus der Umgebung auf, vergleicht diese mit bereits gespeicherten Informationen und setzt sie in adaptive Verhaltensprogramme um. Intuitiv liegt der Vergleich mit menschengemachten Rechnerarchitekturen nahe. Bei näherer Betrachtung allerdings unterscheiden sich die Prinzipien und Mechanismen, mit denen neuronale Netzwerke Informationen verarbeiten, fundamental von denen eines Computers. Beispielsweise werden im Gehirn Reize auf zahlreichen Ebenen parallel verwertet und nicht sequentiell, so wie es im Computer standardgemäß erfolgt.

Die Prozesse, die bei der Informationsverarbeitung im Gehirn ablaufen, lassen sich dementsprechend nicht mit der formalen Programmiersprache der Informatik abbilden. Wesentlich besser eignet sich hierfür die Sprache der Mathematik – genauer die Sprache, mit der Mathematiker nichtlineare dynamische Systeme beschreiben. Denn ebenso wie diese Systeme, deren Verhalten auch als deterministisches Chaos bezeichnet wird, kennzeichnen sich neuronale Netzwerke durch hochgradig komplexe, sich selber organisierende sowie nichtlinear verlaufende und dynamische Prozesse.

Eine einflussreiche Hypothese der letzten zwei Jahrzehnte besagt, dass ein neuronales Netzwerk die Art und Weise, mit der es Informationen verarbeitet, optimieren kann. Voraussetzung hierfür ist, dass es sich direkt am Übergang von relativ komplexem, aber noch geordnetem Verhalten zu irregulärem, quasi zufälligem Verhalten aufhält. Theoretische und experimentelle Ergebnisse Heidelberger Wissenschaftler aus jüngerer Zeit lassen hingegen vermuten, dass das Gehirn chaotische Dynamiken auf einer „Mikroebene“ mit geordnetem Verhalten auf einer „Makroebene“ kombiniert. So ist eine ideale Balance zwischen Flexibilität und Anpassungsfähigkeit einerseits und zuverlässigem, reproduzierbarem Verhalten andererseits gewährleistet. ●

PROF. DR. ANDREAS MEYER-LINDENBERG hält seit 2007 eine Professur für Psychiatrie und Psychotherapie an der Medizinischen Fakultät Mannheim der Universität Heidelberg. Zudem ist er Vorstandsvorsitzender des Mannheimer Zentralinstituts für Seelische Gesundheit (ZI) sowie Ärztlicher Direktor der Klinik für Psychiatrie und Psychotherapie am ZI. Nach dem Medizinstudium und der Promotion arbeitete er zunächst an den Rheinischen Kliniken Bonn, bevor er 1994 an das Universitätsklinikum Gießen wechselte. Von 1997 an folgten ein zehnjähriger Aufenthalt am National Institute of Mental Health in Bethesda, USA, sowie – parallel – die Habilitation an der Universität Gießen (1999). Die Forschungsschwerpunkte des Mediziners liegen auf folgenden Gebieten: neurale Mechanismen von Schizophrenie und Depression, Bildgebungsverfahren in der Genetik, soziale Neurowissenschaften sowie neue Therapieverfahren psychiatrischer Erkrankungen.

Kontakt: a.meyer-lindenberg@zi-mannheim.de

PROF. DR. DANIEL DURSTEWITZ erforscht am Mannheimer Zentralinstitut für Seelische Gesundheit (ZI) die neuronalen Grundlagen höherer kognitiver Fähigkeiten und deren Störungen bei psychiatrischen Erkrankungen. Er leitet dort seit 2008 die Arbeitsgruppe Computationale Neurowissenschaften und übernahm im Jahre 2011 die Heisenberg-Professur für Theoretische Neurowissenschaften an der Universität Heidelberg und dem ZI. Seit 2010 ist er zudem Koordinator des Bernstein-Zentrums für Computationale Neurowissenschaften Heidelberg-Mannheim. Nach dem Studium der Psychologie und Informatik in Berlin und der Promotion an der Ruhr-Universität Bochum war er zwei Jahre am Computational Neurobiology Lab des Salk Institute for Biological Studies in La Jolla (USA) tätig, ehe er im Jahr 2000 die Leitung der Emmy-Noether-Nachwuchsgruppe „Computationale Neurowissenschaften“ an der Ruhr-Universität Bochum übernahm. Von 2005 bis 2008 forschte Daniel Durstewitz am Centre for Theoretical and Computational Neuroscience der Universität Plymouth, England.

Kontakt: daniel.durstewitz@zi-mannheim.de

„Um Informationen flexibel und verlässlich zu verarbeiten, kombiniert das Gehirn chaotische Dynamiken auf einer Mikroebene mit geordnetem Verhalten auf einer Makroebene.“

Chaos and order on different levels

Having highly chaotic dynamics yet sufficient order to allow for useful computations may be possible if these two phenomena happen on two different scales. At the micro-scale of single spikes the dynamics are indeed highly chaotic, as supported by some of our own computational and physiological work. However, at the macro-scale of network or population states there is a lot of structure. This is suggested partly by our own analyses of network states characterised using electrophysiological and neuroimaging tools in both humans and animals. The combination of local chaos with global structure may enable reliable and reproducible computations at the same time as the flexibility that allows our brains to work in the way they do.

In fact, to deliver flexibility and creativity in cognition, the system may deliberately add noise such as unreliable synaptic transmission. It may also create highly divergent dynamics on the micro-scale that amplifies this noise to create different trajectories through the system's state space, even when conditions at the beginning are similar. This way, the neural system may be able to find new solutions to problems, instead of always following the same path, as would be typical of reflex-type behavior. Therefore, according to this view, the nervous system is not so much trying to strike the right balance between order and chaos, but rather it combines deliberately probabilistic chaos at a lower level with emergent order at a higher level in order to allow for flexible, yet reliable, computations. ●