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INSTITUTE FOR SCIENCE IN SOCIETY

Phase Transitions In Psychopathology

MASTER'S THESIS

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Abstract

Complexity science is dedicated to the study of systems consisting of large numbers of mutually interacting components. Complex systems can display sudden unpredictable shifts in their behaviour, occurring at so-called tipping points. In condensed matter physics, abrupt state changes under parameter variation are known as phase transitions. This project aimed to assess the feasibility and usefulness of modelling tipping points in complex systems as phase transitions using theory from physics.

Feasibility was addressed by examining a previously published dataset from a patient with major depressive disorder (MDD) going through gradual reduction of their antidepressant medication as a case study, in which a sudden shift in depressive symptoms was observed midway through the measurement period. Analysis was centred around the identification of an order parameter in the transition. Two criteria were formulated to assess the relation between individual symptoms and a tentative order parameter, namely (1) the presence of a shift over the course of the transition and (2) an increase in fluctuations prior to the transition. The criteria were quantitatively operationalised and symptoms meeting either or both criteria were identified, providing an overview of order parameter candidates or relatives.

Usefulness was addressed by performing semi-structured interviews with four researchers involved with complexity science. The interviews aimed to characterise motivations and challenges for applying interdisciplinary methods in complexity research, as well as potential practical added value. It was found that phase transition modelling fits well within the need for alternative perspectives that appears to exist within complexity-oriented areas of science. However, significant differences in the interpretation of and assumptions behind complexity emerged that should be carefully considered when using physics-inspired methods in other complex systems.

Based on these results, modelling generic tipping points as phase transitions appears to be a viable approach. More study concerning the role of the order parameter in other datasets and the conceptual interpretation of order in psychological illnesses is required. Moreover, further inquiry into the assumptions behind complexity and the nature of interdisciplinarity in this context would also be worthwhile.

Preface

This thesis is the result of the final graduation project required to complete the Science in Society specialisation of my Master's in physics and astronomy, in which I studied the feasibility and usefulness of using phase transition theory from physics to better understand sudden behavioural shifts in systems outside of physics. During my studies at the Radboud University, I was always looking out for ways to go beyond the borders of my discipline and to combine the exact sciences with a broader, more reflective perspective. This project gave me the opportunity to experience just that.

While working on this project, I was fortunate enough to be supported by a number of enthusiastic and knowledgeable people. First and foremost, I want to thank my two main supervisors: Luca Consoli for teaching me the basics of the social sciences and accentuating the incredibly interesting and essential philosophical considerations, and Alix McCollam for introducing me to complexity science in the first place and helping me understand what I learned from physics in a broader light. You were both exceptionally engaged throughout the entire project, for which I am truly grateful, and our discussions were always useful and interesting.

I would also like to thank Merlijn Olthof, Jerrald Rector and René Melis from RICH for their elaborate involvement with the project and for facilitating this collaboration. Your input and feedback during our monthly discussions as well as your help with finding interviews candidates was very valuable; thank you for investing your time in our meetings and sharing your knowledge and enthusiasm on this fascinating subject.

I am also grateful to the interview candidates for participating in my research and to Henk de Regt for being the second reader of my thesis. Thanks to Sanne Kristensen for sharing her experience with qualitative research from a physics perspective. And finally, I would like to thank all the people at ISiS, in particular the other SiS-students: we have managed to form a really nice group in quite a short amount of time, despite all of the circumstances during the pandemic, which made my final year of studying a lot more enjoyable!

Marieke Glazenburg
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1 Introduction

1.1 Background

Over the years, modern science has developed great expertise in analysing isolated properties. Standard research methodology prescribes to focus on particular variables of interest and to purposefully neglect irrelevant influences, either by keeping them constant or averaging them out over large numbers or time. The idea is that all of these separately studied elements can eventually be recombined to retrieve the full picture. Through this approach, complicated objects of study become measurable and intercomparable. Not only has this view proven extremely useful to the scientific world, it is also a powerful tool in industrial settings, organisational management and many other areas where reducing a system to a single set of important characteristics enables calculations and optimisations that would otherwise be impossible.

However, it will not come as a surprise that this method breaks down in some cases. A telling example is the development of European forestry in the late 18th century (Scott, 1998). At some point in history, the management of forests became highly standardised. The entire status and value of a forest was assessed through a single characteristic: its annual production of timber. Everything that did not contribute to this number, such as the presence of underbrush and species diversity, was both literally and conceptually eliminated. This was a revolutionary and initially very successful approach that made it possible to design and manage forests with great efficiency, since every decision could be tested against the quantitative aim of maximising yield. About a century later however, production started stalling and the eminent shortcomings of the simplified view came to the surface. It turned out that a certain degree of biodiversity, through a complex and intricate network of mutual dependencies and interactions, was essential in maintaining the quality of the soil and thus ensuring the growth of the trees. This necessity was not taken into account in the standardised view, since biodiversity has no direct relation with timber yield, but the deliberate standardisation left out parts of the picture that turned out to be vital to understanding the system as a whole.

Modern science has become increasingly aware of the existence of systems in which pure standardisation and aggregation of properties provides inferior or even incorrect predictions. These are systems consisting of large numbers of components that together do not behave additively, but are instead mutually interactive, which causes the system to show collective behaviour that is often not foreseen when analysing the individual components separately. The organised behaviour of large birds flocks is a prime example (Couzin and Krause, 2003), but there are many more instances imaginable from almost every facet of the world, from stock market trends (Hommes, 2001) to the earth's climate (Dakos *et al.*, 2008).

Such a system, made up of a large number of interacting subunits, is known as a complex adaptive system, or complex system for short, and the branch of science dedicated to their study as complexity science (Bar-Yam, 2019). Complexity science is an incredibly wide and diverse field of research that brings together an extensive range of scientific disciplines, from exact to social sciences. Although the essence of what constitutes 'complexity' is impossible to capture concisely, many complex systems across disciplines share certain basic characteristics. These generic properties include self-organisation, unpredictable dynamic or adaptive behaviour and emergence of macroscopic patterns. Generally speaking, the basic premise of a complex system is that its behaviour as an entity cannot be traced back to the behaviour of its separate constituents, i.e. 'the whole is greater than the sum of its parts'.

One widely occurring feature of complex systems that is often of great interest to research, is the presence of tipping points in a system. A tipping point, also referred to as a critical point, is a point at which a system undergoes a sudden, dramatic change in its properties and behaviour (Scheffer *et al.*, 2001). When crossing a tipping point, the system rapidly shifts from one dynamical regime to another, despite the longevity and apparent stability of the state that the system occupied prior to the transition. An example is the sudden accelerated extinction of a certain species in an ecosystem: populations may have been fairly constant in size over a large timespan, only to suddenly decline or even completely vanish with seemingly little warning (Dai *et al.*, 2012). Other examples of tipping points include epilepsy patients going into a seizure (Litt *et al.*, 2001), stock market crashes (National Research Council, 2007), global climate change (Lenton *et al.*, 2008) and many others.

Sudden regime shifts over a tipping point are sometimes also referred to as phase transitions, a term that stems from the physical study of materials moving from one (structured, magnetic, nematic, etc.) state to another under the influence of some external parameter, such as a liquid evaporating into a gas under a temperature increase. In physics, the classical description of phase transitions requires little specific information about the details of the system, but instead depends on more general, macroscopic quantities that describe the evolution of the order in the system as a whole. The original phenomenological theory of phase transitions was formulated by Landau (1937) and has since provided a point of departure for more sophisticated theories of increasingly exotic types of phase transitions, such as magnetism and superconductivity.

The central concept in Landau's basic theory is the notion of the order parameter, which is a quantitative measure indicating the degree of order in the system. Over a typical phase transition, the order parameter will change from zero, indicating total disorder, to some non-zero value, associated with the macroscopic order in the system. A phase transition is induced by the variation of a control parameter, which is temperature in the case of the liquid-gas transition, but there are also other possibilities, such as pressure, external field strength or chemical composition. A typical thermodynamic phase transition that is often brought up as an illustration is ferromagnetism. Some materials, known as ferromagnets, will spontaneously become magnetic below a certain critical temperature. In this case, the order parameter of the magnetic transition is the net magnetisation of the material. Prior to the critical transition, the magnetic constituents of the system are disordered and there is no net magnetisation, which means that the order parameter is zero. After the transition, the individual magnetic moments have started to align and thus produce a net magnetisation that is non-zero.

The apparent parallels between phase transitions in physics and tipping points in other complex systems raise the question whether phase transition theory can be used to better understand these tipping points outside of physics. Since the study of phase transitions in physics begins and ends with the order parameter, identifying an appropriate order parameter for a given tipping point would provide a sensible starting point for this question. The notion of an order parameter or a similar collective variable (e.g. Schoner and Kelso (1988); Davies *et al.* (2011); Haken (1977); Thelen *et al.* (1991)) is already referenced fairly frequently to help characterise regime shifts in complex systems, but more general strategies have not yet been developed. Although this concept is thus pivotal in a study of phase transitions in generic complex systems, the methods used to identify an order parameter in a specific system are often unclear and seem to lack a systematic approach.

More fundamentally however, a question worth asking is to what extent transferring concepts and theory from physics to other areas of science is actually a *useful* undertaking. This question can be posed on a scientific level (will it progress understanding?), but it also touches upon the issue of practical relevance: does the application of physics theory to case studies in a 'non-physics' setting have the potential to improve for instance interventions in practice, or is it a purely theoretical exercise? The resemblance between physical phase transitions and regime shifts in complex dynamic processes is increasingly recognised in complexity research, but the fundamental added value of this approach seems to receive relatively little attention. Since translating mathematics between scientific disciplines is not entirely undisputed (Frigg, 2003) and since the possibility that certain scientific disciplines simply benefit most from field-specific methods should not be ruled out, this is a question that deserves to be explored.

1.2 Objective and research questions

Based on the considerations so far, the aim of this project is to take the first steps towards developing a more systematic approach for identifying an order parameter in generic complex systems undergoing an apparent regime shift, and to assess the potential scientific and societal usefulness of using physics theory in a context outside of pure physics. To this end, a particular dataset has been selected to serve as a case study. The dataset that was chosen is a relatively large set of time series data from momentary observations of daily life experiences by a patient diagnosed with major depressive disorder (MDD), originally studied by Wichers and Groot (2016) and made available by Kossakowski *et al.* (2017). The time series were recorded while the participant was going through gradual discontinuation of their antidepressant medication, which resulted in a sudden increase in depressive symptoms about halfway through the experiment. This shift motivated the participant and their psychiatrist to resume the prescription of antidepressants. More details about this particular dataset will be discussed in section 2.4.

The process of searching for an order parameter in this dataset inevitably also involves addressing the issue of interdisciplinary communication and translation of concepts and methods from physics to behavioural psychology and vice versa. Understanding the paradigm in which the data were obtained and analysed, and how this relates to the paradigm of physics in the context of phase transitions, is a vital prerequisite to the identification of an order parameter. Moreover, the fundamental added value of this attempt in terms of scientific and clinical relevance has to be questioned.

The project therefore essentially consists of two semi-separate elements: (1) using the patient's momentary observation data to develop guidelines for the identification of an order parameter in a generic complex system, and (2) assessing the sensibility and usefulness of this translation of concepts between scientific disciplines. Although these two elements may seem disconnected at first, they should be viewed holistically: the question of *feasibility* in the first element is meaningless without the question of *usefulness* in the second element, and vice versa.

These aspects are summarised in the following research aim and subsequent research questions.

Research aim

The aim of this project is to start developing guidelines for identifying an order parameter, as known from the theory of phase transitions in physics, in a regime shift occurring in a system outside of physics, in particular the shift in depressive symptoms of a patient with MDD going through gradual discontinuation of antidepressants, and to assess the sensibility and usefulness of this interdisciplinary translation.

Research questions

RQ1: "How can the concept of an order parameter, as known from the theory of phase transitions in physics, be applied to or identified in a generic system undergoing an apparent regime shift, in particular the dataset of the patient with MDD?"

- Which methods have been used to study the regime shift in the dataset so far?
- Which guidelines could be used to help identify an order parameter in this dataset and similar complex systems with tentative regime shifts?

RQ2: "To what extent does the application of physical theory of phase transitions to a regime shift in a system outside of physics provide added value to the scientific and clinical practice?"

- What are the motivations of researchers for applying theories from physics to phenomena in complex systems outside of physics?

- What is the potential clinical usefulness of studying regime shifts in generic complex systems through the lens of physical theory of phase transitions?

For the purpose of this project, the phase transition approach is considered to belong to the broad category of 'complexity science' (even though it will become apparent that this categorisation is not easily made). For this reason, the discussion surrounding RQ2 will take general complexity research as a benchmark and from there extend to phase transition modelling in particular. Moreover, it turned out that complexity and interdisciplinarity are correlated in interesting ways. Therefore, the obtained data was broader and richer than the original scope of RQ2. The analysis and discussion corresponding to RQ2 will accommodate for these unanticipated aspects.

The research questions are addressed by a combination of quantitative and qualitative methods. In the following, section 2 develops the theoretical framework required to understand tipping points, phase transitions and interdisciplinary practice. Section 3 describes the methods used to answer each research question. In section 4, the results from both the quantitative and qualitative work are presented and discussed separately. Finally, section 5 returns to the research questions and provides an outlook into possible further study.

1.3 Institutional context

This project was carried out as part of the Radboud Interfaculty Complexity Hub (RICH). RICH is an interfaculty initiative linking the faculties of medicine, mathematics and physics, social sciences, management sciences and philosophy. This initiative aims to consolidate the transdisciplinary expertise in complexity-related research and education that currently exists but is fragmented across the different faculties of the Radboud University. RICH provides an transdisciplinary organisational structure that supports the development of viable complexity research collaborations and an educational program. The goal is to turn Radboud University into a unique international hub for state-of-the-art education and research in complexity science.[1]

As a part of this goal, RICH aims to facilitate (master) student projects under joint supervision, with supervisors and collaborators from different faculties. In this case, the project is formally supervised by a philosopher of science from the Institute for Science in Society (ISiS) and a physicist from the High Field Magnet Laboratory (HFML). Furthermore, the project will be carried out in collaboration with a behavioural scientist from the Behaviour Science Institute (BSI) and two medical scientists from the Radboud Universitair Medisch Centrum (Radboudumc).

[1] Quoted from the former RICH webpage; for the current website, see https://www.radboud-complexity.com/.

2 Theoretical framework

The theoretical framework for this project can be split up into several components. First, section 2.1 will give an introduction to complexity science in general. In section 2.2, a basic overview of the Landau theory of phase transitions will be provided. Section 2.3 will discuss regime shifts in general and methods to study tipping points in different complex systems. Section 2.4 will then discuss the dataset that was used as a case study and relevant previous publications regarding this dataset in more detail. Finally, section 2.5 will go into motivations and barriers for interdisciplinarity in research.

2.1 Complexity science

Complex systems are ubiquitous throughout all of science, from physics and mathematics to sociology and psychology, which makes complexity science a highly interdisciplinary field. There is no single universal definition of the term 'complexity' and the diversity of systems that are classified as complex is huge, but there are certain properties that many of these systems share. Boehnert *et al.* (2018) have comprised a comprehensive overview summarising 16 frequently occurring properties that help characterise many different types of complex systems. Several commonly appearing elements from this overview that are relevant to the research focus of this project will be highlighted below.

First and foremost, most complex systems feature non-negligible interactions. These interactions can take place on different levels, from individual components to subsystems constituting a larger whole. This interdependence of elements renders simple linear statements ('A leads to B') insufficiently explanatory, since causal pathways are intertwined and contain feedback loops. This is why complex systems are often mathematically treated as networks, i.e. collections of nodes and edges modelling the connections and interaction dynamics between components (Cohen and Havlin, 2010). Network analysis can be helpful for studying for example financial structures (Battiston *et al.*, 2016), traffic dynamics (Li *et al.*, 2015) or the earth's climate (Yamasaki *et al.*, 2008).

Another characteristic that is frequently associated with complexity is the occurrence of self-organisation, meaning that the components of a system spontaneously produce global behavioural patterns without the interference of an external 'control unit'. This phenomenon is particularly notable in biology, where for example bird flocks or bee colonies behave in a pattern that appears externally directed, but upon closer inspection turns out to be the result of individuals following a set of relatively simple rules that makes the macroscopic pattern emerge (Couzin and Krause, 2003). However, self-organisation is not limited to living organisms and can occur on all scales, from atomic to cosmological. It is often hypothesised that many systems self-organise at what is referred to as 'the edge of chaos', which is a narrow dynamic regime in between stability and disorder (Packard, 1988).

Related to this is the concept of emergence, i.e. the formation of macroscopic patterns that transcend the properties of the constituents. Philosophically, emergentism is the counterpart of reductionism: the belief that reality can be reduced to individual components without loss of information (Chibbaro *et al.*, 2014). How to properly define and characterise emergence is a question of great interest, to which a multitude of answers exists. The term originates from philosophy of science and has deep roots in mathematics, physics and chemistry, where it applies to for example macroscopic patterns in condensed matter, but also the emergence of classical Newtonian physics from the limits of quantum mechanics and relativity theory. Emergence thus has to do with levels, scales and interactions between those, and how collective structures are related to microscopic properties.

Complex systems are frequently associated with dynamics over time and adaptive behaviour (Holland, 1992). Rather than remaining stationary, complex systems often move between various stability domains and have the ability to evolve and adapt to external conditions, increasing the resilience of the system. This can also lead to unpredictability and chaotic behaviour. Large sets of interdependent components, each with their own dynamics, often have a limited predictive horizon due to an extremely sensitive dependence on external conditions (Strogatz, 1994). Weather forecasting is a prime example of this effect.

Finally, it is remarkable that certain patterns appear to emerge in many complex systems across disciplines, revealing interesting similarities between seemingly unrelated fields. An example is the fractal-like branching of flows that occurs in for instance rivers, blood vessels and trees alike (Woldenberg, 1979). Complexity science is a highly interdisciplinary field, to such an extent that the notions of complexity and interdisciplinarity are becoming increasingly intertwined (Klein, 2004). The exact relation between the two and whether complexity science should strive for universally applicable explanations is still up for debate, but the fact that resemblances between complex systems from different disciplines exist cannot be disputed. This makes the the attempt to model generic tipping points as phase transitions all the more interesting and relevant.

2.2 Landau theory of phase transitions

In order to better understand the relationship between phase transition theory in physics and the study of tipping points in complex systems, the classical phenomenological theory of phase transitions will be outlined below.

Phase transitions are omnipresent in physics, from vaporisation to magnetic ordering. The basic phenomenological theory describing phase transitions was first formulated by Russian physicist Lev Landau during the first half of the 20^{th} century (Landau, 1937). Generally speaking, a phase transition occurs when a system moves from a state of disorder to a state of order, or vice versa, under the continuous change of a control parameter. The point at which the transition occurs is referred to as the critical point. Phase transitions are characterised by their so-called order parameter, which is a quantitative measure of the degree of order in the system. In the disordered state, the order parameter is zero, while it takes on a non-zero value in the ordered state.

Since the order parameter changes from zero to non-zero at the critical point, Landau assumed that it would be relatively small in the vicinity of the transition. He then sought the expression for the free energy as a function of the order parameter. The free energy is a thermodynamic potential that the order parameter seeks to minimise to obtain a stable state. Mathematically, the fact that the order parameter is small near the critical point implies that the Landau free energy f_L can be expressed as a polynomial (a truncated power series) in the order parameter ϕ. Some powers of ϕ are eliminated based on physical arguments, like the ϕ^3 term that would allow an infinitely negative solution for the order parameter. Taking these arguments into account, the free energy can be written as

$$f_L(\phi) = f_0(T) + a(T)\phi^2 + \frac{1}{2}b\phi^4 + \frac{1}{3}c\phi^6 + ... \tag{1}$$

where f_0 is a constant and a, b and c are the coefficients of the expansion. $a(T) = a_0(T - T_c)/T_c \equiv a_0\tau$ is dependent on the control parameter, or temperature in this case, and changes sign at the critical temperature T_c. Due to this change of sign, the free energy function obtains different minima, which causes the change in the value of the order parameter in the stable state.

In many phase transitions, the ordered state has a lower degree of symmetry than the disordered state. Consider the ferromagnetic transition for example: in the disordered state, in which all magnetic moments are directed randomly, the system is (macroscopically) invariant under rotations. In the ordered state however, the magnetic moments have aligned along a preferred direction and the system is no longer rotation invariant. This decrease in symmetry is a general feature of many physical phase transitions and is also known as spontaneous symmetry breaking.

Phase transitions can be categorised into two main types. The first type applies when the order in the system suddenly jumps to a new state when passing the critical point; transitions like these are therefore called discontinuous (or first-order). Discontinuous transitions typically involve latent heat, meaning that the system absorbs or releases a certain amount of energy during the transition, while the temperature remains fixed. During this latent heat stage, the system is in a mixed state where both phases occur simultaneously. An example is the transition of a boiling liquid into a gas: gas bubbles will form in the liquid before all of the liquid expands into the gaseous state. Phase transitions belonging to the second type are called continuous (or second-order): their order continuously changes over the critical point, there is no latent heat involved in the transition and no mixed stage occurs. Examples include superconducting and (anti)ferromagnetic transitions.

Mathemtatically, the two types of transitions are defined by considering the derivatives of the free energy: a discontinuity in the first derivative signifies a first-order transition, whereas a discontinuity in the second derivative means the transition is second-order. The difference between continuous and discontinuous transitions can be demonstrated by looking at equation 1 (Stoof *et al.*, 2009). For a continuous transition, we assume that $b = b_0 > 0$ and truncate the expansion after ϕ^4. This leads to solutions as shown in figure 1a. In this case, the initial $\phi = 0$ minimum continuously changes into a non-zero value below the critical temperature. A discontinuous transition is described by an expansion up until ϕ^6, with $b < 0$ to allow for minima to occur. This is shown in figure 1b: the non-zero local minimum suddenly drops below f_0 for $T < T_c$, becoming a global minimum and thus leading to a jump in the order parameter.

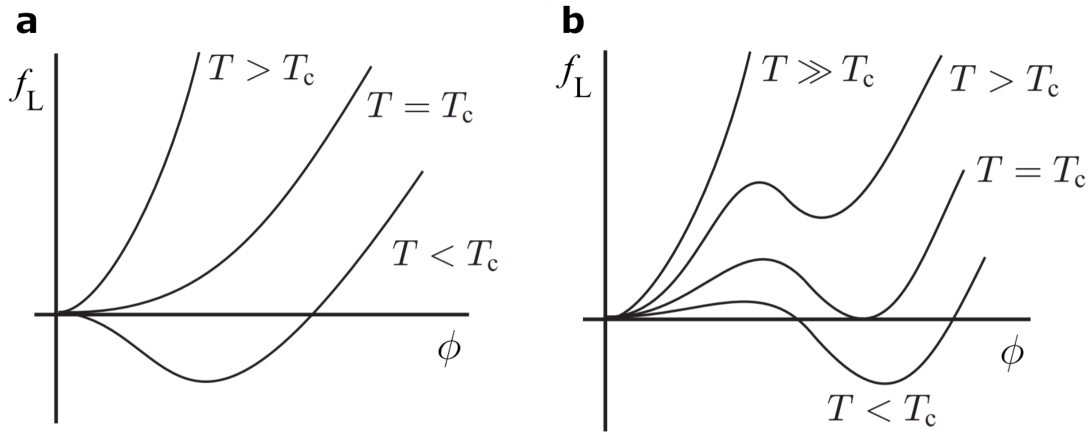

Figure 1: Landau free energy density as a function of the order parameter ϕ at different temperatures compared to T_c for (**a**) a continuous transition and (**b**) a discontinuous transition. Figure adapted from Stoof *et al.* (2009).

It turns out that it is typical for quantities to behave according to power laws when approaching the critical point of a continuous phase transition. The coherence length is one example, but other thermodynamic properties can also be shown to follow similar power laws. These power laws have the general form $X \sim \tau^{-\nu}$ where ν is called the critical exponent. It is interesting to note that certain groups of materials all appear to have the same sets of critical exponents, suggesting that they might be understood by a universal theory despite radical differences in their microscopic structure. These groups of materials are referred to as universality classes (Franklin, 2016).

2.3 Regime shifts and tipping points

Sudden shifts in macroscopic behaviour as a consequence of a certain parameter change are not only important within physics, but they are also frequently observed in a wide range of complex systems in other fields. The point at which such a transition occurs is generally referred to as a tipping point. In contrast to the neutral, 'value-free' context of phase transition theory in physics, tipping points in complex systems outside of physics can have significant and sometimes even irreversible effect on the individuals and their surroundings, therefore adding a layer of personal and societal impact that is not present within physics. In the case of the dataset in this project for example, the tipping point in the depressive symptom scores of the participant marked a decline in his mental health and an increase in his illness. Likewise, tipping points can be followed by positive change and improvement, such as a sudden symptom decline. In both cases, the ability to *predict* a tipping point prior to the regime shift itself can be extremely valuable.

The study of tipping points thus often revolves around attempts to predict these regime shifts. Although the sudden change in the state of the system may come as a surprise and appear unpredictable as a result, in many cases subtle warning signals can be observed prior to the onset of the transition, even when the macroscopic state of the system reveals no signs of an imminent change. One class of such indicators that has proven particularly promising in predicting tipping points stems from a phenomenon known as critical slowing down (Scheffer *et al.*, 2009).

Critical slowing down refers to the phenomenon that systems close to a tipping point become increasingly slow to recover from small perturbations that push them from their equilibrium, which can be understood within the framework of attractor states and potential landscapes. Stable, preferred states of a given system are often referred to as the attractors of the system and are visualised by wells in a potential landscape that is said to describe the system. When perturbed, the state of the system naturally returns to the well that (locally) minimises the potential. Over a regime shift, the potential landscape changes such that different minima emerge and start to act as attractor states. Critical slowing down occurs when the well, or basin of attraction, of a stable state slowly becomes more shallow as the system approaches the critical transition (see figure 2). During this time, the system is much more sensitive to disturbances and becomes more likely to be pushed to a new minimum and thus undergo a regime shift. This means that the system becomes slower to recover from perturbations in the period that precedes a tipping point, which can be quantitatively probed.

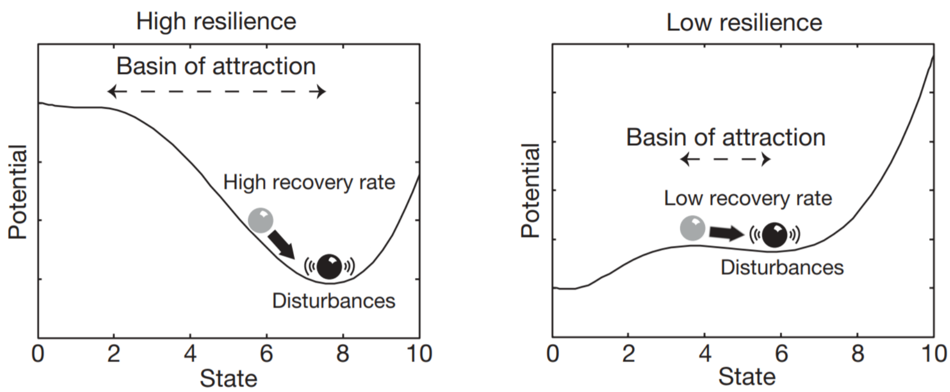

Figure 2: Critical slowing down prior to a tipping point. In the high resilience state, the system will be relatively quick to recover from external disturbances, resulting in a high recovery rate. In the low resilience state just before the transition, the basin of attraction becomes shallower and the recovery rate declines. Figure adapted from Scheffer *et al.* (2009).

In many systems, it is (practically or ethically) impossible to induce small perturbations and measure recovery rate in a controlled setting. However, most systems are naturally subject to perturbations resulting from external forces, as visible in the fluctuations of the system's state. These fluctuations are thought to be indicative of the stability of the current state. If the current state of the system becomes less stable, the recovery rate will decrease and change in the system will take place at a much slower pace. In other words: the system becomes more resemblant to its past states. This can be quantified by means of the autocorrelation (Ives, 1995), which is a measure of the 'memory' of a system and indicates the degree of correlation between subsequent states, calculated at different lags. An increase in the lag-1 autocorrelation has been shown to be associated with critical transitions in various systems, such as the earth's climate (Dakos *et al.*, 2008). Another quantitative consequence of critical slowing down is an increased variance (Carpenter and Brock, 2006). This can be understood as the system becoming more responsive to external forces as a result of the lower resilience, therefore causing the variance to increase.

The striking parallels between phenomena from the exact sciences and regime shifts in more general complex systems have been recognised ever since the field of complexity science emerged as an explicit scientific discipline, resulting in an abundance of methodologies and frameworks that borrow concepts from physics and mathematics to help describe and predict behaviour of systems in other areas of science. A widely used framework is bifurcation theory, a field of mathematics that studies qualitative changes in the structure of dynamic systems that are governed by a set of differential equations. Gradually changing the parameters in these equations can induce sudden qualitative changes in the behaviour of the system, known as bifurcations (Kuznetsov, 2013). The fold bifurcation, where the stable state changes discontinuously, is often used as a typical illustration of sudden regime shifts (Scheffer *et al.*, 2012), but other types of bifurcations can occur as well (Hommes, 2001; Olien and Bélair, 1997; Kot, 2011).

Another example of such a framework for understanding tipping points from a physics point of view is synergetics, a fairly young interdisciplinary research field that aims to provide general answers to questions about self-organisation and regime shifts in systems far from equilibrium, centralised around the order parameter concept from physics and reduction of degrees of freedom in the organised state (Haken, 1977). Haken often uses laser light as an example, where light emission becomes correlated after passing the laser threshold, thus decreasing ('enslaving') the available degrees of freedom. This framework can be used to describe other types of self-organised systems as well.

2.4 Case study details

Based on the discussion in the previous sections, it is clear that there have been many efforts to apply knowledge from physics and mathematics to the study of generic tipping points in diverse complex systems. However, a systematic approach for describing regime shifts as phase transitions by means of order parameter identification seems to be lacking. In order to explore this approach, a particular dataset featuring a tentative tipping point was chosen as a case study. Details regarding this dataset and several relevant results from previous publications will be discussed below.

The dataset used as a case study originates from behavioural science and was originally obtained by Wichers and Groot (2016). The authors were interested in early warning signals for sudden shifts in depressive symptoms, which can occur both positively and negatively. Earlier work on this topic suggested the relevance of several early warning signals by means of statistical analysis on large samples of both healthy and depressed individuals, reporting a correlation between the hypothesised warning signals and a future change in depressive symptoms that would manifest in a follow-up measurement (Van de Leemput *et al.*, 2014). This study however did not allow for the assessment of early warning signals *within* individuals in relation to critical transitions in their particular symptom evolution. The study by Wichers and Groot (2016) was therefore centred around a dataset that did make it possible to look for such person-specific warning signals in a single individual over an extended period of time.

A more detailed description of the background and methods used in collecting the dataset can be found in Kossakowski *et al.* (2017). The participant in question is a 57 year old male who has had multiple depressive episodes and has been using antidepressant medication in the 8.5 years prior to the start of the experiment. Over the course of 238 days, the participant completed a total of 1476 measurements of his daily life experiences using ecological momentary assessment (EMA). During this time, the dosage of the participant's antidepressant was gradually reduced at a rate that was unknown to both the participant and the researchers. Interestingly enough, it was the participant himself who initiated the measurement sequence, since he wanted to gain more insight into his symptoms during the reduction time and explicitly wished for the data to be used in psychological research. The participant was also involved in the selection of the items that appeared in the measurements, adding items that he considered personally relevant. Items were prompted either weekly (measuring depressive symptoms using the Symptom Checklist Revised or SCL-90-R), daily (related to the quality of sleep and assessment of the full day) or momentary (related to daily experiences, up to 10 times a day). The experiment consisted of five phases: (1) a baseline measurement of 4 weeks, (2) a double-blind period without reduction of the antidepressant dosage of between zero and six weeks, (3) a double-blind period in which the dosage was gradually reduced to zero over the course of eight weeks, (4) a post-assessment period with constant zero dosage of eight weeks and (5) a follow-up period of twelve weeks. Around day 127 of the experiment, a significant increase in the SCL-90-R scores was observed. As a consequence of this increase, the participant and his psychiatrist decided to resume the use of antidepressants several weeks after the experiment ended.

The original publication by Wichers and Groot (2016) was the first to identify the shift in depressive symptoms after the antidepressant reduction. Change point analysis, an umbrella term for statistical methods to detect mean changes in time series data, confirmed the significance of the shift. The particular change point detection algorithm was not specified in the article. In the remainder of their analysis, a selection of items was grouped together into five components, or 'mental states', three of which consisted of several items added together (negative affect, positive affect and mental unrest) and two of which were assessed by a single item (subclinical psychotic experiences and cognitive context). The selected items are summarised in table 1.

Mental state	Corresponding items
Negative affect	I feel irritated I feel lonely I feel anxious I feel guilty I feel indecisive
Positive affect	I feel satisfied I feel enthusiastic I feel cheerful I feel strong
Mental unrest	I feel restless I feel agitated
Psychotic experiences	I feel suspicious
Cognitive context	I worry

Table 1: Item selection and categorisation used in the original publication on the dataset by Wichers and Groot (2016).

Analysis in this publication focused on early warning signals prior to the shift. In order to assess this, the items belonging to the five mental states were added together and then detrended (i.e. a polynomial background trend was subtracted to isolate short term fluctuations). The two early warning signals that were considered are lag-1 autocorrelation and variance. Autocorrelation is calculated as the statistical correlation between lagged versions of a time series. Lag-1 autocorrelation $R(k = 1; X)$ and variance $\text{Var}(X)$ of a time series X with elements x_i and length N are thus given by

$$R(k = 1; X) = \frac{\frac{1}{N}\sum_{i=1}^{N-1}(x_i - \mu)(x_{i+1} - \mu)}{\sigma^2} \qquad (2)$$
$$\text{Var}(X) = \sigma^2 = E[(X - \mu)^2]$$

The results from their analysis are shown in figure 3.

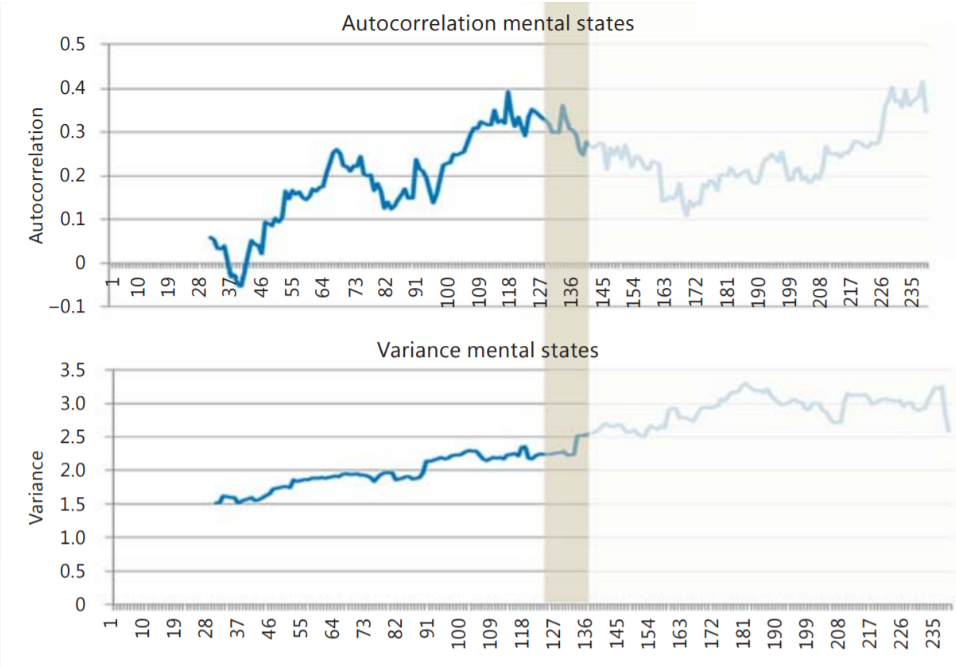

Figure 3: Autocorrelation and variance of the summed, detrended mental states in a moving window with a width of 30 days, as reported in the original publication by Wichers and Groot (2016).

Theory predicts an increase in both autocorrelation and variance prior to a tipping point (Scheffer *et al.*, 2009). Based on their findings, Wichers and Groot (2016) conclude that this increase is indeed observed in this dataset. This statement is based on visual inspection of the plots in figure 3. Several techniques are available to support conclusions like this with statistical arguments, such as surrogate testing and parameter sensitivity analysis (see for example Dakos *et al.* (2008)). No such techniques were mentioned in this publication however. Moreover, the precise link between the variance and the shift in depressive symptoms remains unclear, since its slope is mostly constant and the increase persists even long after the transition took place. Nevertheless, this publication provides the first evidence towards the presence of early warning signals within a single individual regarding tipping points in depression.

Another publication by Smit *et al.* (2019) focused on restlessness as a potential early warning signal. They compared the item 'I feel restless' of the original participant to the item scores of six other participants, one of which reported a similar increase in depressive symptoms over the course of their antidepressant reduction. By comparing an exponentially weighted moving average (EWMA) of the item scores during the first observations to the scores just prior to the shift in symptom severity, they found that in both participants the shift was preceded by an increase in restlessness, as illustrated in figure 4. This trend was not observed in participants who did not experience a significant increase in depressive symptoms. From these findings, they conclude that monitoring restlessness may be useful to provide possible early warning signals of an impending depression relapse.

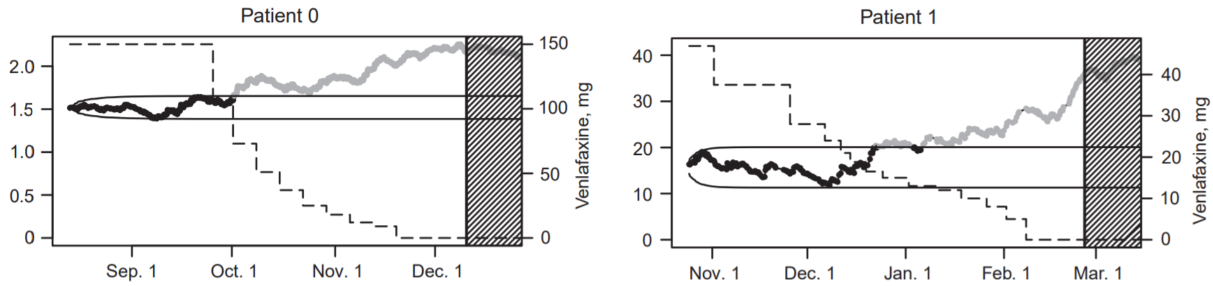

Figure 4: Comparison of the EWMA of the item 'I feel restless' from the first observations to the scores prior to the shift in depressive symptoms in the participant studied here (patient 0) as well as a new case (patient 1). An increase in restlessness scores is observed in both patients. Figure obtained from Smit *et al.* (2019).

Finally, Olthof *et al.* (2020) performed an extensive analysis on the dataset with the aim of identifying what they refer to as 'markers of complexity' within the self-ratings of an individual patient. The three markers they consider are memory (long-range temporal correlations), regime shifts (non-stationarity) and sensitivity to initial conditions (limited predictive horizon). They conclude that self-ratings from psychological states exhibit all three markers of complexity, whereas self-ratings of physical sensations behave more similar to random variables. Based on their findings, they advocate a complex systems perspective on psychopathology rather than popular group-based statistical methods.

The three publications discussed here all contribute to a better understanding of the dataset, both in the area of potential early warning signals as well as fundamental knowledge about the nature of psychological systems. Although comparison to these findings is valuable, the order parameter analysis that will be attempted in this project is not necessarily meant to build upon these efforts, but rather to explore a possible alternative pathway. The procedure for this will be elaborated upon in section 3.1 and 4.1.

2.5 Interdisciplinary practice

From the analysis techniques applied in the previous publications together with the discussion on regime shift frameworks from section 2.3, it becomes apparent that different takes on the use of mathematics and physics in generic complex systems are applied parallel to one another and have all achieved success to various degrees. Many of these approaches share similar terminology, at least to some extent, but the exact overlap and differences between them are often unclear. Moreover, due to the great diversity in systems that display features of complexity and regime shifts, the scientific paradigms in which they are embedded tend to make use of field-specific jargon that is not always compatible between disciplines. When considering an interdisciplinary application of methods, such as the translation of phase transition theory to more general complex systems, it is important to keep these communicative challenges in mind. So far, the discussion of phase transitions and regime shifts has been focused on the practical feasibility aspect and quantitative data analysis, corresponding to the first research question. However, to consider the potential usefulness of this approach addressed in the second research question, a broader reflection on interdisciplinary methods and practice is required. The question of how problems, concepts and methodologies can be related between scientific disciplines in an interdisciplinary research approach calls for a discussion about what 'interdisciplinarity' actually means and how it is executed in practice. Moreover, an understanding of what drives interdisciplinary research in science is required, as well as insight into potential barriers and challenges.

In order to better conceptualise what is understood by interdisciplinarity, it is important to first address how a scientific *discipline* can be defined. Plainly put, a discipline is a branch of knowledge, instruction, learning, teaching or education (Alvargonzález, 2011; Choi and Pak, 2006). However, this definition does not provide any suggestion on how to demarcate different disciplines or how disciplines can dynamically evolve over time, merging or splitting throughout history. In the natural sciences for example, physics, chemistry and biology were all united together with natural philosophy under the name of 'the study of nature' and were not separated into their own distinct branches as we know them today until the 19th century (Cahan, 2003). Even in the current time, the borders between disciplines are fluid and often depend as much on external factors like institutional organisation as on fundamental distinctiveness (Austin *et al.*, 1996). Several attempts have been made at formulating a fitting and workable definition of a scientific discipline, such as "a comparatively self-contained and isolated domain of human experience which possesses its own community of experts" (Nissani, 1995). Yet, there is no single exhaustive definition to fully cover the current categorisation of science.

These ambiguities and unclarities in the definition of a scientific discipline persist into the understanding of interdisciplinarity. Generally speaking, research is referred to as interdisciplinary if it combines input from different disciplines, which of course hinges heavily on how the division of scientific expertise into disciplines is organised in the first place: if two areas of science are not considered separate disciplines then research combining these areas strictly cannot be considered interdisciplinary, and vice versa. This also implies that a higher degree of fragmentation in the categorisation of science automatically leads to more 'interdisciplinary' research, as disciplines that might have previously been united are now considered separate entities. These issues aside, several working definitions of interdisciplinarity have been put forward over the years. For instance, Klein (1990) defines interdisciplinarity as "a synthesis of two or more disciplines, establishing a new level of discourse and integration of knowledge." Nissani (1995) proposed a minimalist definition of interdisciplinarity as "bringing together in some fashion distinctive components of two or more disciplines". Alvargonzález (2011) takes a more general angle and refers to interdisciplinarity as "an activity that exists among existing disciplines or in a reciprocal relationship between them", while still recognising the independence of each discipline. Each of these definitions emphasises a different element of interdisciplinarity, be it creating new discourse, connecting distinctive elements or simply occurring in different domains.

Finding an exact definition of interdisciplinarity is perhaps less insightful than comparing the term to other similar yet distinct forms of combining scientific disciplines in research. Interdisciplinarity is most frequently contrasted to multidisciplinarity, which also brings together multiple areas of science. The difference here is that multidisciplinary research does not truly merge or integrate the disciplines that are involved; rather, the disciplines are maintained separately and stay within their own boundaries (Klein, 2004; Choi and Pak, 2006; Alvargonzález, 2011). In this case, knowledge and input is collected to study a particular problem from multiple angles, without integrating or combining the different perspectives. Finally, transdisciplinarity refers to the integration of the natural, social and health sciences in a humanities context, completely transcending traditional boundaries and therefore providing the most holistic view of all three (Choi and Pak, 2006). Although the terms are sometimes used interchangeably, they all refer to different levels of integration and transcension of scientific disciplines. In practice, research that is labelled as interdisciplinary is often more resemblant to multidisciplinarity, i.e. the different disciplines that are involved each contribute their own perspective and knowledge to a certain problem, but these contributions remain separate. It is therefore important to pay explicit attention to the operationalisation of the desired interdisciplinarity in research projects to better characterise the relation between the collaborating areas of science and to assess whether true interdisciplinarity has been achieved at all.

Moreover, it has been observed that the relation between complexity science and interdisciplinarity has become increasingly tight over the recent decades (Klein, 2004). Several authors' interpretations of and motivations for interdisciplinarity even directly involve complexity (e.g. Klein and Newell (1997); Hubenthal (1994); Turner (1990)). With boundaries between disciplines continuously shifting and reshaping, the connections and areas of overlap and distinction between these concepts are becoming a progressively prominent theme. This point also emerges when considering incentives for interdisciplinarity in science, which will be discussed in the following.

Motivations to engage with interdisciplinary research are diverse. Perhaps most importantly, it is fuelled by an increasing awareness that many contemporary scientific problems contain a level of intricacy (or 'complexity') that demands the integration of expertise from a range of different disciplines, rather than deep specialisation within a single field (Buanes and Jentoft, 2009; Balsiger, 2004). Issues like climate change, technological advancements and global health crises cannot be appropriately addressed from a single scientific perspective, but instead benefit from a combination of sociological, biological, technological and other expertise. Moreover, the application of techniques or knowledge from one field to a problem in another field can improve the understanding on both sides of the collaboration (Knight and Pettigrew, 2007), possibly opening up new promising areas of research (Zahra and Newey, 2009). Curiosity and excitement about these new research directions provides a compelling personal incentive for scientists to engage with interdisciplinary efforts. Interdisciplinary research is also often associated with innovation and creativity: bringing together a great diversity of different perspectives and backgrounds is assumed to lead to more surprising and innovative outcomes (He *et al.*, 2009; Frost and Jean, 2003). The unification of knowledge from different disciplines in order to provide more universal explanations and solutions to scientific problems is known as consilience (Wilson, 1999). Some even argue that consilience in research will be the most important path to new scientific breakthroughs and will eventually replace the more traditional disciplinary and hierarchical forms of research (Gibbons *et al.*, 1994).

In practice however, there are quite a few barriers that tend to undermine truly interdisciplinary research. Funding can be one of those barriers: sometimes it can be difficult to acquire funding at all, or sometimes funding agencies maintain specific requirements about the composition of the team that lead to artificial collaborations and unnecessary complications (Knight and Pettigrew, 2007; Carayol and Thi, 2005). However, it can be argued that this is not the main impediment. While intrinsic motivation from scholars is mostly abundant and extrinsic attention from funding agencies is generally sufficient for successful collaboration, systemic implementation is often still lacking (Rhoten, 2004). In many cases, institutions centred around interdisciplinary work tend to maintain their 'old' disciplinary structures underneath broader research themes. This means that in practice, researchers are often working alongside one another within their own disciplinary customs, rather than being involved in intimate collaboration. Hence, the interdisciplinarity is more of a labelling than a structurally different approach, referring back to the earlier discussion on multi- versus interdisciplinarity. This can also be a consequence of inadequately formulated research themes, where the scope of a collaboration becomes so broad that no explicit problem definition can be extracted and the roles of the individual researchers within the network remain unclear. It is therefore important to be explicitly aware of the relevant boundary objects (Star, 1989): these are concrete research targets that appear in multiple disciplines, but can be interpreted differently depending on the scientific perspective. A lack of explicitly specified boundary objects tends to complicate interdisciplinary communication and fruitful research.

Finally, differences in traditions between scientific disciplines can also be a barrier. Not only does this relate to differences in understanding of concepts and methodologies, but it also touches upon diversity in habits, values and behaviours that are dominant within a particular scientific community. Members of interdisciplinary collaboration tend to be faithful to their own disciplinary traditions (Klein, 1990), either consciously or subconsciously, which can lead to an inability to abandon or adapt their perspective in favour of a more interdisciplinary view. This inability does not necessarily need to originate from unwillingness, but can also just be a consequence of many years of experience in the familiar disciplinary tradition. Although a strong tradition can be useful to enhance the sense of community within disciplines and to enable methodological unity, interdisciplinary research still lacks such a strong community and is therefore more prone to miscommunication and a lack of mutual understanding.

It is to be expected that the challenges and drivers described so far also play a role in the application of phase transition theory to tipping points in general complex systems. Which aspects are most relevant and how the phase transition approach can be positioned remains an open question. These issues will be explored and incorporated into the second half of the project as described in section 3.2 and 4.2.

3 Methods

The two research questions as formulated in section 1.2 each require a different methodological approach. Research question 1 will be addressed by performing quantitative data analysis; the precise methods used will only be briefly outlined here and further elaborated upon in section 4.1. Research question 2 is qualitative in nature and will be addressed by conducting a small number of interviews, the details of which will be discussed below.

3.1 Data analysis

Analysis of the dataset was performed using a Python script written for this purpose. As a starting point, two criteria were formulated to assess the connection between the items in the dataset and an order parameter: the presence of a shift over the course of the tentative transition and a peak in fluctuations prior to the transition. These criteria were quantitatively operationalised and applied to all items in the dataset, yielding a list of items meeting one or both criteria. A parameter sensitivity analysis was performed to check the robustness of these conclusions.

3.2 Interviews

In order to study the usefulness of applying phase transition theory to complex systems outside of physics and to position this approach within a wider scientific context, several interviews were performed with researchers who are active in the field of complexity science. The decision to use interviews was based on the need for rich, in-depth information about motivations and perspectives of scientists in the field, which is best obtained through conversation. The interviews were semi-structured, i.e. they were conducted according to a pre-made interview guide, whilst maintaining possibility to diverge from the predetermined topics and ask follow-up questions if necessary. This style of interviewing is particularly useful for exploring individuals' perspectives on a topic since it allows for flexibility and adjustment to the input of the interviewee (Jensen and Laurie, 2016; Kvale, 1996), which fits a subject as diverse as complexity science well. The interviews were transcribed, coded in ATLAS.ti and analysed based on the research sub-questions, as well as other relevant themes that emerged. These steps will be further clarified below.

3.2.1 Participants

Due to restraints concerning the time available for this project, a limited number of four candidates was selected and invited to participate in the interviews. Selection was based on references from collaborators. For the selection, three main criteria were used: level of involvement with complexity science, interest in interdisciplinarity and societal implications, and amount of research experience. Explicit research interests (e.g. tipping points) were not used as a criterion to avoid limiting the pool of suitable candidates too much. To make sure a proper level of comparison remained possible despite the relatively small sample size, while simultaneously allowing for a large diversity of views, participants were chosen from either a medical or a psychological background. Details regarding each participant and their background are given in table 2. Participants 2 through 4 gave permission to publish their full names and affiliations to provide context for the discussion.

3.2.2 Interview guide

The semi-structured interviews were conducted with the help of an interview guide, containing an overview of the themes and corresponding questions to be addressed in the conversations. The ordering of the questions and the time spent on each theme were adjusted based on the

Participant	Name	Affiliation	Background	Specialisation
1	Anonymous	-	Psychology	-
2	J. Naaldenberg	Radboudumc	Medical science	Primary care
3	A. Lichtwarck-Aschoff	RUG	Psychology	Psychopathology
4	M. Olde-Rikkert	Radboudumc	Medical science	Geriatrics

Table 2: Overview of the interview participants and their respective backgrounds and specialisations.

input from the participants, in order to initiate a dialogue with room for extensive and freely formulated replies (Flick, 2011).

The interview guide was composed based on a combination of the research sub-questions (section 1.2), theoretical considerations (motivations and barriers for interdisciplinary practice from section 2.5) and informal conversations with collaborators. The interviews can be divided into the following main themes:

- Introduction to participant's research topic
  General introductory questions about the field in which the participant is active.
- The concept of complexity
  Questions about what the participant understands by complexity and the role of this notion in their research.
- Interdisciplinary methodology and collaboration
  Questions about complexity related and/or interdisciplinary methods used in the participant's research, the motivations for using these methods and their experiences in working with scientists from other disciplines.
- Relevance and practice
  Questions about the distance of the participant's research to clinical practice, potential applications of their work, and the practical added value they ascribe to complexity science and interdisciplinarity with regard to these applications.

The themes were intentionally formulated to go beyond the translation of phase transition theory by itself and instead seek to gain a broader overview of the current practice and added value of complexity science in general. These insights could then be translated and compared to the phase transition modelling approach attempted in this project during the analysis and discussion of the interview results.

Questions and follow-ups were formulated to be as open as possible. General strategies for phrasing and ordering of questions were taken from Patton (2001). Each interview had a duration of approximately one hour and was conducted over a video call. The interviews were performed in Dutch, since this was the native language of three out of four interviewees and the non-native participant was also fluent in Dutch. The full interview guide is given in Appendix B.

3.2.3 Coding and analysis

The analysis procedure was based on Jensen and Laurie (2016), loosely following the steps formulated by Kelle (2000). First, the interviews were fully transcribed with minimal editing: filler words ('uhm') and direct repetitions were omitted, but interjections and grammatical errors were maintained. After transcription, a codebook was composed based on the most important themes that emerged during the interviews. The codes were then applied to each transcript in

ATLAS.ti, while the codebook was iteratively adjusted to match new findings in the process. Observations and discussion points were noted during coding. After the first fine-tuning of the codebook, a final round of coding was performed to iron out inconsistencies and irregularities. Potential ambiguities or unclarities in code definitions were annotated if they could not be resolved. This process resulted in a collection of quotes labelled with codes from eight different categories, being:

- Descriptive information
  The participant provides a factual description of e.g. their research subject or a collaboration.

- Elements of complexity
  Aspects of the definition and interpretation of complexity according to the participant. Partly based on Boehnert et al. *(2018).*

- Integration of complexity in research
  Ways in which the notion of complexity is operationalised and integrated into the research of the participant.

- Motivations for complexity perspective
  Reasons for the participant to engage with complexity science.

- Challenges to complexity perspective
  Possible obstructions or limitations to complexity science.

- Motivations for interdisciplinarity
  Reasons for the participant to engage with interdisciplinary research.

- Challenges to interdisciplinarity
  Possible obstructions or limitations to interdisciplinary research.

- Practical relevance
  Possible applications of the participant's research and the added value of complexity and interdisciplinarity in this regard.

The full codebook and the groundedness per code are given in Appendix C.

Ideally, the coding should be repeated by an independent second coder to check the validity of the conclusions and to unveil potential missed information. However, practical constraints did not allow for this to be executed within the scope of this project. Should the project be continued or expanded upon in the future, then the incorporation of feedback from a second coder would have high priority.

Analysis of the interviews was then structured around the themes that were most relevant to the research questions, explicitly relating general results to the particular phase transition modelling approach that is the focus of this project. The codes were used to collect and compare views per subtopic or argument in order to be incorporated into the discussion. Due to the limited number of interviews that could be performed, usual reliability standards like data saturation were not feasible in this case. However, sufficient overlap and shared themes emerged for an exploratory analysis.

4 Results and discussion

The results can be split up according to the two research questions as formulated in section 1.2. In the following, section 4.1 will describe the analysis performed on the dataset and the preliminary conclusions from this analysis, corresponding to RQ1. Section 4.2 will discuss the interview outcomes and conclusions related to RQ2.

4.1 Data analysis and the order parameter

4.1.1 Data structure

The dataset consists of 1476 measurement points, spread over 238 consecutive days. Each of the in total 76 item columns contains the numeric scores from a different item that was prompted at a certain frequency. Other information that is available for each measurement point is the date, current antidepressant concentration and start and end time of the response. The participant would receive a maximum of 10 prompts per measurement day; the data also contain information about which of these prompts were answered and whether the response was aborted midway. The participant completed on average 6.2 assessments per day with a standard deviation of 1.9 and only a total of 5 responses were aborted before completion. More details can be found in Kossakowski *et al.* (2017).

Items were prompted at different time intervals: multiple times a day, once a day or once a week. The weekly items concerned the 13 items from the Symptom Checklist Revised (SCL-90-R) depression scale. The final column contains a calculated average score based on these 13 items. The daily items are divided into six items collected each morning regarding quality of sleep and six items collected each evening regarding the quality of the day as a whole. The momentary items appeared in all 10 measurement prompts and were divided into the following categories: mood states, self esteem, social company, physical sensations, the activity at the moment of the assessment and the occurrence of events in between the assessments. 33 items were scored on a 7-point Likert scale, ranging from 1 (not) to 7 (very). 6 items (related to mood states and events) were measured on a different 7-point scale ranging from -3 (not) to 3 (very), because it was found that this range increased the variation that the participant reported in his responses. Items related to social company, activities and events were categorised to allow for numeric response (e.g. “I am with friends” = 30).

Figure 5 shows an example of (b) a weekly item, (c) a daily item and (d) a momentary item. The shift in symptom scores as identified by Wichers and Groot (2016) is illustrated in figure 5a and highlighted by the yellow region in all subsequent plots. The experimental phases (see section 2.4) are demarcated by the dashed vertical lines.

4.1.2 Item selection and pre-processing

Not all 76 items were considered for the purpose of order parameter identification. For this process, the momentary items were deemed most valuable due to their high temporal resolution. The daily items were not taken into account because they provided a significantly smaller number of data points, and discrepancies between items could obstruct equal comparison. The weekly SCL-90-R items were only used in the form of the averaged item score, which identifies the region in which the tentative transition took place, and were not considered individually. Furthermore, momentary item categories that involved numerical categorisation or had conditional requirements (i.e. social company, activities and events) were omitted.

First, the momentary items scores were averaged for each measurement day. This was done to make sure all measurement points are equidistant for the rest of the analysis. Furthermore, in order to make the data more legible and to assess long-range trends, an exponentially weighted moving average (EWMA) was taken. This is a moving average that assigns weights to previous data points according to a decaying exponential. The half life of this exponential, determining

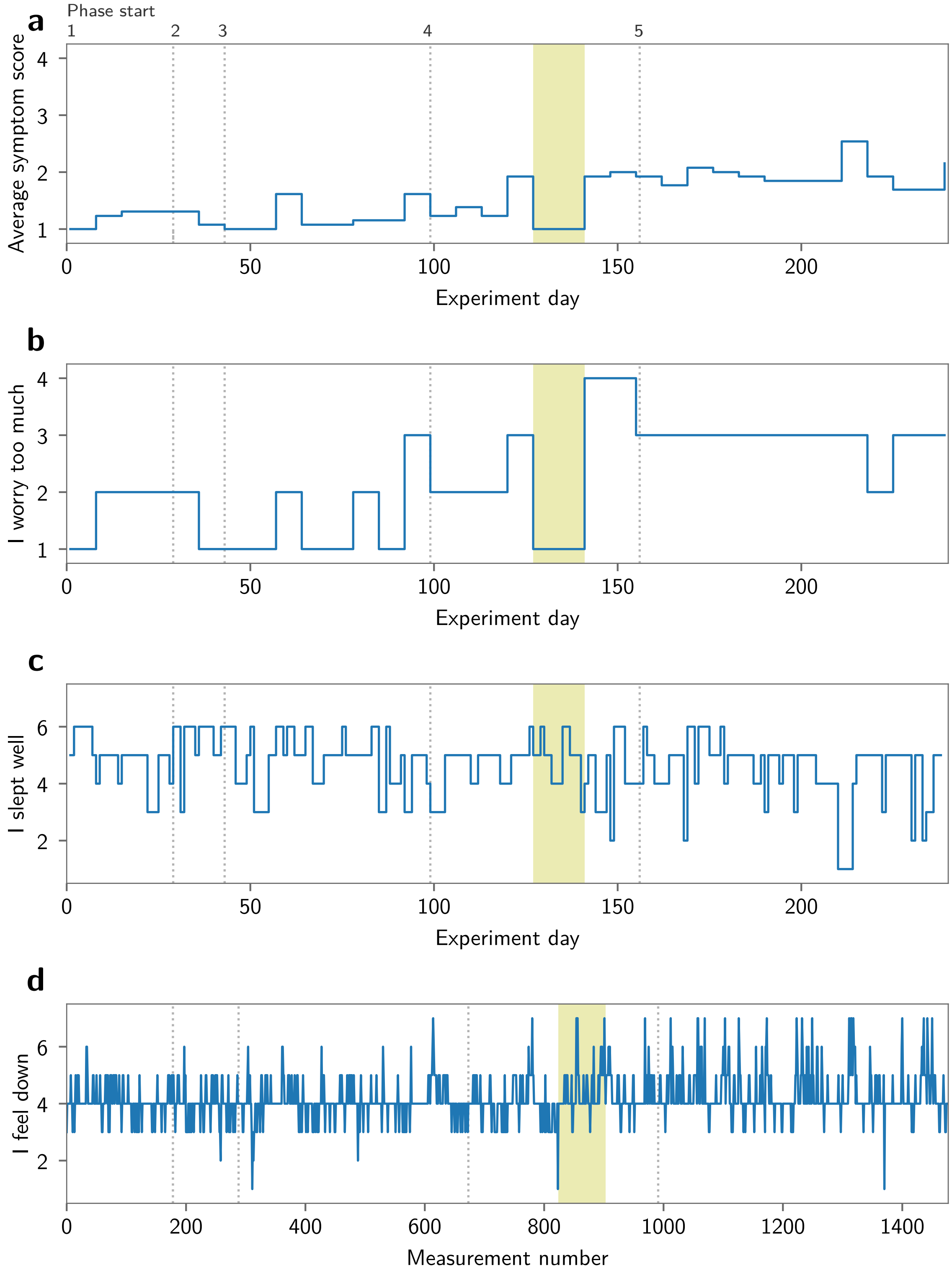

Figure 5: (**a**) Average score of all weekly SCL-90-R symptomatic items, showing a shift between day 127 and 141 (shaded yellow region). The experimental phases as described in section 2.4 are demarcated by the dashed vertical lines. (**b**) A weekly SCL-90-R item. (**c**) A daily item. (**d**) A momentary item. All items are plotted with the full available scoring range on the y-axis.

the time scale of the fluctuations that are filtered out by this procedure, was taken to be 14 days as a first estimate. This estimate was chosen as a relevant time scale because the DSM-5 requires symptom persistence of 14 days in order for the classification of depression to apply (American Psychiatric Association, 2013). Time scale dependence is further discussed in section 4.1.5. An example of an item and its corresponding EWMA is shown in figure 6.

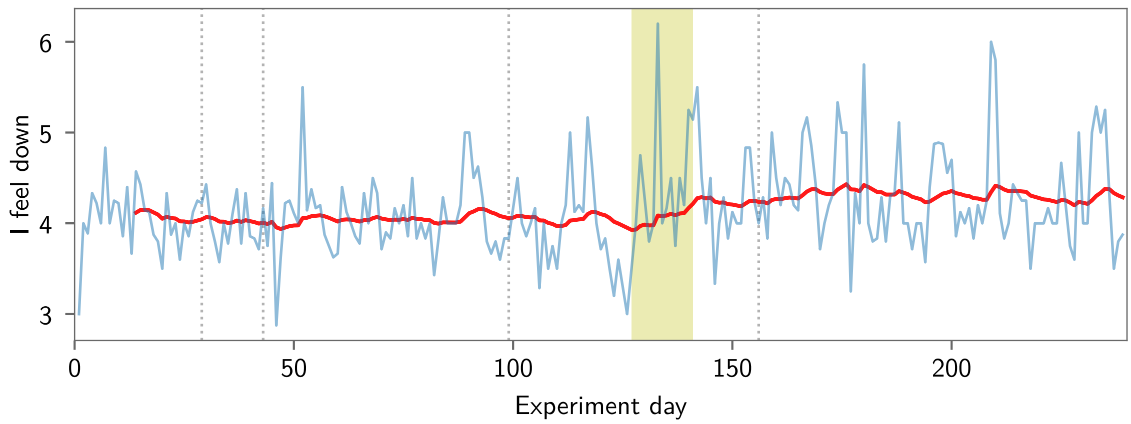

Figure 6: Example of an exponentially weighted moving average with a half life of 14 days (red) taken from a momentary item after averaging per day (blue).

4.1.3 Criteria and operationalisation

The aim of the analysis was to take the first steps towards identifying an order parameter for the tentative transition by systematically applying relevant criteria. Note that the analysis presented here does not claim to result in an exact determination of 'the' order parameter; rather, it attempts to identify the elements of the dataset that are likely to be coupled to such an order parameter. To this end, two basic criteria were verbally formulated as follows:

Criterion 1 The item undergoes a noticeable *shift* over the course of the tentative transition.

Criterion 2 The item displays *increased fluctuations* prior to the tentative transition.

The two criteria were operationalised in a quantitative way to allow for systematic testing of the available data.

Criterion 1 – Shift The presence of a shift was assessed through comparison of the mean EWMA level after the transition (day no. ≥ 141) to the mean EWMA level in the baseline period prior to antidepressant reduction (phases 1 & 2, day no. < 43). If a shift was registered that exceeded the standard deviations of both levels, the criterion was met. Note that this operationalisation also includes items that display a gradual shift occurring over the full course of the medication reduction rather than a distinct shift at the tentative transition point. Although in an ideal case a sharp and clean increase may be expected, an order parameter (or quantities related to that order parameter) can also show more smeared behaviour depending on the nature of the transition, the level of homogeneity in system or the tuning parameter that is driving the transition.

The procedure is illustrated in figure 7. Both upward and downward shifts were considered; positive (negative) items displaying an upward (downward) shift were manually excluded, as will be discussed in section 4.1.4.

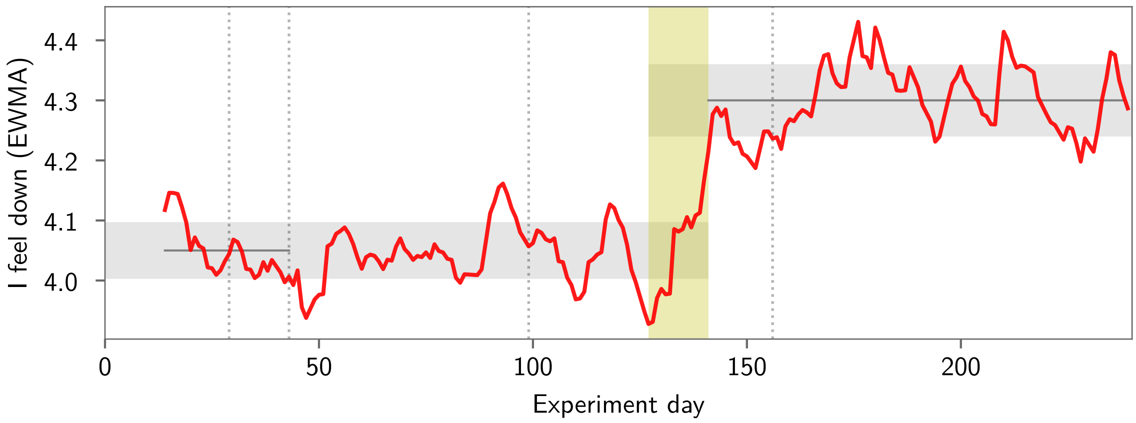

Figure 7: Example of the assessment of a shift (criterion 1) in a particular momentary item. The horizontal grey lines indicate the baseline and post-transition means. The grey shaded areas indicate the corresponding standard deviations. Since the standard deviations do not overlap, the criterion for was met for this item.

Criterion 2 – Fluctuation increase In a (continuous) phase transition, the order parameter is expected to show increasingly large fluctuations that extend through the entirety of the system at the moment of the transition. Therefore, we expect to see heavier fluctuations before the transition than in the baseline period or after the transition in items that are related to the order parameter.

The fluctuations were first detrended to remove the effect of long-term behaviour (such as the shift from the first criterion). This was achieved by subtracting the EWMA from the item scores averaged per day. This means that effectively only fluctuations on a timescale below 14 days were considered; more on this in section 4.1.5.

The items were then divided into four regions: (I) the baseline region (phase 1 & 2, day no. < 43, as above), (II) the region of antidepressant reduction (phase 3, $43 \leq$ day no. < 99), (III) the region prior to and during the transition where the concentration was zero (part of phase 4, $99 \leq$ day no. < 141) and (IV) the region after the transition (rest of phase 4 and phase 5, day no. ≥ 141). The criterion of fluctuation increase was then met if:

$$\text{Var(I)} < \text{Var(II)} < \text{Var(III)} > \text{Var(IV)} \tag{3}$$

thus indicating an increase in variance prior to and during the tentative transition. Note that the variance in this case does not correspond to noise but instead captures the true fluctuations of the relevant quantity, since the scores directly reflect changes in the actual mental or physical state of the participant. The procedure is illustrated in figure 8.

4.1.4 Results

All selected items were subjected to the two criteria as formulated above. The selected items and the results from each criterion are shown in table 3. Starred items did show a shift that met criterion 1, but the shift was downward (upward) for positive (negative) items and thus manually excluded. The items to which this applies appear to be related to the participant feeling increasingly energetic, which might be a consequence of declining side effects of the medication (Fava *et al.*, 2006) rather than being inherent to the depression itself. Items adhering to both criteria are printed in bold.

Full plots of all items, including their EWMA, are available in Appendix A.

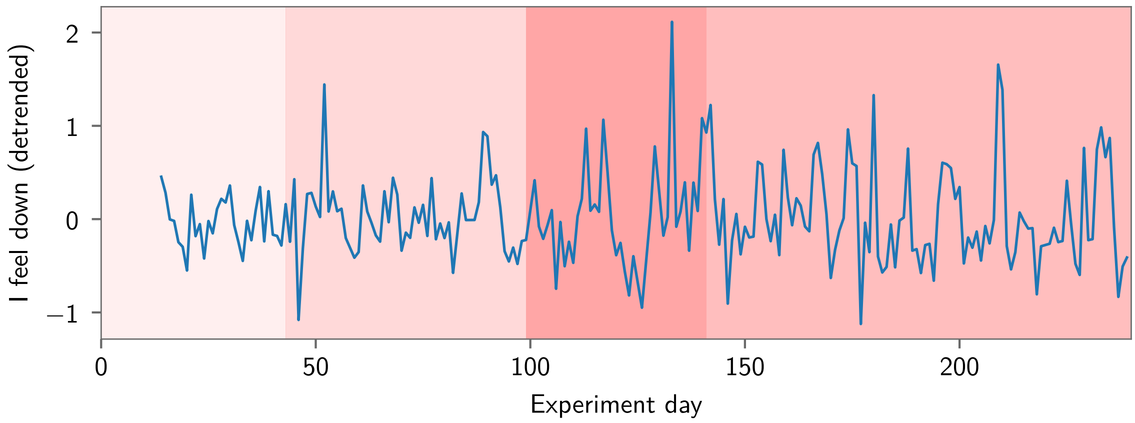

Figure 8: Example of the assessment of a fluctuation increase (criterion 2) in the detrended fluctuations (item score per day minus EWMA) of a particular momentary item. The red shaded areas indicate the different regions as described in the text; the intensity of the colour corresponds to the magnitude of the variance in that region. Since the evolution of the variance fulfils requirement from equation 3, the criterion was met for this item.

4.1.5 Timescale dependence

A potentially weak point of the analysis so far is that the half life of the EWMA, determining the amount of smoothing applied to the data as well as the time scale below which the fluctuations are considered, is not easily determined by *a priori* reasoning. Although a half life of 14 days was suggested in section 4.1.2, arguments can be made for other timescales as well. Therefore, the robustness of the conclusions from the previous section with respect to this parameter has to be assessed.

To this end, all selected items were passed through the same analysis as above, but this time with a EWMA half life varying between 5 and 80 days. This means that, for longer half lives, a) the EWMA used to assess the presence of a shift undergoes more smoothing, and b) fluctuations of longer timescales are taken into account, since the detrending procedure determines the upper limit to this timescale. In order to consider the two criteria as a function of EWMA half life, their outcomes were quantified as follows. The relative shift ΔEWMA compared to the baseline was defined as

$$\Delta\text{EWMA} := \frac{\mu(t \geq 141) - \mu(t < 43)}{\mu(t < 43)} \cdot 100\% \tag{4}$$

with μ the mean of the EWMA in the indicated region and t the time in days.

The relative variance increase ΔVar compared to the average of the baseline variance and the variance after the transition was defined as

$$\Delta\text{Var} := \frac{\text{Var(III)} - \frac{1}{2}(\text{Var(I)} + \text{Var(IV)})}{\frac{1}{2}(\text{Var(I)} + \text{Var(IV)})} \cdot 100\% \tag{5}$$

with Var(X) the variance in region X, as defined in section 4.1.3.

Both ΔEWMA and ΔVar were set to zero if their respective criterion as formulated in section 4.1.3 was not met. Their definitions are not meant to have much quantitative meaning by themselves, but rather serve to provide an comparative measure to help visualise the half life parameter dependence. ΔEWMA and ΔVar were then calculated for each of the included items, for half lives ranging between 5 and 80 days. Items meeting both criteria for at least one half life value were plotted. The results are shown in figure 9.

Item name	Shift	Increased fluctuations
I feel relaxed	X	
I feel down	X	X
I feel irritated	X	
I feel satisfied		
I feel lonely	X	X
I feel anxious	X	X
I feel enthusiastic		
I feel suspicious	X	
I feel cheerful		X
I feel guilty	X	X
I feel indecisive		X
I feel strong		X
I feel restless	X	
I feel agitated	X	X
I worry	X	
I can concentrate well	*	X
I like myself		
I am ashamed of myself	X	
I doubt myself	X	
I can handle everything		X
I am hungry	X	
I am tired	*	X
I am in pain		
I feel dizzy		
I have a dry mouth		
I feel nauseous	X	
I have a headache		
I am sleepy	*	

Table 3: Results from testing the selected items to the formulated order parameter criteria. If a criterion was met, the item is marked with an X. Starred items (*) did show a shift, but the shift was downward (upward) for positive (negative) items and thus excluded from meeting the criterion. Bold items meet both criteria.

Figure 9 illustrates how some items can go from not meeting one of the criteria to meeting it (i.e. changing from zero to non-zero) depending on the chosen value for the EWMA half life. Nevertheless, the procedure shows that the dependence of the criteria on the EWMA half life is only weak for most items. The relative shift corresponding to criterion 1 shows a slight decrease with increasing half life, which is to be expected due to the enhanced ‘smearing’ of the transition with heavier averaging. The relative variance increase corresponding to criterion 2 seems largely unaffected by a change in half life, meaning that considering fluctuations at larger time scales does not change the relative height of the peak nor does it have much effect on which items are identified as meeting the threshold. The items ‘I feel down’, ‘I feel lonely’ and ‘I feel agitated’ were most stable with respect to the parameter change; they met both criteria for the entire considered range. The shift in the item ‘I feel guilty’ was no longer considered large enough to meet criterion 1 for half lives longer than 15 days, and the shift in the item ‘I feel anxious’ only meets the criterion for certain half live values up to 69 days. Finally, the item ‘I feel restless’, which was not previously identified as an order parameter candidate, was found to consistently meet both criteria for half lives of 15 days and up.

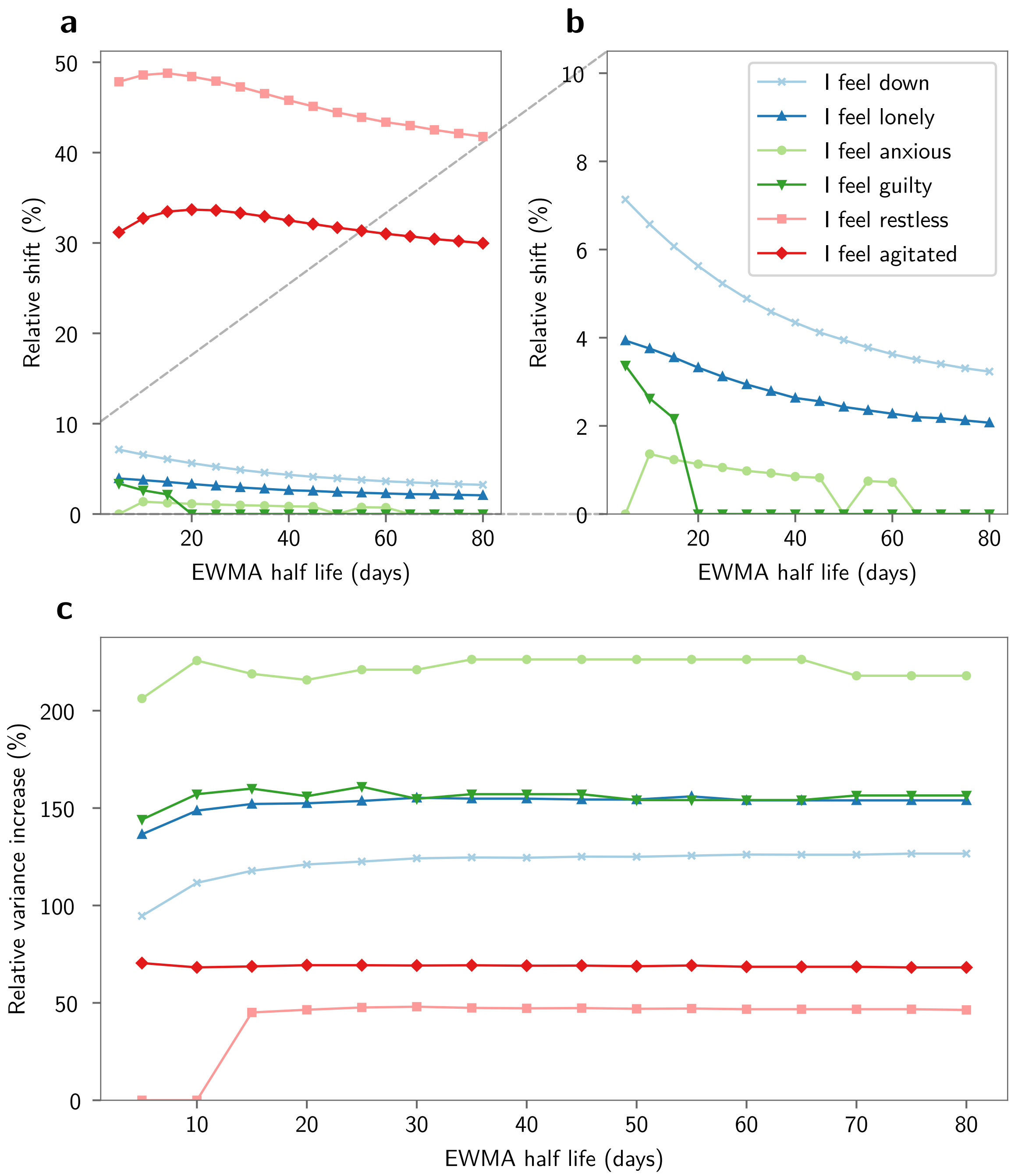

Figure 9: Half life dependence of the relative shift (**a** + **b**) and relative variance increase (**c**) for items meeting both criteria for at least one half life value. Figure (**b**) shows a zoomed in view of the items with a smaller relative shift. Values are set to zero if their respective criterion is not met. Varying the half life primarily affects which items meet criterion 1 (related to the relative shift), whereas criterion 2 (related to relative variance increase) remains largely unaffected.

The choice of half life therefore mildly affects the items that are identified as order parameter candidates by the two criteria. In practice, the relevant timescale should be determined by knowledge about the underlying process that generated the data; this discussion will not be developed here. Nevertheless, it should be noted that the criteria in their current form do not allow for intermediate outcomes (e.g. partially meeting a criterion) and can thus lead to unintended exclusion of possibly relevant items. To avoid this, it seems sensible to consider a range of timescales rather than a single fixed timescale.

4.1.6 Comments and discussion

A few remarks can be made based on the results so far.

First of all, as discussed earlier, the analysis does not claim to result in an exact definition of the order parameter of this particular transition. Instead, it provides hints about the types of items that might be related to an order parameter, if there is one at all. The next step would be to further examine the highlighted items from table 3 and figure 9 from a psychological perspective to see if they can be grouped according to a certain pattern. An important aspect of phase transitions that has thus far not been addressed is symmetry breaking: transitioning into the ordered state, the symmetry of the system (translational, temporal, gauge etc.) is reduced due to the emerging patterns in the post-transition phase. Identifying such a change in symmetry in the system would require extensive knowledge about the underlying mechanisms of depression and relapse and is therefore not attempted here, but it would be an interesting subject to study in the future.

The results of a phase transition based analysis such as presented here could potentially be a useful asset in the design of future momentary assessment studies. Extensive longitudinal experiments for obtaining time series data can be incredibly demanding in terms of the time investment and dedication required from the participants. If further study into this area could highlight certain items as particularly relevant or irrelevant to a certain transition, some of the burden might be alleviated by reducing the number of items necessary to understand the participant's development over time. It is also interesting to consider the items that emerged as order parameter candidates as potentially suitable treatment targets, similar to what is attempted by certain studies based on network analysis (Borsboom and Cramer, 2013; Contreras *et al.*, 2019). Order parameter analysis could thus help identify the core symptoms that are central to how the illness manifests itself in a particular individual.

The question remains whether the results from this n=1 study (including only one participant) could be extended to other cases of clinical tipping points. As will also become apparent from the interviews discussed in section 4.2, the complexity science perspective in psychology puts heavy emphasis on individualisation and personalisation of psychological conditions, due to the fact that psychological systems appear to violate certain properties required for a valid statistical analysis on aggregated groups (Olthof *et al.*, 2020). The aim of this approach is to move away from the standardised intervention protocols that are currently common in mental health care, in favour of a focus on the individual and the aspects of psychological disorder that are particularly relevant to each individual. However, the study of phase transitions in physics is rooted in the idea that there exist certain properties or characteristics that apply to larger classes of systems, regardless of their microscopic details. This idea is known as universality and it explains how systems that are (microscopically) inherently different can display similar (macroscopic) behaviour close to a critical point. This suggests a tension between the the wish for personalisation in psychology on the one hand and the tendency to generalise in physics on the other. The discussion is likely more nuanced than this binary contrast, since focusing on intrapersonal experiences does not exclude the principle of universal similarities between individual cases. Nevertheless, it might be the case that this discrepancy limits the usefulness of the phase transition approach to tipping points in a clinical psychological setting. However, it could also raise the possibility that we are dealing with a different level of universality: rather than expecting a universal set of symptoms related to an order parameter that is the same across all individuals, we assume the existence of certain universal features of phase transitions that occur across scientific disciplines. Assuming universality of phase transitions in general validates the idea that core symptoms can be identified over the course of sudden clinical change by means of order parameter analysis, while simultaneously not implying generalised or population-wide uniformity.

These interpretative reservations aside, it would be interesting for a follow-up study to perform the same analysis to similar datasets from other individuals, to examine the overlap and differences between order parameter candidates identified in different systems. Although core symptoms do not need to be the same for all individuals, it is interesting in its own right to study whether order parameter analysis is even possible in every system undergoing a shift, and what it would mean if it failed to produce intelligible results. Repetition of the analysis with new data would therefore be highly valuable.

Moreover, figure 9 does trigger questions about qualitative differences between the items found to meet the order parameter criteria. The items can be roughly divided into two categories: items with a larger shift and a smaller variance increase ('Restless', 'Agitated') and items with a smaller shift and larger variance increase ('Down', 'Lonely', 'Anxious', 'Guilty'). Upon inspection, there appears to be a difference in the evolution of these items over time. Figure 10 illustrates this difference by comparing the item 'I feel agitated' to the item 'I feel lonely' (see also Appendix A to compare the other items).

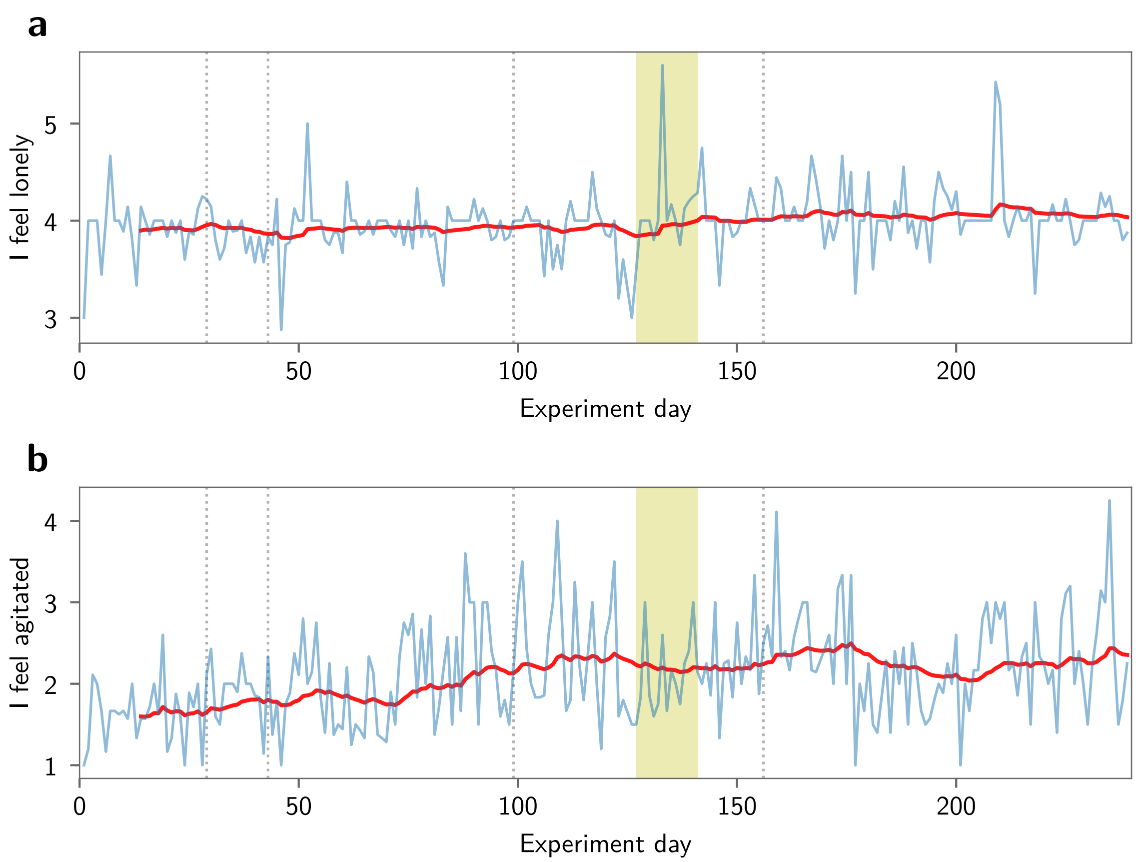

Figure 10: Comparison of items (**a**) feeling lonely and (**b**) feeling agitated. Both items consistently met both criteria, but their behaviour is qualitatively different.

The items from the first category, such as 'I feel lonely', have a shift that is relatively small, but also sharp. The items from the second category on the other hand, such as 'I feel agitated', show a much larger shift that occurs more gradually over time. Although both groups of items thus meet the formulated criteria, they may be driven by different mechanisms or coupled to the order parameter in different ways.

This observation ties into another point of discussion: the hidden control parameter. Phase transitions in physics are driven by a certain control or tuning parameter, be it temperature, pressure or some other external driving force. Depending on the nature and homogeneity of a particular system and the effect that the control parameter has on that system, a transition can appear more sharp or more smeared out. In the case of the tentative transition in symptom severity studied here, the control parameter is unknown. Of course the antidepressant concentration is assumed to be related to the control parameter, since the increase in depressive symptoms is said to be a direct consequence of the medication reduction. Strictly speaking however, the concentration itself cannot be the control parameter of this transition, since it is reduced to zero and remains stationary before and during the transition. It could be possible that the reduced concentration triggers a delayed biochemical response in the participant's body that can be interpreted as the actual control parameter, but this is speculative at this point. The inherent uncertainty surrounding the control parameter should therefore be explicitly recognised: the presence of a shift can only be assessed as a function of time by implicitly assuming the existence of some unidentified control parameter that more or less monotonically increases over time. In this light, it might be sensible to consider items with a large, gradual increase over time to be coupled to the (unknown) control parameter, rather than the order parameter. This means that the items 'I feel restless' and 'I feel agitated' might not be related to an expression of the order in the system, but instead echo the evolution of a hypothetical tuning parameter driving the transition. Although this proposition is speculative, it would be interesting to explore further.

More study into this area could be interesting. Experimentally, this could take the form of regularly probing relevant biomarkers during the measurement period in order to map out the delayed response to antidepressant reduction and to learn more about the behaviour of a possible control parameter and items coupling to this control parameter. Moreover, having data for the period in which the participant and their doctor decided to reintroduce the antidepressant would also be highly valuable in assessing the inverse behaviour of the transition. Hypothetically, it would also be interesting to vary the rate at which the medication is reduced to see if the transition increases or decreases in sharpness. Such an experiment would have to be performed on a single participant however due to large expected interpersonal differences when it comes to biochemical response, which makes this proposal unfeasible in practice. In general, it should be recognised that experiments like these are difficult or impossible to perform due to ethical considerations, the large uncertainty in the occurrence of a transition and the substantial effort required from the participant. However, findings and recommendations such as presented here could provide direction for experimental design in the future.

4.2 Interview results

Now that the results from the quantitative data analysis belonging to RQ1 have been discussed, we can proceed to the qualitative results from the interviews belonging to RQ2.

Four participants were interviewed and their transcripts coded and analysed. The full procedure, as well as more detailed information about the participants and their backgrounds, is described in section 3.2. Although research question 2 and its subquestions as formulated in section 1.2 did not explicitly acknowledge this, the general role of interdisciplinarity in complexity science was found to be an important theme throughout the interviews. The discussion therefore focuses on three main axes:

1. Understanding the position of the phase transition approach in the diverse landscape of complexity science.
2. Identifying motivations and barriers for using interdisciplinary methods in complexity science.
3. Exploring the possible practical relevance and distance to clinical application of interdisciplinary methods in complexity science.

The discussion of the insights obtained from the interviews will be loosely structured around these three axes, cross-referencing each other if necessary. The interpretation will focus on relating the general insights from these themes to the particular approach of analysing regime shifts as phase transitions put forward by the data analysis described in section 4.1. Remarkable findings that do not fall within the scope of the research question are mentioned in section 4.2.7. Quotes from the transcripts are translated to English as faithfully as possible; the original Dutch wording is given in footnotes.

4.2.1 The complexity science landscape

The phrase 'complexity science' is often used as an umbrella term covering an extremely diverse collection of scientific disciplines. Although there are common denominators, the interpretation of complexity and the particular role of this concept in actual research differs vastly. Sometimes this is a matter of emphasis or nuance, but in some cases the opinions on what complexity is or is not are diametrically opposed. In order to explore this landscape and simultaneously introduce the participants and their background, the different flavours of complexity adopted by each participant will be outlined below.

Each of the descriptions is illustrated by a word cloud, visualising the frequency of occurrence of a pre-compiled word list containing terms related to different aspects of complexity. The reliability of the word clouds is limited by several impediments: the word list was composed manually and might therefore miss relevant entries, similar words (e.g. *lineair* and *lineaire*, different declensions of 'linear') are counted separately and thus skew the visualisation, only single-word entries are allowed by the ATLAS.ti software (e.g. *tipping point* cannot be included as a whole) and words with broader uses may be used out of the complexity context but counted regardless (e.g. *tijd*, 'time'). The word clouds are therefore explicitly not meant to be interpreted as a formal analysis tool, but rather to serve as an illustration to the discussion that follows. Due to the fact that the interview transcripts were not fully translated, the word clouds are displayed in Dutch.

Participant 1 (anonymous, psychology) indicates to view complexity science as a tool to help answer particular research questions or as a enrichment to the empirical cycle of their research. The objective of this approach is to be able to develop better interventions for people suffering from mental health issues. They do not consider themselves a complexity science expert, but rather a coordinator attracting experts to commit their expertise and methods to

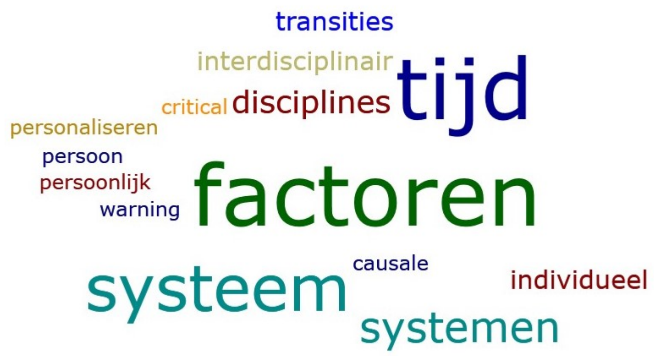

Figure 11: Word cloud illustrating the interpretation of complexity by participant 1 (anonymous, psychology).

psychological questions. Their research is deeply rooted in and motivated by clinical practice, which characterises their view on complexity. Complex systems theory is therefore not considered an intrinsic goal in itself, but rather serves as a stepping stone towards a better understanding of mental disorders, intervention methods and individual differences in susceptibility to psychological conditions.

In their interpretation and integration of complexity in their research, participant 1 stresses multicausality (or the inadequacy of singular causal explanations) and the importance of the interplay between different causal factors as the main distinctive characteristics, as well as their development over time.

> "...the central point of departure is that in the development of psychological conditions [...] there [...] are no singular causal factors [...] and those factors all affect each other."[2]

Participant 1 also refers to the fact that complex systems that are very different in nature can nevertheless display similar behaviour or features, making it possible to draw parallels between phenomena occurring in different fields. The concrete methods they associate with complexity are mostly quantitative, such as network analysis or agent-based modelling.

Figure 12: Word cloud illustrating the interpretation of complexity by participant 2 (J. Naaldenberg, medical science).

Participant 2 (J. Naaldenberg, medical science) also mentions multicausality and complex relations as important elements of complexity. She contrasts this to the more common linear research approach, in which the effect of, for example, a single intervention is measured in a single stakeholder group. According to her, the complexity approach gives room for the recognition

[2] "...het centrale uitgangspunt is dat bij het ontwikkelen van psychische aandoeningen [...] er [...] geen enkelvoudige causale factoren zijn [...] en die factoren die werken allemaal op elkaar in."

of non-linear relations that underlie a particular issue, the diversity of causal factors within the system as a whole and their evolution over time.

> "I think for me it is mostly that you look more broadly than just linear relations. So not just A leads to B, but [...] that you look at it more broadly [...], that time plays an important role [...] so more at complex relations that just the linear relations."[3]

This perspective allows for different research questions to be asked compared to the linear statistical studies that are more common in medical science. In contrast to participant 1, Naaldenberg answers these questions by using qualitative methods, e.g. interviewing different stakeholder groups in order to better understand and possibly solve a particular issue. She notices a dichotomy in the world of complexity science, with quantitative, data-driven methods on the one hand and qualitative, systemic approaches on the other. She does not usually refer to herself as using 'techniques' from complexity science, but instead describes her perspective as 'systems thinking', i.e. a particular way of looking at issues that makes room for more complex solutions as opposed to interventions targeting a single symptom.

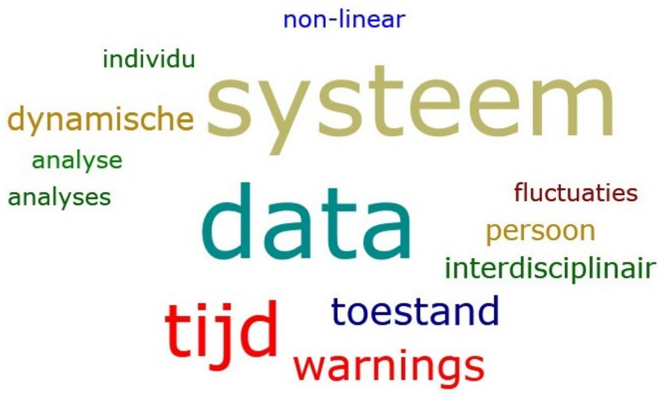

Figure 13: Word cloud illustrating the interpretation of complexity by participant 3 (A. Lichtwarck-Aschoff, psychology).

Participant 3 (A. Lichtwarck-Aschoff, psychology) takes a more explicitly quantitative approach. Of all participants, she maintains the clearest definition of what complexity is and also what should not be considered complexity. According to her, the two most important elements of complexity are individuality (i.e. studying individual subjects rather than aggregated groups) and temporal evolution (i.e. dynamics and change over time); she does not consider methods or approaches that do not incorporate both of these principles (e.g. momentary network analysis or group averaged temporal dynamics) to be truly about complexity.

> "...so I think the most important difference is to [...] analyse first and then aggregate, so in principle we start from the case, and [...] if we have multiple cases, then we look for regularities instead of throwing everything on one pile and looking for connections then."[4]

The emphasis on temporal evolution likely originates from her background in developmental science, where the progression of a system over time is seen as crucial for understanding the

[3] "Ik denk dat voor mij het vooral is dat je breder kijkt dan alleen lineaire verbanden. Dus niet alleen maar A leidt tot B, maar [...] dat je daar wat breder naar kijkt [...], dat de tijd een belangrijke rol speelt [...] dus meer naar complexe relaties dan alleen de lineaire relaties."

[4] "...ik denk dus dat het belangrijkste verschil is [..] *analyse first and then aggregate*, dus in principe laten we uitgaan van de case, en [...] als we meerdere cases hebben dan zoeken naar wetmatigheden in plaats van alles op één hoop gooien en dan de verbanden zoeken."

system's current state. She comments that complexity is at risk of becoming a buzzword that is applied to all kinds of research without proper justification or operationalisation.

Moreover, unpredictability of outcomes and inherent unknowns in underlying relations also play an important part in her interpretation. She mentions that this is not immediately related to the number of variables in a system (which she refers to as 'complicated'), and that even seemingly simple systems can display complex dynamics. She notices that over the years, the complexity view in psychology has moved from a primarily metaphorical use to being supported by quantitative analysis techniques. In her research, this mostly translates to data analysis focused on time series from individuals.

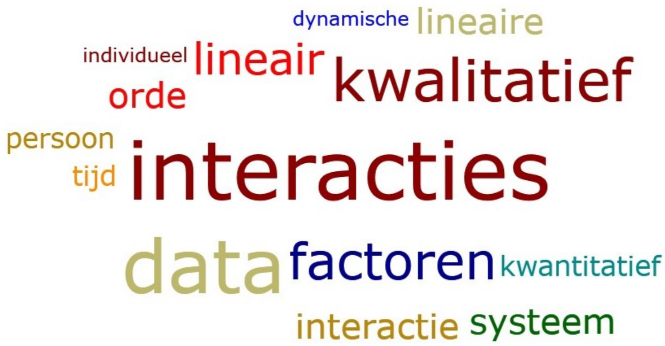

Figure 14: Word cloud illustrating the interpretation of complexity by participant 4 (M. Olde Rikkert, medical science).

Participant 4 (M. Olde Rikkert, medical science), similar to participant 1 and 2, puts the emphasis on multicausality and interactions between causal factors. He contrasts this to the more linear, single-cause approach in medical research, from which his research line tries to move away. Non-linearity and unpredictability of outcomes are also important elements. His interpretation seems the most diverse of all participants, incorporating elements from both a qualitative and a quantitative perspective.

> "To us that has to do with complexity of [...] the research focus that you have, so that it's about multicausal problems with many interactions, that are often also not linear, and where also the history of the system is important to understand where the system is going and where you also want to take phenomena into account like emergence, the formation of new equilibria that you cannot predict, and also non-linear tipping points."[5]

He considers complexity science to be a helpful approach for systems in which properties like these are recognised. His research is focused on complex disease interactions and multimorbidity, to which according to him linear methods do not provide appropriate answers. The methods he applies combine what he refers to as qualitative techniques (e.g. mapping out complex causal interactions in a theoretical model) and quantitative analysis (e.g. the translation of such a theoretical model into quantitative simulations and comparison to empirical data). Although the qualitative techniques he applies are not those traditionally associated with qualitative research, such as interviews or focus groups, they are still considered to be qualitative since they do not (yet) involve quantitative data comparison but instead primarily focus on mapping out the structure of a theoretical model.

[5]"Voor ons heeft dat te maken met complexity van [...] het onderzoeksfocus wat je hebt, dus dat het gaat om multicausale problemen met veel interacties, die vaak ook niet lineair zijn, en waar ook de historie van het systeem belangrijk is om te begrijpen waar het systeem naartoe gaat en waar je ook rekening wilt houden met fenomenen zoals emergentie, het ontstaan van nieuwe evenwichten die je niet kunt voorspellen, en ook met niet-lineaire kantelpunten."

In general, all participants contrasted the complexity related approach to traditional research methods that are more common in their field. Although some mentioned that the two perspectives can be used alongside each other, methods originating from complexity are positioned as inherent counterparts to the linear, statistical, evidenced-based practice which has become the gold standard in psychology and medicine. This contrasting positioning leads to the participants having fairly explicit motivations for their choice of methods, but it also gives rise to additional challenges, both of which will be addressed in more detail later.

Sketching out the complexity landscape based on the four interviews, the diversity of views and interpretations becomes apparent once again. However, it is clear that overlap and similarities exist as well. Comparing these views to the analysis approach based on phase transitions presented in section 4.1, a few remarks can be made.

Sudden, dramatic changes in the state of a system are mentioned by several participants as a characteristic of complexity. Regarding the distinction between quantitative and qualitative complexity, the phase transition approach is clearly moving towards quantitative interpretation. What stands out is that the most commonly mentioned elements of complexity, being multicausality and interactions between causal factors, are not necessarily a part of this approach: modelling a sudden shift as a phase transition does not imply knowledge about a multitude of causal factors, but instead assumes the existence of (at least) one unknown control parameter and subsequently abstracts the individual constituents of the system in an attempt to identify macroscopic order. For these reasons, the approach might fit best within the quantitatively oriented perspective of participant 3, highlighting inherent unknowns in underlying relations and the contrast to 'complicatedness'. However, the temporal element that she stresses as vital to her complexity view is not inherent to the phase transition approach either. The focus on individuality is also a point of discussion, since it might interfere with the classic concept of universality as known in physics (see also the discussion of section 4.1). Perhaps the phase transition approach would therefore be most at place within the view of participant 1, who described complexity as a generic 'tool' to help answer particular research questions. Regardless, the position of the phase transition approach in the plethora of interpretations of complexity science is not easily characterised in a few sentences, but instead shows contrasts and resemblances to a range of different complexity characteristics.

It is interesting to note however that the position of 'complexity' in physics is quite different to the interpretations sketched so far. In physics, a complex system is often loosely defined as a system consisting of a large number of components featuring non-negligible mutual interactions, which applies to e.g. certain phases of matter. However, the study of complex systems in physics is not a distinctive or alternative approach compared to 'traditional' physics research. For that reason, physicists working with complex systems often do not explicitly identify themselves as such, as their methods are not inherently different to those used in other areas of physics. This point should be kept in mind throughout the rest of the discussion.

4.2.2 Motivations for engaging with complexity science

Now that each participant and their interpretations of complexity have been introduced, the motivations, challenges and practical implications of complexity science and interdisciplinarity that emerged from their conversations can be addressed.

By far the most frequently mentioned motivation for adopting the complexity science perspective is the perceived shortcomings of traditional 'non-complex' approaches. All participants recalled anecdotes or examples of research lines that either left out important elements in favour of a linearised view (which relates to multicausality as a characteristic of complexity) or focused on standardised approaches that lacked intrapersonal effectiveness (which relates to individuality), which led these studies into useless conclusions or dead ends.

Participant 4 for example gives an example of a large body of research which hypothesises the aggregation of a particular protein as the single most important cause of Alzheimer's disease.

However, medicinal treatments based on this hypothesis have never proven effective in clinical trials, despite decades of attempts. He then comments:

> "...so then you need a very different kind of paradigm and you also need different methods to escape from yet another simple linear statement that runs the risk of basing another forty years of research on one mechanism."[6]

In other words, the participants considered the complexity perspective to be a (possible) answer to questions in which a more common, non-complex approach had failed or produced unsatisfying results. This observation also surged in the previous discussion about the characterisation of complexity: systems or research subjects that display certain complexity-related features and somehow fail to be understood by common empirical or statistical methods might be candidates for a radically different, complexity oriented approach.

This ties in to the observation by the participants that the complexity perspective better fitted the reality or practice of their object of study. Participants indicated that (their interpretation of) a complexity approach did more justice to the subjects they were studying, allowing for new realisations or insights that could not have been achieved within the traditional paradigm. Participant 2 described the added value of complex systems thinking in discovering the effects of interventions that would not have been noticed in the standard evaluative approach, which she phrases as follows:

> "So if you had had a slightly broader view, [...] at the time I didn't know that that would be called complexity or [...] systems thinking, then maybe you would have been able to make this visible, and that would have yielded a lot of extra information about what something means in people's daily lives. And that's why I [...] started seeing it as a very valuable perspective, [...] it is such a shame if you only approach this linearly, [...] that requires a lot of time and energy and money from everyone and it looks just like nothing has happend, while in reality quite a lot has happened."[7]

Complexity can thus also be interpreted as a lens through which elements of reality can be discovered that would otherwise go unnoticed, in particular according to participant 2 and 4. Participant 1 also expected new insights from complexity methods, but they were mostly driven by the desire to improve clinical interventions and were interested in complexity as a possible means to this end. Participant 3 seemed to maintain the strongest opinion, suggesting that the area of science in which she is active is unlikely to make much more progress by continuing the standardised methodological tradition and stressing the necessity of new conceptualisation and methodology. In this context, the phase transition perspective could potentially prove a suitable candidate to be explored in cases where alternative views are particularly desirable.

4.2.3 Motivations for engaging with interdisciplinary studies

Interdisciplinary methods and collaborations appear to be commonplace within the field of complexity science. Participant 2 in particular, and to a lesser extent also participant 1 and 4, mentioned that an interdisciplinary approach is inherent to their type of research and their

[6] "...dan heb je dus een heel ander soort paradigma en heb je ook andere methoden nodig om te ontsnappen aan weer een volgende simpele lineaire statement die het gevaar loopt opnieuw veertig jaar onderzoek op één mechanisme te baseren."

[7] "Dus als je een iets bredere bril had gehad, [...] toen wist ik nog niet dat dat dan complexiteit of [...] systems thinking zou heten, dan had je dit misschien wel zichtbaar kunnen maken, en dat had heel veel extra informatie opgeleverd over wat iets betekent in het dagelijks leven van mensen. En dat is waarom ik het [...] als heel waardevol perspectief ook ben gaan zien, [...] dat is echt zonde als je dit alleen maar lineair aanvliegt, [...] dat kost iedereen heel veel tijd en energie en geld en het is net alsof er niks gebeurd is, terwijl er best wel wat is gebeurd."

operationalisation of complexity. For participant 1, this implied making use of expertise that is not naturally available within psychological science, such as computational modelling. Participant 2 and 4 on the other hand described interdisciplinarity as the incorporation of a range of different stakeholder groups and medical disciplines into their research, which relates to the large weight of multicausality in their respective interpretations of complexity. Participant 2 phrased it as follows:

> "For me that is also a characteristic, [...] the types of questions that you get from such a complexity perspective are just very interdisciplinary."[8]

The interdisciplinarity is operationalised in different ways by the participants, the most frequently mentioned of which is the joint supervision of PhD projects. In this case, a student is supervised by two or more researchers from different groups or faculties, with the aim of bringing together multiple areas of expertise and viewpoints into a single project. In practice, these collaborations were sometimes arranged such that the level of involvement of either supervisor would shift from one discipline to the other depending on the specific research project at hand, making the process slightly more indirect. Yet, the participants indicated to have gained significant advancements from such efforts.

With regard to interdisciplinary methodology, several examples were mentioned. For participant 2 and 4, this mostly came down to qualitative modelling and data acquisition methods, which are particularly uncommon in medical science. Participant 1 and 3 are more quantitatively oriented and referred to computational methods and analysis techniques. For participant 1, these methods are initiated and applied by generic complex systems experts that have no specific background in an applied field. Participant 3 was the only one to explicitly mention the use of concepts from mathematics and physics, phase transition theory being one of those.

The most important motivations for pursuing these interdisciplinary efforts boiled down to the added value of additional expertise and the possibility to obtain new insights, similar to the motivation for engaging with complexity science in general. This ties in to the previous observations on how the participants pointed at the failures and limitations of traditional techniques from within their own discipline; with this in mind, it is not surprising that they then chose to look out for methods across the disciplinary borders. Again, the phase transition approach could provide a potential avenue to pursue in this regard. Participant 3 describes the added value of interdisciplinary collaboration as follows:

> "...I'm also just a psychologist, and I have read some literature, but I don't feel skilled enough to properly understand all of these things. On the other hand, physicists don't have a clue what we are talking about, so I [...] think especially this interdisciplinary collaboration and testing with each other, okay, that is what we mean, and that is what we would expect, [...] I would find that immensely valuable."[9]

In short, the participants observed that the traditional research methods within their field fall short when it comes to certain research questions, to which end they decide to look for alternative approaches in the realm of complexity science. This very often implies interdisciplinary collaboration and exchange of methodology. Together, these approaches aim to shed a different light on reality, giving access to insights and information that would otherwise remain hidden. The phase transition approach appears to fit well within these objectives. However, the

[8] "Dat is ook wel voor mij een kenmerk [...] dat het heel erg interdisciplinair is, [...] het soort vragen wat je dus krijgt vanuit zo'n complexiteitsperspectief die zijn gewoon heel erg interdisciplinair."

[9] "...ik ben ook maar een psycholoog, en heb wel wat literatuur gelezen, maar voel me natuurlijk lang niet bekwaam genoeg om al die dingen goed te begrijpen. Aan de andere kant, natuurkundigen die hebben dan weer geen idee waar wij het over hebben, dus ik [...] vind juist die interdisciplinaire samenwerking en toetsen bij elkaar, oké, dat bedoelen wij ermee, en dit is wat wij dan zouden verwachten, [...] dat zou ik ontzettend vruchtbaar vinden."

scientific practice of complexity and interdisciplinary studies is not without potential barriers, which will be discussed in the next section.

4.2.4 Challenges to the complexity approach

The fact that complexity science appears to occupy such a distinctive niche in the scientific world comes with a few challenges. Participants mentioned particular difficulties with the lack of acceptance of the complexity perspective by other areas of science. Because complexity provides an alternative conceptual view or even a replacement to traditional methods, recognition of complexity methods within 'mainstream' science requires a substantial paradigm shift. Participants also expressed difficulties in communicating with scientists outside of complexity science or even conveying the added value of their perspective to others, as well as frequent misunderstandings by outsiders about what complexity entails. Once again, the confusion with 'complicatedness' was brought up multiple times. Participant 2 comments:

> "...I still think it's difficult to explain, that you are working on complexity and systems thinking and what the added value of that is and why you should do that. If someone understands and also works with it themselves, then it's easy to talk for two hours and you know exactly what you're talking about, [but] if you have to explain it to someone who comes from a linear perspective, I still [...] think that's difficult."[10]

The difference between qualitative and quantitative approaches to complexity also seems to play a role here. Qualitative research is generally less easily recognised as valuable compared to quantitative methods, especially in medical science. Participant 2, who only uses qualitative methods, noticed this the most, as well as participant 4, who combines qualitative with quantitative methods and found that quantitative results were easier to publish in medical journals. Making use of concepts such as phase transitions might be an advantage on this front, as it explicitly aims to quantitatively operationalise a qualitative, conceptual metaphor. However, participant 1 mentioned another acceptance issue that is relevant to such a translation. They stated that it is not at all self-evident for the psychology field to adopt ideas about predictable behaviour and parallels between non-psychological complex systems and mental well-being:

> "...that means that you [...] have to [...] accept that there are certain laws that maybe apply to bird flocks, as well as to how you feel. [...] Anyway, I think on the other hand to be honest that there are many people within the field of psychiatry and psychology, and also outside of that, [...] there are many fields that don't want to accept this."[11]

Predictable or universal behaviour is common in exact sciences like physics, but that paradigm does not automatically translate to more human-oriented fields like psychology. This might also be a factor in the focus of participant 3 on individuality, whereas physics generally aims to avoid descriptions applying to only individual cases in favour of a more universal explanation. This may provide a substantial barrier to introducing an approach based on phase transitions in medical science or psychology.

[10] "...ik vind het ook nog steeds ingewikkeld uit te leggen hoor, dat je bezig bent met complexity en systems thinking en wat daar dan de meerwaarde van is en waarom je dat zou moeten doen. Als iemand het begrijpt en er ook mee werkt dan praat je zo twee uur vol en dan weet je precies waar je het over hebt, [maar] als je het aan iemand uit moet leggen die vanuit een lineair perspectief komt, blijf ik [...] dat heel ingewikkeld vinden."

[11] "...dat betekent dat je [...] moet [...] accepteren dat er bepaalde wetmatigheden zijn die misschien wel kunnen opgaan voor zwermen vogels, alsook voor hoe jij je voelt. [...] Maar goed, ik denk aan de andere kant om heel eerlijk te zijn dat er heel veel mensen zijn binnen het veld van de psychiatrie en psychologie, overigens ook daarbuiten, [...] er zijn heel veel velden die dit niet aan willen."

Finally, due to the fact that complexity science is a relatively young discipline, the effectiveness or adequacy of complexity research compared to traditional methods is not yet established. This appears to be less applicable to the qualitatively oriented research of participant 2, who has already observed the added value of her context-driven approach in practice. In quantitative research on the other hand, many studies are still in a relatively conceptual phase and have only recently become more analytically applied, which means that their added value to e.g. clinical interventions is not certain. Participant 1 in particular expresses caution in this regard, emphasising the importance of being willing to abandon a new research direction if it cannot be proven to be more effective than existing approaches. Therefore, it is important to pay explicit attention to possible experiments or tests that could verify or falsify a certain unconventional method, such as the phase transition approach.

4.2.5 Challenges to interdisciplinarity

Interdisciplinary collaborations are also subject to potential barriers. Firstly, all participants have experienced communication issues in one form or another during their interdisciplinary research. Even among researchers working with complexity science, the interpretations of concepts and methods can be so divergent that communication becomes difficult. Judging by the shear variety of elements of complexity and the respective weights they were given in the views of the four participants within the scope of this project alone, it is not surprising that having complexity science as a common denominator does not at all guarantee smooth communication. Participants all have their own associations and implications related to complexity and without explicit exposition of these differences, misunderstandings can easily arise. Differences occurred on many levels, from the interpretation of concepts to the comparison of results obtained by different methods. Participants stressed the necessity to make these dissimilarities as explicit as possible in advance, to avoid unwanted surprises midway through a project.

This might be especially relevant when it comes to a interdisciplinary application of the physics of phase transitions. As discussed in section 4.2.1, the meaning and importance of the term 'complexity' appears to be different in physics compared to other scientific disciplines. Although the systems under study might show interesting similarities, one could draw different conclusions and attach different values to observations from a physics perspective, which might not always be fitting or relevant to the research objectives of other disciplines. This issue already surfaced during the interpretation of the data analysis in section 4.1, where it became clear the emphasis on individualisation in complexity-oriented psychology does not immediately fit with the idea of universality that plays a central part in physics. Observations like these should be taken into account when attempting to model generic complex systems based on physics.

Apart from these forms of miscommunication, a lack of understanding in terms of content can also be an obstructing factor. Depending on the nature of the collaboration, the researchers involved might come from very different scientific backgrounds and therefore have trouble understanding concepts from other disciplines or simply lack relevant background knowledge. This becomes more problematic for collaborations between disciplines that are further separated; participants 2 and 4, who primarily worked with other medical experts, did not experience as much direct misunderstanding as participant 1 and in particular participant 3. This might happen on the level of individual collaborations, but participant 3 also noticed this on for example interdisciplinary conferences. She comments on the limitations to her collaboration with a mathematics professor for the supervision of one of her students:

> "...it is really at the edge of what I can still follow with my own background, what he is actually doing."[12]

[12] "...het is echt een beetje aan de *edge* van wat ik ook nog met mijn eigen achtergrond kan volgen, wat hij eigenlijk aan het doen is."

Mathematics and other exact sciences are generally less accessible to people without explicit background in these fields. However, the issue of understanding goes both ways: participant 1 for example mentioned how it takes a lot of time and effort from e.g. computational experts to get acquainted with psychology, as they will always lack a considerable amount of background knowledge compared to trained behavioural scientists.

Finally, some participants also commented on their difficulties translating the methodologies and concepts they use from other disciplines to their own. Sometimes metaphorical similarities between fields are easy to identify, but it can be more challenging to translate these to concrete research methods which can then be tested and emperically verified. This relates to the previous argument on the fact that the effectiveness of these translations is often still doubtful. Participant 3 notices that the conceptual applicability of phase transitions in psychology is high, but she remains wary of premature conclusions:

> "...we really still have to see to what extent all of these metaphors that we use from physics for example [...] are really suitable for us, and whether it all really works the same."[13]

Again, this stresses the importance of developing concrete operationalisations of conceptual ideas and paying attention to (empirical) verifiability and falsifiability, which brings us to the final point of discussion.

4.2.6 Practical applicability of complexity research

The relative focus on applicability versus fundamental understanding differed for each participant. The research of participant 2 and 4 appeared to be particularly close to clinical practice, with participant 4 describing his research as translational (i.e. being directly beneficial to particular real life problems). Applications in this category are for example the implementation of interventions based on a multi-stakeholder study, or advisory tools to demonstrate intervention effects in patients with multimorbidity. Participant 1 has a very strong rooting in clinical practice, but their complexity-related research currently resides in a more experimental phase that is still moving towards practical applicability, as is the case with participant 3. Some of the applications they mention are individual monitoring, personalised timed interventions or modelling of policy effects.

Participant 3, whose research line is the most relevant to the phase transition approach presented here, has noticed an intuitive match of her conceptual ideas with therapists in clinical practice. Current psychological interventions are often based on standardised procedures, which both therapists and patients tend to dislike. Her individualised and personalised approach, which also pays attention to the specific timing of interventions, might therefore better fit the needs of clinical situations. She also mentions that the phase transition metaphor in particular resonates well with clinicians, who recognise the idea of periods of instability or fluctuations that precede significant clinical change. However, referring back to the point made in section 4.2.4, she urges caution in this respect, stressing the importance of empirical and quantitative backup to these conceptual claims.

Another point that was brought up by both participant 3 and 4 was the increasing role of uncertainty that comes with the practical implementation of complexity methods. This relates to the limited predictive horizon that is often associated with complex systems, in contrast to a more traditional deterministic, standardised view. Participant 4 for example advocates a different approach to the medical decision making processes in which information about probabilities of success and failure is no longer presented as rigid numbers, but instead leaves room for uncertainty and variability of outcomes:

[13] "...we moeten het ook nog wel zien in hoeverre al die metaforen die we dan gebruiken uit de natuurkunde dan bijvoorbeeld [...] ook echt passen voor ons, en of het nou echt allemaal hetzelfde werkt."

> "So we will have to learn to speak much more about certainties and uncertainties as coupled to interventions and the people [...] who it's about."[14]

According to participant 3, the uncertainty of intervention effects calls for continuous monitoring and the ability to adjust based on individual responses. She referred to this as "driving in the mist"[15], i.e. having to move at an adjusted speed and constantly maintaining the possibility to stop or react to changes in circumstances if necessary. This may appear like a step back compared to the idea of science as a means of providing definite answers and calculable outcomes, but participant 4 argues that this ideal can simply not be obtained in the case of complex systems, and therefore the inherent uncertainty should be embraced and incorporated into decision making rather than hidden in heavily averaged numbers.

The actual practical applicability of phase transition modelling is difficult to predict at this stage. As participant 3 made clear, the conceptualisation might metaphorically match well with clinical intuition, but translating this insight into practical added value is yet to be achieved. Based on the preliminary results presented in section 4.1, analysing a clinical transition in terms of order and disorder could help highlight symptoms that are particularly strongly coupled to a certain type of transition, which could provide potentially valuable treatment targets and help limit the number of elements required to characterise disease progression. It might also shed light on similarities and differences between the nature of the potential transitions occurring in people with other psychological disorders, such as bipolar disorder or schizophrenia. An increase or change in the structure of fluctuations, similar to what has been studied here, has often been associated with predicting critical transitions (Scheffer *et al.*, 2009). However, predictive power is probably not the strongest benefit of the phase transition approach; rather, it could advance fundamental understanding and provide one of the alternative views on psychopathology that complexity-oriented behaviour scientists are looking for.

4.2.7 Miscellaneous findings

A theme that emerged prominently during the interviews, but falls outside of the scope of this project, is the meaning of interdisciplinarity in research. As discussed in section 2.5, the word 'interdisciplinarity' is often used in contexts where actually 'multidisciplinarity' is meant, the difference being that interdisciplinarity tries to integrate scientific perspective and go beyond the traditional boundaries of each discipline, while multidisciplinarity incorporates expertise from other disciplines while maintaining their own paradigm. The tension between these two concepts was noticeable throughout the interviews. For example, some participants mentioned that complexity science and interdisciplinarity made it possible to ask different research questions, signifying a step outside of the traditional paradigm into a new, integrated area of research. Other participants on the other hand viewed combining scientific disciplines more as a 'means to an end'; in other words, expertise from outside of their own discipline might help answer existing research questions within their own discipline. Some participants mentioned that complexity science is inherently interdisciplinary, but at the same time indicated to primarily use this interdisciplinary expertise within their field without necessarily transcending boundaries. The same goes for the factual execution of interdisciplinary (PhD) projects, which is often arranged such that the leading discipline is alternated depending on the specific topic at hand, rather than equally contributing and integrating perspectives at all times. All of these interpretations are more resemblant of multidisciplinarity than interdisciplinarity, while they are commonly referred to as the latter. Interestingly enough, the interchangeable use of terminology related to interdisciplinarity already emerged in section 1.3, where the description of the RICH network from their former webpage contains the word 'transdisciplinary' when referring to interfaculty

[14] "Dus wij zullen veel meer, in die zin, moeten leren spreken over zekerheden en onzekerheden als [...] gekoppeld aan interventies en personen [...] over wie het gaat."

[15] "rijden in de mist"

expertise. The term does not occur on their new website. This illustrates how this question of what is understood by the different flavours of interdisciplinarity and how they are interpreted and implemented in practice seems to permeate complexity science as a whole.

It thus appears that there exists a strong tension between the desire to reform a scientific discipline within its own boundaries on the one hand, and the wish to establish a completely new area of science that incorporates multiple forms of disciplinary expertise on the other. It should be noted that this contrast is not meant to suggest a hierarchical judgement: 'true' interdisciplinarity does not necessarily have a higher value than multidisciplinary research. However, it is important to realise that this difference exists in order to better characterise scientific cross-over and to help establish what is expected and required for a collaborative effort to be considered successful in a particular context.

A final interesting remark to be made in the context of practical applicability relates to the consequences of implementing new interventions in clinical practice. Participant 1 had the strongest reservations about the clinical applicability of insights from complexity science in general, not necessarily because of fundamental doubts about the complexity perspective, but rather due to their experience with clinical practice. They emphasised the danger of hypothesising new intervention targets without sufficient evidence:

> "And then you can say like, hypothesising, what does it matter, that's fine, but in my world [...] it really matters, because [...] then you're going to give people an experimental treatment, and [...] if that is actually too wild of a hypothesis, [...] then you do withhold a different active treatment from people. So that does have a lot of weight, because sometimes it can literally be about life or death."[16]

In other words, translating new experimental hypotheses into clinical interventions should be approached with caution, since ineffective treatment can have severe personal consequences that go beyond a failed laboratory experiment or the need to redesign a theory. This of course holds for all attempts at developing new interventions and is not limited to complexity science, but it is still something that should be kept in mind, especially since these kinds of consequences generally do not play a role in more exact sciences like physics.

4.2.8 Comments and discussion

The interviews have illustrated the potential added value and possible limitations of using interdisciplinary methods in complexity science, and allow for constructive reflection on the phase transition approach in this context. Several of the anticipated motivations and challenges that were described in section 2.5 were observed during the interviews. Access to novel expertise and subsequent insights was often mentioned as a motivation, as well as necessity depending on the type of problem. Moreover, the challenge of creating a truly interdisciplinary practice strongly emerged, and participants mentioned incompatibility and communicative issues when collaborating with different disciplines. Personal curiosity and excitement perhaps played a smaller role than expected, as this was not brought up by most participants. Also, difficulties with acquiring funding were not directly indicated as an obstacle, although several participants might have referred to this indirectly when stating that the interest in complexity science has increased over the years, making it easier to perform this type of research.

The way in which the interviews were conducted did have some limitations. First of all, the number of interviews that was performed is relatively small compared to the standard in fully interview-based studies, due to practical constraints concerning the weight and duration of this

[16] "En dan kan je zeggen van ja, hypothetiseren, wat maakt dat nou uit, dat mag toch wel, maar in mijn wereld [...] maakt het echt uit, want [...] dan ga je mensen een experimentele behandeling aandoen, en [...] als dat eigenlijk een te wilde hypothese is, [...] dan onthoud je mensen wel een andere actieve behandeling. Dus dat weegt wel zwaar, want dat kan soms letterlijk over leven of dood gaan."

project. For this reason, usual reliability checks such as data saturation could not be considered. Moreover, the scientific backgrounds of the participants were quite diverse and their approaches to complexity greatly differed, which did allow for a broad and varied illustrative overview as intended, but it also made direct comparison of views challenging. Further expansion of the interview coverage by including more subjects would therefore be desirable.

Another element to consider is the information that might have been missed during the interviews. For instance, using the unedited interview guide for a condensed matter physicist would probably have led to an awkward conversation and unsatisfactory results, due to the aforementioned observation that physicists often do not explicitly consider complexity as a key element of their research, even though the systems they study might be characterised as complex. Implicit theoretical views and actual 'methods' related to complexity likely would not have surfaced. Although the interviewees in this study could respond well to most questions, this effect still might have played a role and useful implicit information might therefore not have been brought up.

A final interesting question that is left unanswered is the potential added value of interdisciplinary collaboration to physics. So far, the discussion has been framed from the perspective of medical scientists and psychologists, who set out to answer certain questions and to this end seek expertise from physics. However, the chances of success of such a collaboration would increase if both ends could benefit from the transaction of knowledge. It is easy to say that physicists do not need knowledge from medical science or psychology to answer their fundamental questions, but it might very well be that these collaborations deepen or solidify their understanding by being forced to consider familiar theory from a different perspective, or even that insights from an interdisciplinary study can be translated back to systems in physics. The potential added value of these interdisciplinary collaborations from the perspective of a physicist could thus provide an interesting avenue for further study.

5 Conclusions & outlook

This project aimed to assess both the feasibility and usefulness of modelling tipping points in complex systems using phase transition theory from physics, through a psychological case study involving a tentative transition in depressive symptoms over the course of antidepressant reduction within an individual. To address both practical viability and fundamental relevance, two separate research questions were formulated. The findings and discussion corresponding to each research question and their respective sub-questions (see section 1.2) will be presented below.

Research question 1 *"How can the concept of an order parameter, as known from the theory of phase transitions in physics, be applied to or identified in a generic system undergoing an apparent regime shift, in particular the dataset of the patient with MDD?"*

A dataset from a patient with MDD going through gradual reduction of their antidepressant was used as a case study. The data were obtained and first studied by Wichers and Groot (2016) through an extensive EMA study and consisted of a large collection of momentary, daily and weekly prompted questionnaire items concerning the participant's mental and physical condition, recorded over the course of 238 consecutive days. A sharp increase in depressive symptoms was observed part way through the measurement period.

Earlier publications on this dataset reported the presence of early warning signals related to critical slowing down just prior to the tentative transition (Wichers and Groot, 2016). Moreover, an increase in restlessness was found to be associated with the symptomatic increase (Smit *et al.*, 2019) and several common markers of complexity were observed in the data (Olthof *et al.*, 2020). These findings provided evidence of the relevance of generic resilience indicators in psychological systems, as well insight into the fundamental nature of psychopathology.

The analysis presented in this project revolved around the concept of the order parameter as known from basic phase transitions in physics. Two criteria were formulated to assess the potential relatedness between each item and a tentative order parameter: the presence of a shift over the course of the transition and an increase in fluctuations prior to the transition. These criteria were quantitatively operationalised and applied to a selection of items, resulting in a list of items meeting both criteria. The conclusions were fairly stable with respect to parameter choices. Two categories of items could be distinguished: one displaying a gradual shift starting after the baseline period of the experiment, and one where the shift was sharp and occurred over the course of a few weeks. This might be related to the question of the control parameter, which is unknown in this experiment; it could be that gradually increasing items are more strongly coupled to this control parameter rather than to the health condition itself, highlighting the delayed effect of the changing medication dosage. If it is indeed the case that the items adhering to both criteria are coupled to an order parameter, the existence of an underlying order and corresponding symmetry characterising the depressive transition is implied. Performing the same analysis on other datasets and comparing the resulting items would be worthwhile, as well as further studying the correlation between the highlighted items and analysing the potential for a common (latent) variable from a behavioural science perspective.

The results discussed here therefore add on to previous findings from an alternative angle. Wichers and Groot (2016) also observed an increase in fluctuations (variance) prior to the symptomatic shift, but they did so for an aggregated sum of items. The order parameter analysis was able to highlight items for which the fluctuation increase is particularly noticeable and links this observation to the presence of a shift. Moreover, Olthof *et al.* (2020) studied both regime shifts (i.e. change points) and the structure of the fluctuations as common features of complex processes, but they explicitly separated both characteristics and their discussion was mostly detached from the shift in symptom severity. The phase transition approach adds to this body of work by implicitly making use of such 'complexity characteristics', but simultaneously being rooted in condensed matter physics and focusing the discussion on the tentative depressive transition from a physics point of view.

Research question 2 *"To what extent does the application of physical theory of phase transitions to a regime shift in a system outside of physics provide added value to the scientific and clinical practice?"*

In order to examine the potential added value of a modelling approach based on phase transitions to (complexity) science and eventually clinical practice, four interviews with scientists active in complexity-related research were performed. Mutual comparison of the elements of complexity that were most important to each participant facilitated characterisation of the position of the phase transition approach in the diverse landscape of complexity science. Many common characteristics were recognised, but the interpretations were obviously different, both explicitly and implicitly. It became apparent that, although the term 'tipping points' is a commonly mentioned feature of complex systems, the underlying view on complexity in physics is quite different to the interpretations that exist in other areas of science: it does not necessarily involve multicausality, individuality or the incorporation of multiple perspectives (or at least these characteristics are not explicitly referred to as such), which were most frequently mentioned during the interviews, nor does complexity science occupy a distinctive niche in physics research. This implies that an application of physics theory to other complex systems will not always be straightforward, since the underlying points of view can differ substantially.

The original research (sub-)questions were focused on motivations and challenges related to the particular application of theories from physics to other complex systems. In practice however, a broadening of the subject to the general use of interdisciplinary techniques in complexity science yielded richer and more informative results, which could then be related to the phase transition approach. Moreover, the relation between complexity science and interdisciplinarity turned out to be an important theme in the interpretation of the data, which was not anticipated in the original research question. Participants considered complexity science an alternative to traditional research techniques in their fields in cases where those fall short, which allows them to ask different research questions and to obtain insights which would otherwise have remained hidden. Interdisciplinarity was deemed useful in this respect to provide such a new perspective and to supply the knowledge and expertise required to obtain a different understanding of reality; some participants even considered it inherent to complexity science. However, the implicit definitions and operationalisations of interdisciplinarity in research were found to be ambiguous and sometimes more akin to multidisciplinarity. The challenges that the participants faced were mainly related to acceptance of the complexity perspective by traditional science, requiring a significant paradigm shift as well as more substantial empirical backup of conceptual ideas. Moreover, working interdisciplinarily can lead to issues in communication and understanding between different disciplines, along with difficulties in translating conceptualisations from one discipline to a concrete implementation in another.

Considering the phase transition approach specifically, it is clear that people in some areas of science are seeking new ways to address certain problems in their field and are looking for inspiration and expertise beyond the disciplinary boundaries, in which respect phase transition modelling could prove a promising approach. A quantitative foundation and concrete operationalisation might help with acceptance and establishment in this regard. However, it should be carefully considered that the way in which physics interprets complexity in some ways distinctly contrasts with the conceptions that exist within other areas of complexity science, which could lead to difficulties with communicating and aligning views. A particular theme that emerged is discrepancy between universality as observed (and valued) in phase transitions in physics on the one hand and the pursuit of individuality before aggregation that is central to complexity science in psychology on the other. Whether, for instance, a hypothetical order parameter and particular symptoms related to this order parameter are expected to be universal or person-specific thus remains an open question. However, focusing research on individual patients before statistical averaging does not necessarily exclude the possibility of universal patterns and explanations, so this difference need not be insurmountable. Still, dissimilarities like this should be carefully considered and discussed in order to avoid misconceptions and also to be able to recognise the limits of applying physics theory elsewhere.

The clinical usefulness of an approach based on phase transitions is difficult to assess at this point. Although the metaphor was said to resonate well with clinical therapists, actual added value in terms of interventions remains to be demonstrated. In the nearer future however, the order parameter analysis could help characterise the relation between the transition and individual symptoms and thus identify particularly relevant items to probe during an experiment in an effort to reduce the burden on the participants. Predictive power is likely not the strongest benefit of this approach, but it could be a useful additional perspective to better understand the nature of clinical transitions and compare disease progression for different diagnoses.

Outlook and final remarks

With the results presented here, several possible directions for further study have emerged. Regarding the first research question, it would be interesting to further study the relation between the items that came up as order parameter relatives, both by means of quantitative methods as well as qualitative evaluation of possible underlying connections in relation to psychopathology. In this light, repetition of the analysis on comparable datasets would be very valuable. This could also help illuminate the level of individuality of symptomatic structures. Additionally, further study into the asymmetry of the relation between physics and other areas of science could reveal the potential added value of this knowledge transaction from the perspective of physics, which could strengthen collaborations in the future. For the second research question, an additional number of interviews could be performed, including validity checks such as data saturation or the involvement of a second coder. This would deepen the general picture sketched by the project so far and identify potentially underexposed subjects. Moreover, a theme that emerged strongly from the interviews is the interpretation and operationalisation of interdisciplinarity in complexity research, which is subject to significant and often subconscious interpretative differences. Extended study into this topic would be useful to help characterise efforts to bring together scientific disciplines and to better establish the objectives and practical organisation of interdisciplinary research.

This project took a first step towards modelling tipping points in complex systems as phase transitions. The fact that interpretable results were produced and avenues for additional study emerged implies that this approach contains potential and is worth pursuing further. Moreover, the interviews suggest that there exists a growing need for radically alternative, interdisciplinary views on current problems, to which the phase transition approach could provide one possible answer. New questions emerged related to the nature of interdisciplinarity and the meaning and assumptions behind complexity in physics as opposed to other areas of science, which could shape to what extent and in what way physics-based methods can be applied to social sciences, medical science and the like.

These exploratory results can be used as a stepping stone towards more advanced studies, both in the area of complexity-related data analysis and philosophy of interdisciplinary science. The role and implementation of interdisciplinary concepts such as phase transition theory within complexity science remains a fascinating area of research. Whether physics will eventually be able to provide answers to pressing questions in social or life sciences is yet to be determined; nevertheless, further pursuit and investigation of these novel ideas definitely seems promising.

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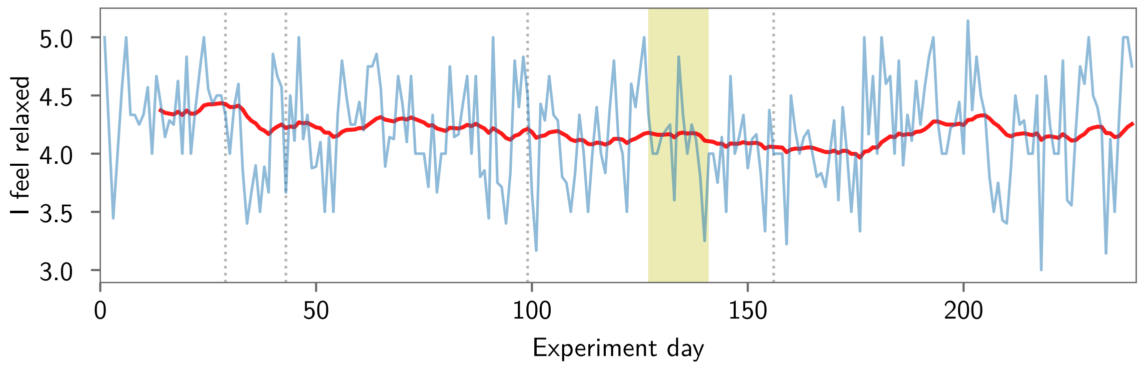
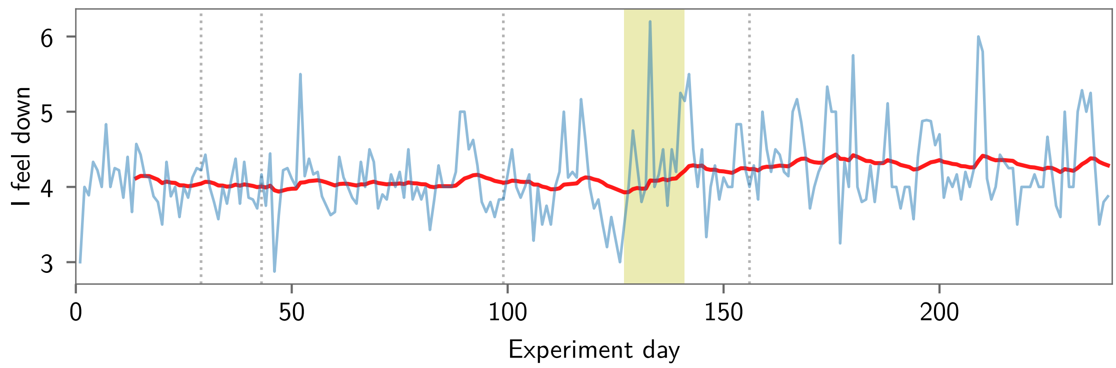
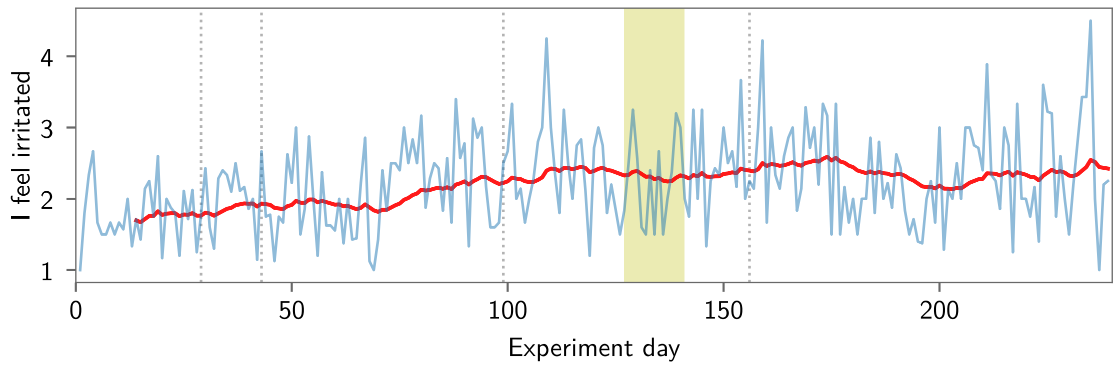
Appendices

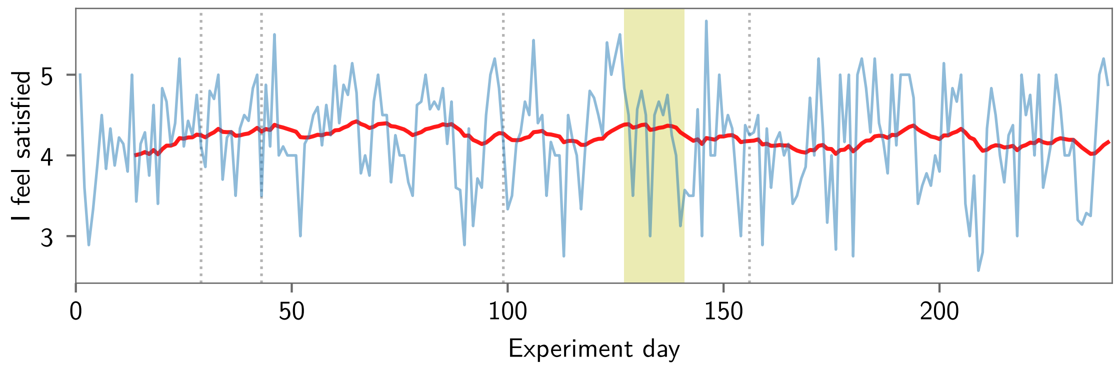
A All included items & EWMA's

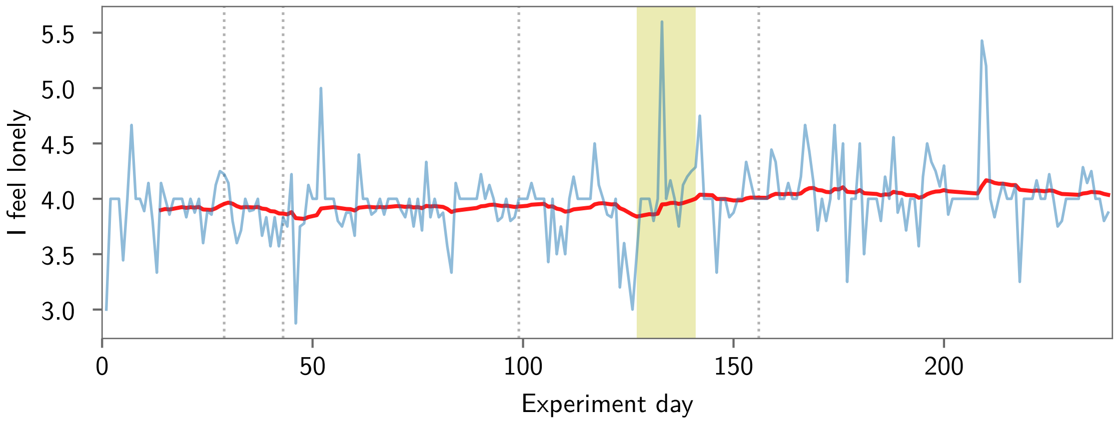
Plots of all items from the dataset that were included in the order parameter analysis, averaged per day (blue lines), together with their EWMA's with a half life of 14 days (red line). The tentative transition is indicated by the yellow shaded region.



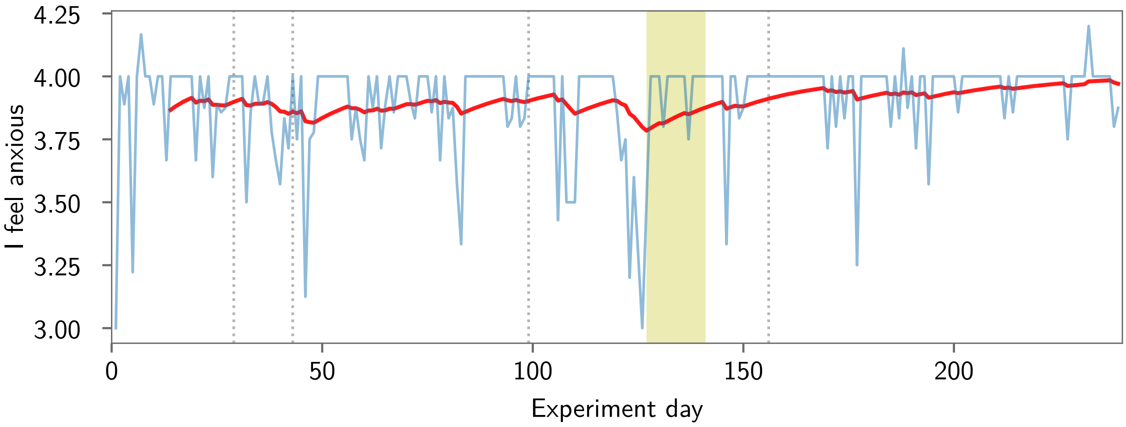




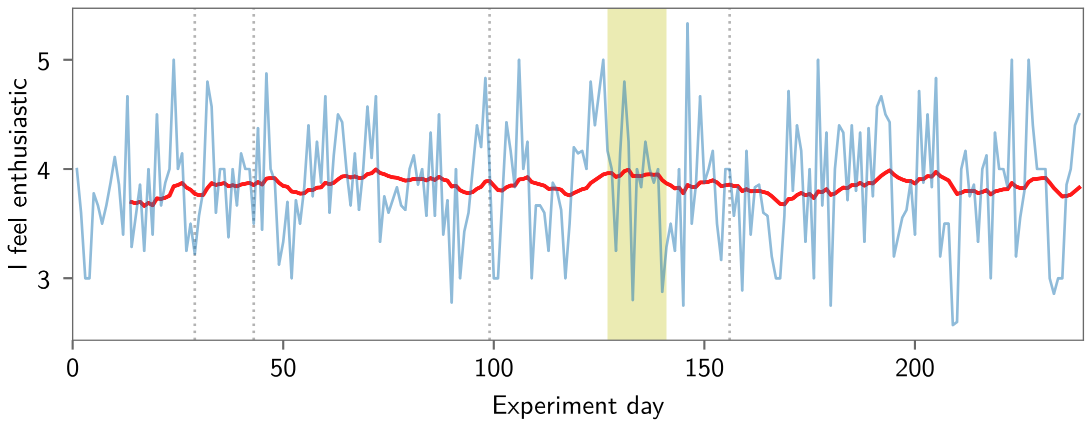




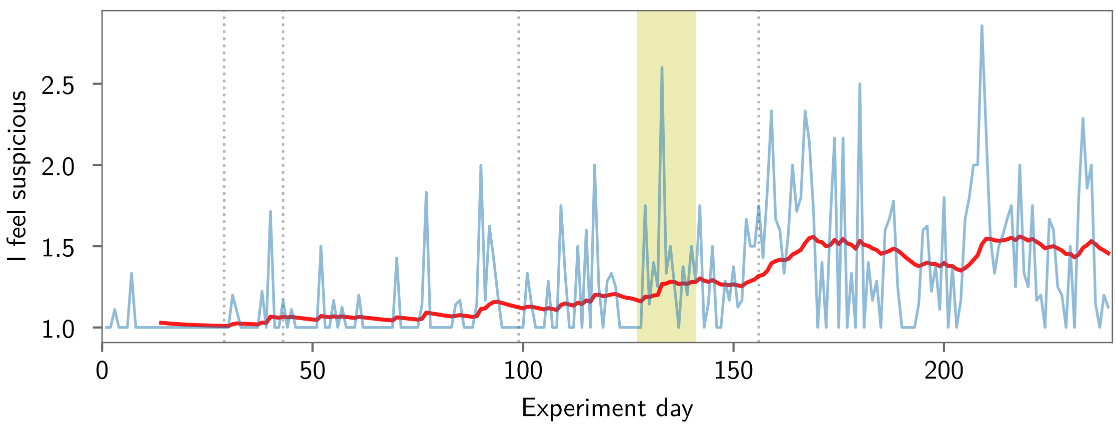
I feel lonely
5.5
5.0
4.5
4.0
3.5
3.0
0
50
100
150
200
Experiment day



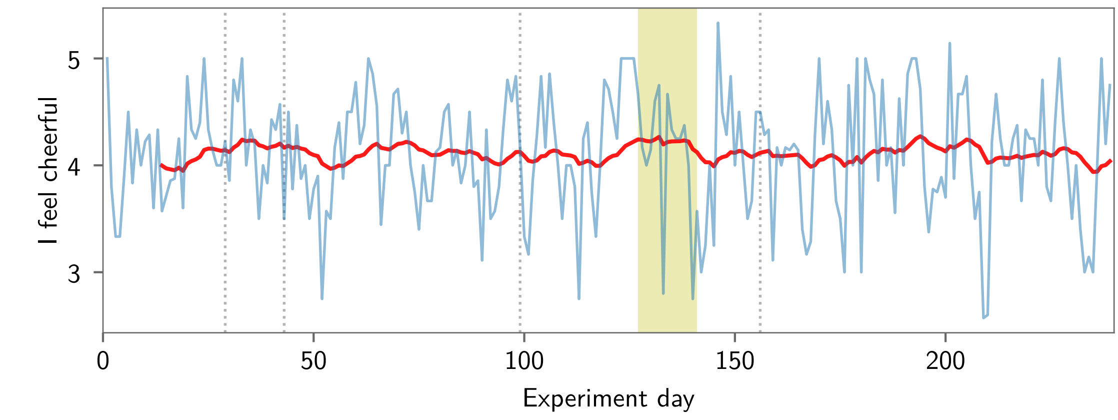
I feel anxious
4.25
4.00
3.75
3.50
3.25
3.00
0
50
100
150
200
Experiment day

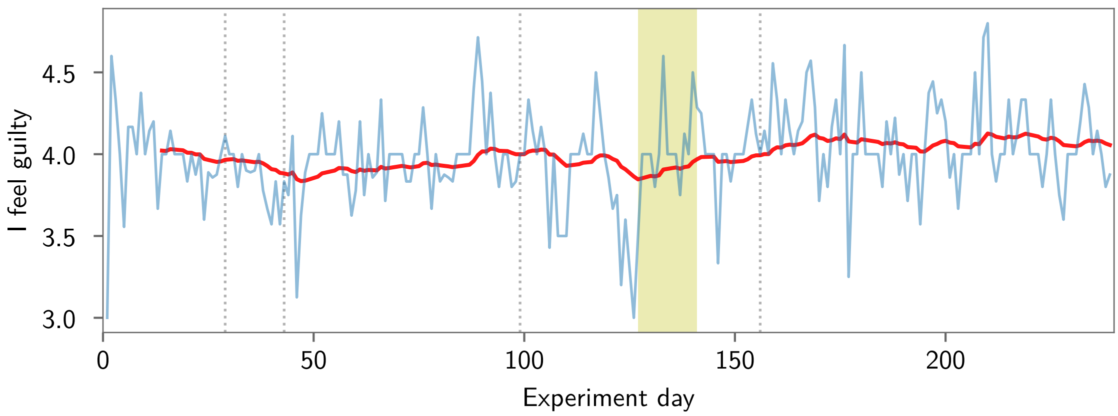


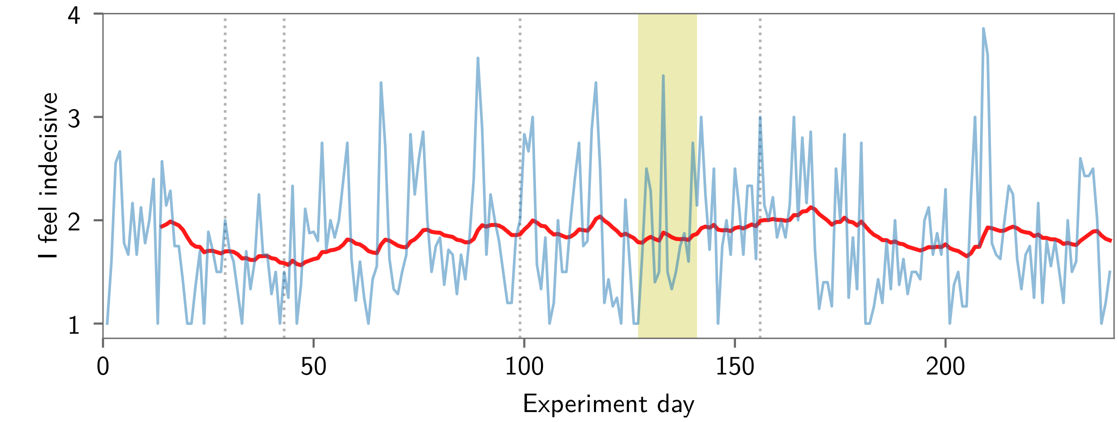
I feel enthusiastic
5
4
3
0
50
100
150
200
Experiment day

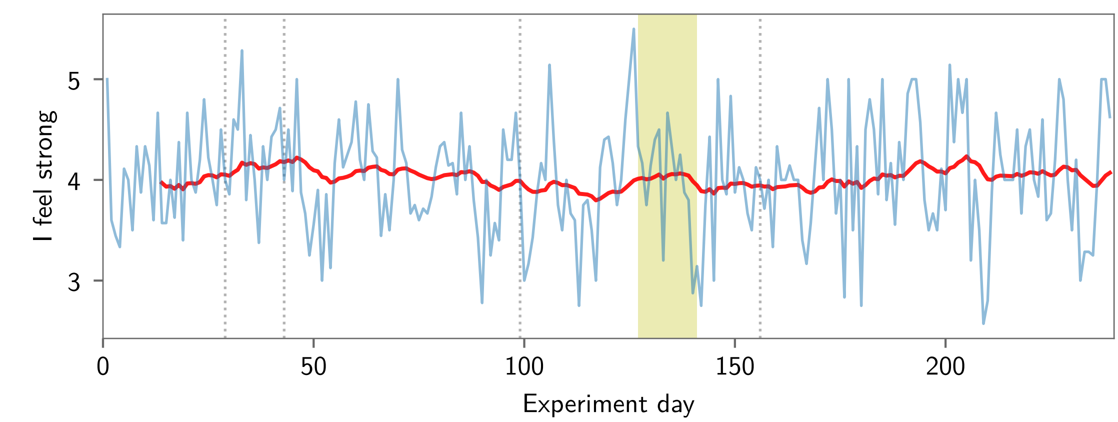


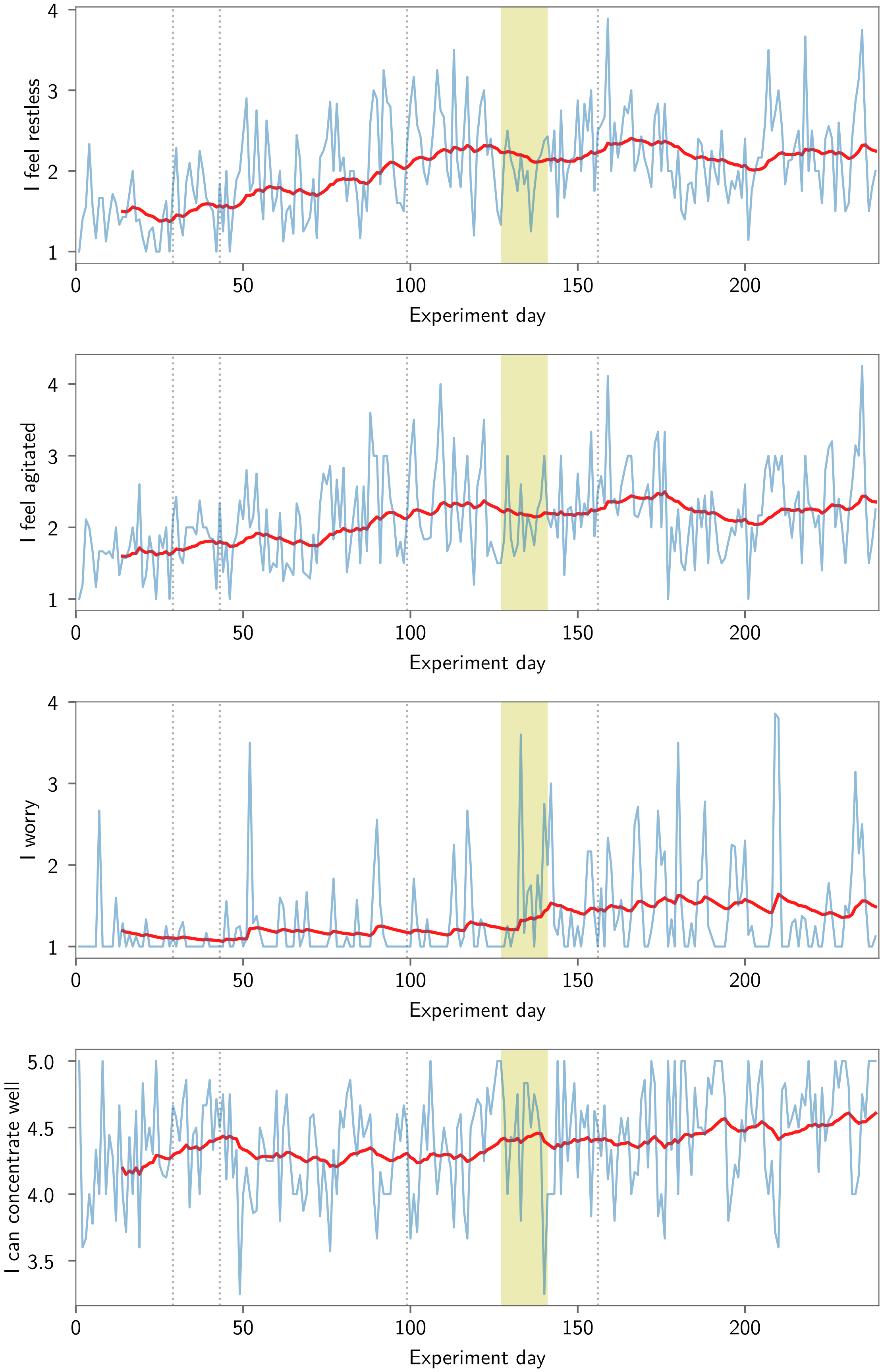
I feel suspicious
2.5
2.0
1.5
1.0
0
50
100
150
200
Experiment day

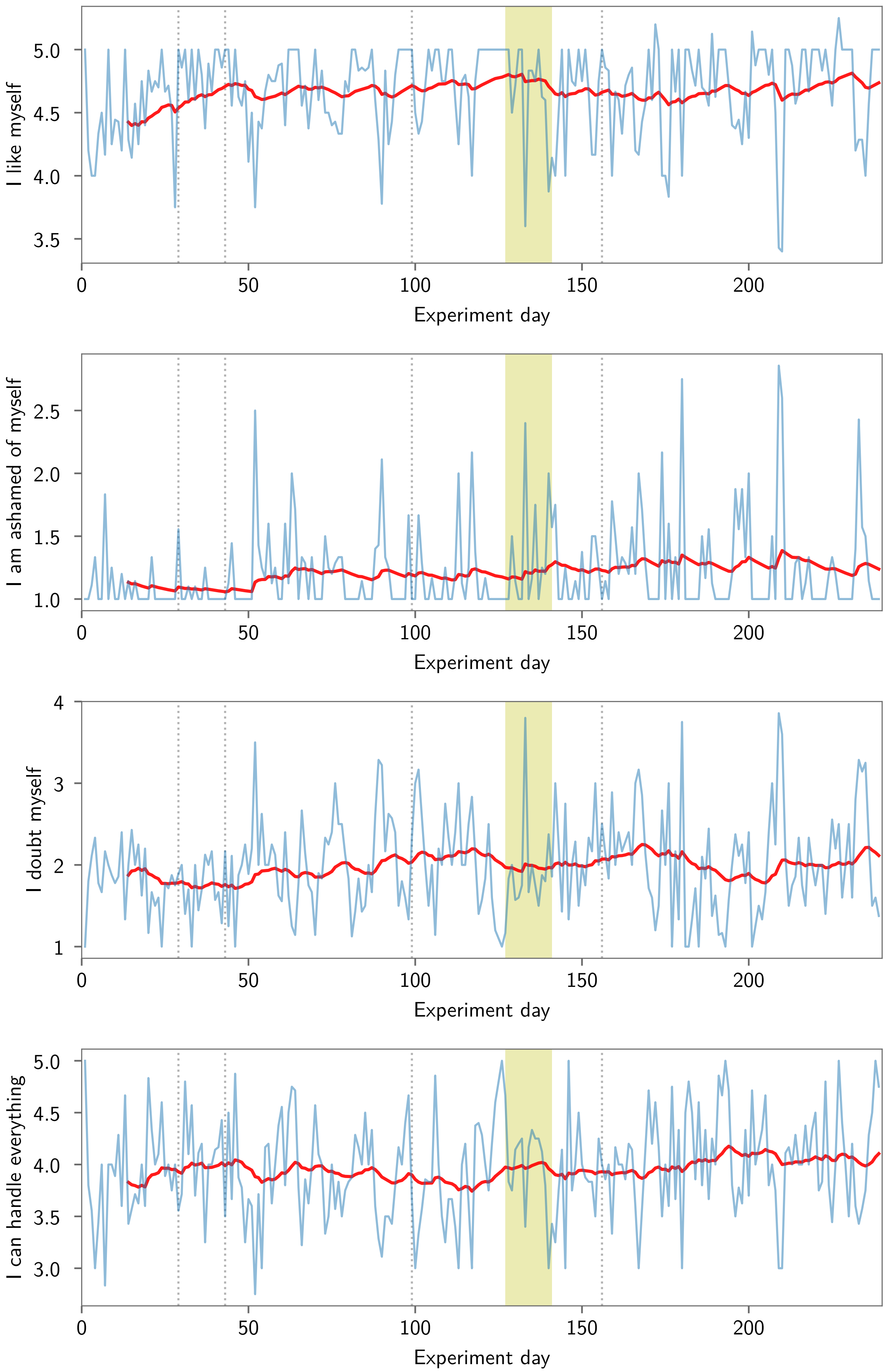

I feel cheerful
5
4
3
0
50
100
150
200
Experiment day


I feel guilty
4.5
4.0
3.5
3.0
0
50
100
150
200
Experiment day

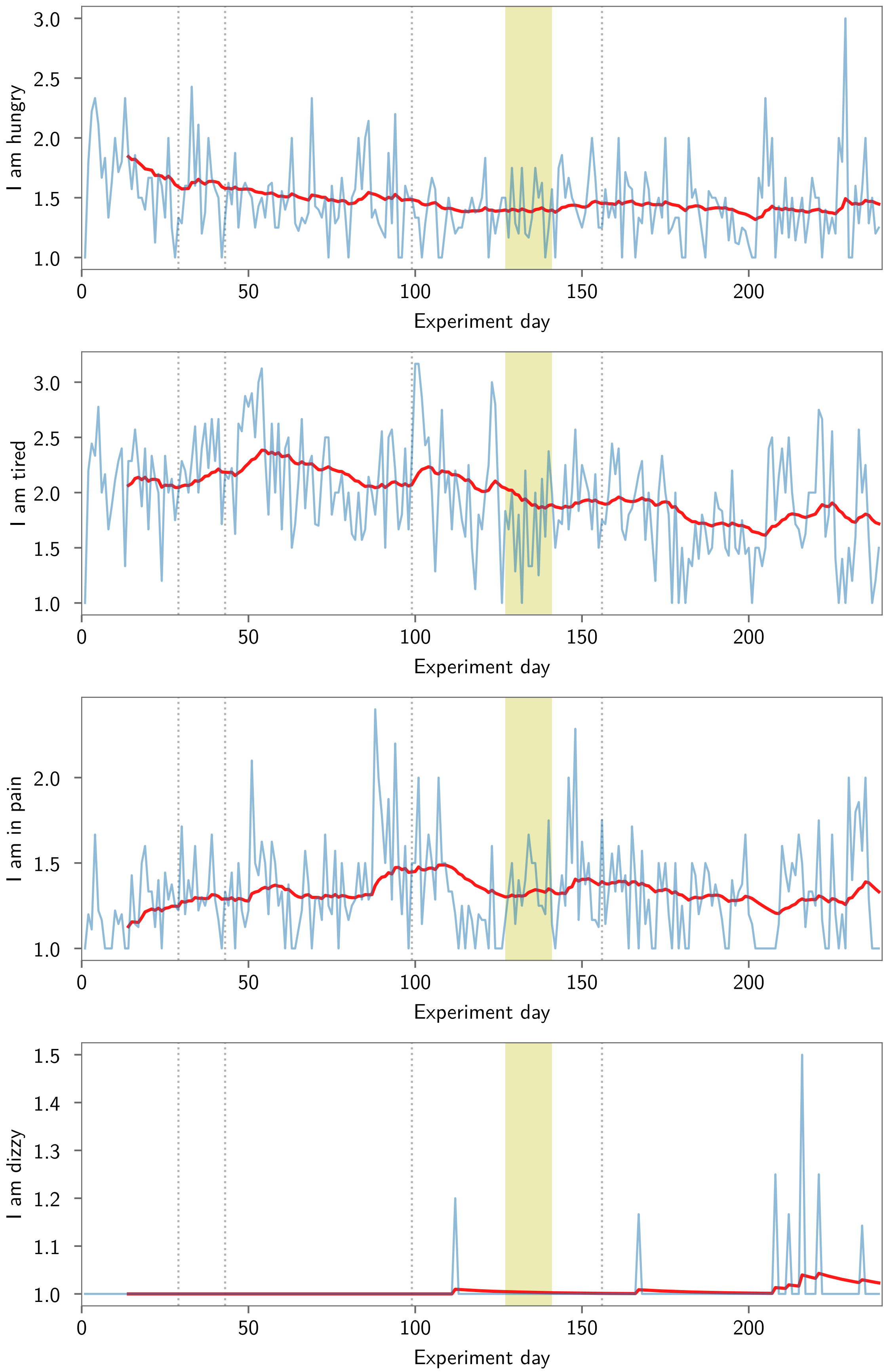

I feel indecisive
4
3
2
1
0
50
100
150
200
Experiment day


I feel strong
5
4
3
0
50
100
150
200
Experiment day

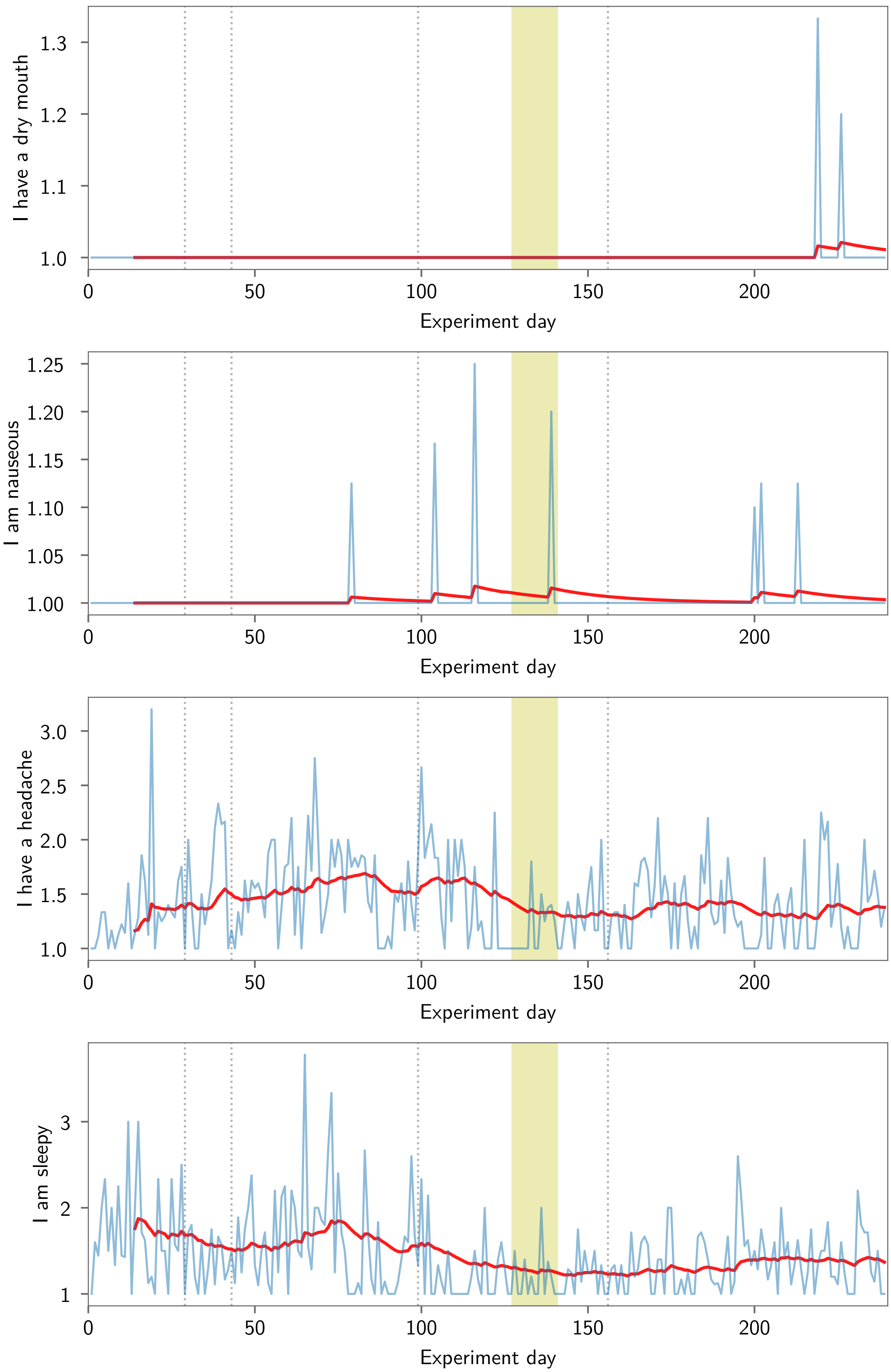

I feel restless
Experiment day
I feel agitated
Experiment day
I worry
Experiment day
I can concentrate well
Experiment day



I like myself
Experiment day
I am ashamed of myself
Experiment day
I doubt myself
Experiment day
I can handle everything
Experiment day



I am hungry
Experiment day
I am tired
Experiment day
I am in pain
Experiment day
I am dizzy
Experiment day


I have a dry mouth
1.0
1.1
1.2
1.3
0
50
100
150
200
Experiment day
I am nauseous
1.00
1.05
1.10
1.15
1.20
1.25
0
50
100
150
200
Experiment day
I have a headache
1.0
1.5
2.0
2.5
3.0
0
50
100
150
200
Experiment day
I am sleepy
1
2
3
0
50
100
150
200
Experiment day

B Interview guide

The interviews were divided into four main sections (excluding the closing statement), the order of which was partly based on the interviewee's responses. The interview guide is written in Dutch.

Introductie

Als korte introductie zou ik u eerst graag wat willen vragen over uw onderzoek in het algemeen.

→ Als u in een paar zinnen moest beschrijven waar uw onderzoek over gaat aan een wetenschappelijk opgeleide collega die geen expertise heeft in de psychologie/medische wetenschap, wat zou u dan zeggen?

Interdisciplinaire methodiek

Ik heb begrepen dat u werkt vanuit het perspectief van complexe systeemtheorie, klopt dat? Ik ben geïnteresseerd in de methodiek die u toepast om uw onderzoeksvragen te beantwoorden. Denk bijvoorbeeld eens terug aan een onderzoekslijn of -project waar u de afgelopen jaren aan gewerkt heeft.

→ Welke technieken en methoden heeft u in dit onderzoek ingezet om uw onderzoeksvragen te beantwoorden?

→ Welke theoretische uitgangspunten lagen ten grondslag aan deze methoden?

→ In hoeverre onderscheidt de door u gehanteerde aanpak zich van de manier van onderzoek doen die het meest gangbaar is in de psychologie/medische wetenschap?

- Wat zijn de belangrijkste verschillen tussen de door u gebruikte methodiek en deze gangbare methodiek?
- Hoe bent u erbij gekomen om deze methode toe te passen, in plaats van de gangbare methodiek?

→ Maakte u in uw onderzoek wel eens gebruik van technieken of ideeën die afkomstig zijn uit een ander vakgebied dan de psychologie/medische wetenschap?

- Welke technieken of ideeën zijn dit?
- Op wat voor manier integreert u deze technieken of ideeën in de methodiek van uw vakgebied?
- In hoeverre heeft u daarbij moeilijkheden ervaren als het gaat om het vertalen van deze technieken of ideeën naar uw eigen onderzoek?

→ Heeft u voor uw onderzoek ook wel eens samengewerkt met wetenschappers buiten de psychologie/medische wetenschap?

Zo ja:

- Welke achtergrond had(den) diegene(n)?
- Als u terugdenkt aan uw meest recente samenwerking, hoe waren de rollen toen verdeeld? Hoe zag de samenwerking er concreet uit?
- Is er wel eens sprake geweest van communicatieproblemen of zelfs misverstanden tussen de vakgebieden in de samenwerking, en zo ja, hoe zag dat eruit?

- In hoeverre heeft die samenwerking resultaten opgeleverd die niet behaald hadden kunnen worden door puur binnen de psychologie/medische wetenschap te blijven?

  Zo nee:

- Wat zijn de redenen dat zo'n samenwerking niet is voorgekomen?

Het concept complexiteit

Integreren in voorgaande wanneer kandidaat complexiteit of gerelateerd begrip noemt.

Ik hoorde u net het woord complexity/complexiteit/etc. gebruiken. 'Complexity science' is natuurlijk een brede term, die vaak heel verschillend wordt opgevat.

→ Wat verstaat u precies onder het begrip 'complexity'?

→ Hoe groot is de rol van het begrip complexiteit in uw eigen onderzoek?

Indien niet natuurlijk aan bod gekomen:

Het valt me op dat u het woord complexiteit niet gebruikt.

→ Hoe komt dat?

→ (vervolg als hierboven)

Relevantie en praktijk

Tot slot wil ik het graag hebben over de relatie van uw onderzoek met de klinische praktijk. Sommige vormen van wetenschap zijn heel toepassingsgericht en staan in direct verband met de praktijk, terwijl ander onderzoek juist heel fundamenteel is en nog ver weg is van een concrete toepassing.

→ Waar in dit spectrum zou u uw eigen onderzoek plaatsen?

Stelt u zich eens een ideaal toekomstbeeld voor van uw onderzoeksveld over een paar decennia. Uw onderzoek heeft grote vooruitgang mogelijk gemaakt en wordt nu op dagelijkse basis toegepast in de klinische praktijk.

→ Voor welk praktisch doel zou uw onderzoek in dit geval worden ingezet?

→ Welke technieken worden er op dit moment gehanteerd in de klinische praktijk voor dit doeleinde, als die er zijn?

→ Op welke manier zou het resultaat van uw onderzoek deze huidige technieken aanvullen of vervangen?

→ *(indien van toepassing)* Welke rol zou de eerder genoemde interdisciplinaire methodiek hebben gespeeld in deze bijdrage?

Afsluiting

Dan zijn we nu wat mij betreft bij het einde van het interview aangekomen.

→ Is er iets wat u nog zou willen toevoegen wat nog niet ter sprake is gekomen?

C Codebook

Overview of all codes used in the analysis of the four interviews, including their frequency of occurrence in the transcripts (groundedness).

Code name	Comment	Grounded
	Descriptive information	
Research topic	Describes the topic of their research.	7
Methods	Describes a method used in their research.	22
Collaborations	Describes an interdisciplinary collaboration or origin of concepts/methods.	26
	Elements of complexity	
Non-linearity	Effects of inputs on outcomes are not proportional.	10
Stability domains	Existence of multiple stable states, which can change as the context evolved.	5
Tipping points	Occurrence of a sudden shift in behaviour past a certain threshold.	7
Change over time	Intrinsic development and change over time.	11
Unpredictability	Forecasting impossibility and inability to collect all information.	5
Unknowns	Unknown factors that can influence the system, leading to indirect effects.	2
Multiple scales and levels	Interactions in the system occur across multiple scales and levels, study required from multiple perspectives.	2
Path dependency	The state of the system depends on its history or path to its current state.	1
Strong interactions	Components within a system strongly interact.	11
Similarities with other systems	Complex systems can show similarities with completely different systems.	8
Individuality	Focus on the individual and personalisation.	8
Multicausality	Phenomena cannot be explained by singular causal relations.	11
Emergence	Interactions between components in the system can lead to emergence of new higher level behaviour.	1
Quantitative versus qualitative implementation	Highlighting a contrast between quantitative and qualitative implementation of complexity.	16
	Integration of complexity in research	
General role of complexity in research	Describes the general role of the notion of complexity in their research.	13
Research question	The complexity perspective is reflected in the research questions that are posed.	14
Concepts and theory	The complexity perspective is reflected in the concepts and theory behind the research.	14
Study design	The complexity perspective is reflected in the design of the study.	11

Code name	Comment	Grounded
Methods	The complexity perspective is reflected in the methods used to collect data.	23
Analysis techniques	The complexity perspective is reflected in the techniques used for data analysis.	5
Motivations for complexity perspective		
Shortcomings of other methods	Mentioning shortcomings of and differences to non-complexity oriented science.	32
Better fits practice	The complexity perspective better suits the daily reality or practice of the object of study.	20
Yields new insights	The complexity perspective can yield different insights compared to other methods.	9
Developing applications	The complexity perspective can help develop practical applications.	4
Monetary gains	The complexity perspective can help obtain monetary gains.	3
Personally interesting	Studying complex subjects is interesting and exciting.	4
Increased interest	Mentions growing traction of or increasing general interest in complexity science.	8
Challenges to complexity perspective		
Uncertainty in effectiveness	The effectiveness of complexity methods in research is often still unknown and can disappoint.	16
Differences in definition	The notion of complexity can be interpreted differently by different actors.	16
Acceptance by other areas of science	The complexity perspective is not always easily accepted by other areas of science.	21
Misunderstanding by other areas of science	The complexity perspective can be misunderstood or misinterpreted by other areas of science.	9
Unjustified application	The complexity perspective can sometimes be applied too easily or loosely without proper justification.	4
No access to required data	Research from a complexity perspective requires a specific type of data that may not be available everywhere.	5
Requires more effort	Working from the complexity perspective requires more effort.	5
Facilitators	Approaches or circumstances that help overcome or alleviate challenges in complexity science.	19
Motivations for interdisciplinarity		
Yields new insights	Interdisciplinary work can yield insights that would not have been discovered otherwise.	11
Necessity	It is necessary to work interdisciplinarily in this field.	3
Personal inspiration	Working with other disciplines is personally inspiring.	2

Code name	Comment	Grounded
Access to extra expertise	Interdisciplinary work give access to extra expertise that is not available otherwise.	9
Better fits practice	An interdisciplinary approach better fits the daily practice related to the object of study.	4
	Challenges to interdisciplinarity	
Differences in approach	Members of an interdisciplinary collaboration can have different approaches or paradigms.	24
Translation	Concepts or methods can be difficult to translate between disciplines.	9
Understanding	It can be difficult to understand input from other disciplines.	12
Miscommunication	Interdisciplinary work can lead to miscommunication or language barriers between participants.	20
Slower progress	Interdisciplinary collaboration can delay research and lead to slower progress.	7
Facilitators	Approaches or circumstances that help overcome or alleviate challenges in interdisciplinary collaborations.	20
	Practical relevance	
Application in practice	Mentions a possible practical application of the outcomes of their research.	34
Added value of complexity	Mentions an added value of the complexity perspective in practice.	12
Added value of interdisciplinarity	Mentions an added value of interdisciplinary work in practice.	4
Challenges to practical implementation	Mentions challenges in transferring their research to clinical practice.	5
Requirements for successful implementation	Mentions requirements for successful implementation of their research outcomes in practice.	12