Social dynamics of substance use through minds and models

van den Ende, M.

Publication date
2025

Chapter 1

Introduction: Advancing Psychology through Formalisation

Substance abuse is among the most common and costly of all mental health and brain disorders (Effertz and Mann, 2013b; Arias et al., 2022). It affects individuals by causing a myriad of health complications and impairing cognitive function, emotional regulation, and decision-making processes. Additionally, substance abuse can strain personal relationships, introduce significant barriers to maintaining employment, and hinder the ability to fulfill roles within families and communities, which can contribute to a cycle of poverty and further mental health challenges. Beyond the personal costs to individuals, substance abuse imposes substantial economic burdens on society, including increased healthcare costs, lost productivity, and legal expenses. Socially, it can exacerbate issues such as homelessness, child neglect, and domestic violence, creating ripple effects that disrupt community stability and wellbeing. The cumulative impact of these factors underscores the pressing need for effective prevention and intervention strategies to address the multifaceted challenges posed by substance abuse disorder. Similar to the way substance use affects individuals in many different ways, it is also the result of a complex interplay of many factors, including biological predispositions, psychological processes, social influences, and societal factors (Heilig et al., 2016; Reiter et al., 2017; Heyman, 2009; Prom-Wormley et al., 2017). For example, the complex relationships between alcohol use and complementary behaviors such as smoking show that these behaviors mutually influence each other, particularly in relation to relapse rates (Bien and Burge, 1990; Bobo and Husten, 2000; Room, 2004; Blok et al., 2017; Cooney et al., 2015; Weinberger et al., 2015).

One factor that has a major impact on substance use at all stages is one's social environment (de Visser, 2021; Sönmez Güngör et al., 2021). Social dynamics, including peer pressure, family dynamics, and societal influences, play pivotal roles in the initiation and continuation of substance use, especially during adolescence (Hawkins et al., 1992; Donovan, 2004). These influences can have lasting effects on patterns of use well into adulthood (Chassin et al., 2002). The social environment can also be a major source of support in recovery: social support systems such as Alcoholics Anonymous, have proven effective in promoting abstinence and reducing relapse rates by leveraging the positive influences within social networks (Witkiewitz and Marlatt, 2009; van den Ende et al., 2024a; Ariss and Fairbairn, 2020; Bliuc et al., 2018). As I demonstrate in Chapter 2, theories of substance use often forego addressing the interplay between substance use and the social environment, and formal modeling approaches in psychology and the social environment are disjointed.

In this thesis, I present my work in advancing the psychological understanding of substance use and its social dynamics through a formal modeling approach, representing an effort to adopt a more holistic view by considering both social and psychological perspectives, as well as their interactions. This introduces three concepts that need to be defined precisely in order to be fully understood: what do we mean by advancing psychological knowledge, what is substance abuse, and what is the formal modelling approach? In the following sections of the introduction I will explore these concepts, elaborate on their relationship with data, set out the rationale for my methodology, and describe the psychological academic context in which this research is taking place, while also highlighting the reasons why it is both challenging and essential to take this approach.

The scientific method and advancing psychology

Revisiting the scientific method briefly, despite being developed as far back as the 16th and 17th century, remains crucial for fully grasping the context of my thesis within the psychological sciences, as it describes what I mean with advancing psychological knowledge. This methodical process of observation, hypothesis formulation, and experimentation provides a structured framework for research. Its findings are reproducible and objective. It therefore allows the accumulation of robust knowledge. This method has been used for centuries and has led to the development of theories and models that have allowed us to understand and predict the behaviour of the physical world. However, applying this method to the behavioural sciences presents some unique challenges (Borsboom et al., 2021). Therefore, in the following sections, I will draw an analogy between the scientific method as applied in astronomy and psychology to highlight the different challenges.

> *Mercury's orbit shifts or precesses around the Sun a tiny bit, moving its perihelion by about 574 arcseconds per century. However, in classical mechanics, described by Newtons laws of motion, the perihelion, the point of closest approach to the Sun, should remain fixed. 531 of these arcseconds can be explained by gravitational influences of other planets in the Solar System, a precession of 43 arcseconds per century remains unexplained. To account for this, several theories, such as revisions to Newtons laws, or the existence of a new planet were suggested. Then Einstein altered our understanding of gravity: according to general relativity, massive objects like the Sun cause a curvature of spacetime. Mercury's orbit, therefore, is affected by the curvature of spacetime near the Sun. As it moves closer and further in its ellipse around the sun, it is impacted not just by space but also by time as it is closer, which causes the observed precession of its orbit. The successful precise prediction of this precession was a landmark test of general relativity and a final confirmation of its validity.*

Although the technological and methodological requirements for generating hypotheses and testing theories and models in astronomy continue to grow, the requirements and measurement goals are clear. Moreover, while there remain large unobservable and mysterious concepts such as dark matter and dark energy, many individual objects can be studied and observed; the functioning of a single star does not depend crucially on knowledge of the dark matter around it. We can therefore take a reductionist approach: we are able to understand the workings of a single star system, and by combining information about that star system we can infer knowledge about the galaxy in which that star lives. In contrast, the study of human behaviour presents significant challenges due to the difficulty of isolating and manipulating variables and accounting for confounding factors. In terms of describing psychological, high-level behaviour, the brain is more like a black hole: we can observe the information coming in, but it is impossible to measure the dynamics within. Therefore, it is an impossible task to take a reductionist approach and break down the inner workings of the human brain into simpler, fundamental components that can then be combined to explain the behaviour of the whole system.

It is therefore not surprising that psychological research has focused on collecting data, analysing the data and reporting the findings, effectively stalling at step one of the scientific method (Oberauer and Lewandowsky, 2019a). Moreover, even in this discovery-oriented type of research, it has been found that many of these findings are not replicable. Psychology has therefore been said to be in a 'crisis' since 1978 (Meehl, 1978), and according to some, the situation has not improved 40 years later (Eronen and Bringmann, 2021). The solution is as simple in theory as it is difficult in practice: we need to develop theories that generate hypotheses, which we can then use to design experiments and test these hypotheses. However, every step of the scientific method is difficult to apply in psychology. Phenomena are often not robust; consider the data obtained from the orbit of Mercury: while it is difficult to get the right precision of measurement, the observed progression is exactly the same every year. This makes the data very restrictive about the behaviour of the orbit, and therefore suitable for hypothesis generation. In psychology, there are ethical and practical constraints on the collection of data, and the results are impacted by confounding factors: similar to trying to measure the orbit of Mercury without being able to measure the mass of Jupiter, and the mass of Venus changing over time. Moreover, the awareness of being observed can lead individuals to modify their behavior, known as the Hawthorne effect (McCambridge et al., 2014), and thus the act of observing can impact the observation. Additionally, self-reporting can lead people to tailor their responses based on perceived expectations or demand characteristics (Orne, 2009), further complicating the measurement process. In addition, when generating hypotheses, constructs need to be clearly defined — it is easy to define what a perihelion is, but it is much harder to define the concept of 'craving' in such a way that everyone always has exactly the same understanding of it.

In conclusion, in describing psychology we are dealing with the results of the workings of an extraordinarily complex system, and we are trying to describe what emerges from the workings of that complex system. It is therefore inevitable to try to describe what happens in reality using fewer variables than would be necessary to describe all the underlying components. So, to take the scientific method one step further, we need to take a complex system approach: to create a system that behaves similarly to what we observe and captures the essence of the phenomena we are interested in, even if not every detail and underlying process is modelled exactly. In this way, we can focus on the macroscopic patterns and behaviours that are most relevant to our understanding and advance our psychological knowledge.

Psychological constructs

The American Psychological Association (APA) Dictionary of Psychology describes addiction as 'a state of psychological and/or physical dependence on the use of drugs or other substances, such as alcohol, or on activities or behaviours'. This definition is entirely dependent on one's interpretation of 'addiction', making it inherently ambiguous and unable to guarantee consistent understanding between different people. Fortunately, the APA Dictionary of Psychology also provides a definition for 'substance dependence': 'a cluster of cognitive, behavioral, and physiological symptoms indicating continued use of a substance despite significant substance-related problems. There is a persistent pattern of repeated substance use resulting in a strong internal drive to continue use, tolerance to the effects of the substance, and withdrawal symptoms if use is suspended'.

This definition is more precise, but it still depends on what exactly is meant by ‘significant substance-related problems’, ‘strong internal drive’, ‘tolerance’ or ‘withdrawal symptoms’.

Taking alcohol as an example, the DSM-5 defines alcohol use disorder by setting a certain number of criteria, three of which are physiological: (1) tolerance, (2) craving, and (3) symptoms of withdrawal (Association, 2013). Looking at the definition of ‘craving’, the APA Dictionary of Psychology gives ‘an unrelenting desire, urge, or yearning’. It is often one of the criteria for diagnosing a substance or alcohol use disorder. This definition is circular: craving is a symptom of substance use disorder, but substance use disorder is diagnosed by the presence of craving. This circularity is a common occurrence in psychology: constructs are often defined in terms of other constructs, which are defined in terms of the first construct. This is only logical; in practice it can be seen as a verbal description of a causal loop diagram (Cavana and Mares, 2004) — describing the relationships between constructs — the first step in systems thinking, which in turn can be seen as a precursor to formal modelling. However, as both the constructs and their relationships are only described verbally, ambiguity is increased and the constructs are difficult to measure.

In conclusion, the definition of psychological terms related to addiction is complex and multifaceted, and it is not easy to define addiction in a clear and unambiguous way. One approach to addressing this issue is to formalize these constructs, as I demonstrate in Chapter 6, which necessitates a clear and unambiguous description of these concepts and their dynamics through mathematical relationships. This defines them in terms of other constructs and makes the relationships between these constructs explicit. However, this first requires clear narrative definitions of the constructs: if certain constructs are ambiguous and therefore difficult to measure, it is difficult to formally define another construct in terms of that construct. Fortunately, progress is being made with narrative reviews, such as the definition of recovery (Witkiewitz et al., 2020), leading to increasingly clear and precise definitions of constructs, which can then be more easily used in formal descriptions.

Data

A major reason for the difficulties in effectively applying scientific methods to human behaviour is the availability, robustness and precision of data. In astronomy, it is expensive to build a telescope, but once built the data is abundant and increasingly precise, and stars shine consistently or in consistent patterns. However, these patterns can only be discovered when confounding factors such as atmospheric conditions, light pollution and gravitational lensing are taken into account. Similarly, isolating the different components of human behaviour is complex due to the interplay of confounding variables. Social influences, cultural norms, personal histories, cognitive biases and emotional states are all intertwined, making it difficult to ignore their effects; but whereas in astronomy these can be resolved by additional observations and increased theoretical sophistication, obtaining more accurate data on individuals raises ethical and practical issues.

Furthermore, while astronomy continuously benefits from new observational methods, such as X-ray astronomy, which provide fresh insights and new information, the study of human behavior faces significant limitations. We are primarily restricted to increasing the number of observations and participants, as radically new methods of observation rarely emerge in psychology.

In addition, the act of observation itself affects the measurement, as being observed can alter an individual's actions, potentially inducing artificial responses that do not accurately reflect behaviour shown otherwise. In addition to confounding variables and the observer effect, many theories in psychology use constructs that are not directly measurable. Rather than measuring a substance in the blood or the amount of a drug taken, concepts such as craving or tolerance are highly dependent on how one experiences these concepts, which is entirely subjective not only to one's own feelings, but also to the precise definition of that construct.

The collection of better data in the behavioural sciences is not only a matter of technical capacity and funding; data are difficult to obtain because of additional ethical, practical and legal constraints. Some issues in human behaviour require information on both sociological and psychological data, as they are often highly intertwined. This further exacerbates the ethical and practical limitations. Fortunately, recent developments in data collection have greatly reduced the practical limitations of collecting large amounts of data. Similarly, advances in computing power have increased the capacity for detailed data analysis. This enables new methodologies that were previously impossible.

For example, these advancements have facilitated the rise of artificial intelligence, which could be highly useful for predicting behaviour. However, advancing psychological knowledge requires an understanding of why and how it predicts that behaviour, which is sometimes as unclear as the subject it is predicting. As a result, machine learning is difficult to use for constructing theories because it does not immediately provide insight into the underlying mechanisms that drive behaviour. Improved psychological understanding resulting from better data collection and computational methods will come by increased statistical power and better replication of results, thereby increasing the credibility and robustness of findings. In addition, advances in data are highly synergistic with the development of theory and formal models. While complexity in models does not inherently imply greater accuracy, representing behaviour on shorter timescales and incorporating more parameters requires that the granularity and timescale of the data match the complexity of the model. In addition, an adequate number of variables and confounders must be measured to validate such models effectively. Therefore, as formal models become more complex, the need for precise and accurate data to test and refine them increases proportionally.

Formal Models

The second step in the scientific method is to formulate a hypothesis, theory, or model that can be tested through experimentation, and this step varies in complexity depending on the objective (Oberauer and Lewandowsky, 2019a). A hypothesis is a simple, testable statement, such as 'the anomalous precession of Mercury's orbit cannot be explained by Newtonian mechanics'. A theory is an integrated set of hypotheses that explain a phenomenon: 'gravity distorts the fabric of space-time, leading to a variation in time dilation when Mercury is close to the Sun compared to when it is farther away, causing precession of Mercury's orbit'. A theory can only be expressed verbally, but it is often 'formalised' in a mathematical model which allows precise predictions and tests to be made (Borsboom et al., 2021). The exact, formal way of describing the distortion of space-time that explains the precession of Mercury can be derived by combining the theory of general relativity with Kepler's 3rd law, called the law of harmonics, showing how mathematical, formal frameworks can be combined and how the accumulation of knowledge leads to ever more complicated, yet very well understood (by some at least) models:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad \text{Einstein's Field Equations}$$

$$\frac{T^2}{L^3} = \frac{4\pi^2}{GM} \qquad \text{Law of Harmonics}$$

$$\Delta\phi = \frac{24\pi^3 L^2}{T^2 c^2 (1 - e^2)} \qquad \text{Precession of Perihelion}$$

This is a representation of the real world — in the case of physics, precise and accurate, but still representing the real world only in certain limited ways. While Newtonian dynamics were accurate for most of the classical mechanics observed in normal human time scales, masses and spaces, it falls short of accurately describing the interactions of massive objects at high speeds or in strong gravitational fields, such as Mercury's orbit around the Sun.

General relativity, on the other hand, can describe these phenomena accurately. However, it too is only a representation, because at the scale of galaxies we find that general relativity is unable to explain our observations, and we need to introduce dark matter and dark energy to explain the observed phenomena. Theoretical frameworks are therefore often limited in their scope. However, although they do not represent exactly what happens in the real world, they have proved invaluable in predicting and explaining phenomena, and have led to many advances that have had a very real impact on our lives.

As we can put the modelling framework into different scenarios and see how it behaves, it allows us to experiment without having to perform physical experiments. We can therefore use the framework as an 'infinitely' accurate telescope, apply observations, and find new, undiscovered behaviours emerging from the system, which we can then use to generate new hypotheses to test with actual telescopes. From this we can develop improved frameworks, and so on. In the case of human behaviour modelling frameworks, the same is true: formal models are representations of the real world, and they are limited in scope, but they are useful in predicting and explaining phenomena, and have led to many advances that have a very real impact on our lives. A recent example is the COVID-19 pandemic. Using a highly simplified model of virus spread — assuming that it is transmitted from an infected person to a healthy person, that individuals can be in different states (infected, recovered, or dead), and with numerous simplifying assumptions such as constant infection probabilities, no influence of weather or cultural practices, no role for the immune system, and equal social interactions for all — this model still successfully predicted the spread of the pandemic and the effects of various interventions.

Outline

This thesis is structured to follow the chronological sequence of the research undertaken during my doctoral studies.

Chapter 2 is an inventory of the state of formalised models of substance abuse currently available in the literature. It also serves as an introduction to the dominant psychological theories in substance use research. This review examines formal models of substance use that are based on theories from a purely psychological perspective, as well as models from a sociological perspective that focuses primarily on the influence of the social environment.

The following Chapter 3 describes the workings of a programming ‘toolbox’; a Python package developed to apply formal models of individual behaviour to a (social) network. It aims to provide the tools to easily simulate different individual and social models in a simulation — it combines adaptive networks (Gross and Blasius, 2007) with models of individual behaviour (also called agents) to simulate complex agent networks (Mei et al., 2015). The user provides the network structure, the individual dynamic system model and the interaction rules, and the toolbox takes care of the network and the simulations.

In the next chapter, Chapter 4, I apply this approach to a simplified model of addiction in a social network, based on the single hypothesis that substance use behaviour spreads in a network similar to a disease. This hypothesis is tested using longitudinal empirical data on substance use and the social environment.

The data used in this study are from the Framingham Heart Study, covering the period from 1971 to 2001 and including both the original cohort and the offspring cohort. This dataset includes comprehensive physical and mental health assessments as well as behavioural data such as sleep patterns, cigarette smoking and, in particular, alcohol consumption. A unique aspect of this dataset is the inclusion of social network information, with many social connections being fellow participants due to their shared residence in the same city. The social network data, constructed from direct reports of social relationships, were compiled by Nicholas A. Christakis and James H. Fowler. Their work has led to several controversial but influential papers on social contagion theory and has contributed significantly to our understanding of the role of social networks in health behaviour (Fowler and Christakis, 2008; Christakis and Fowler, 2007, 2008, 2013).

Following the approach of Hill et al. (2010a,b), this chapter poses a simple hypothesis: the model used is a highly stylised SIR (Pastor-Satorras et al., 2015, Susceptible, Infected, Recovered) type, well known in the field of epidemiology — appropriate for the long time scale and high granularity of the available data. The results are striking: the social dynamics of abstinence and heavy drinking can be aptly described as a ‘disease’ spreading through a population of non-problematic, recreational drinkers.

In Chapter 5 I analyse the aforementioned data on substance use behaviour and social environment in a fully data-driven manner, using psychometric network techniques. Here I show how these modern techniques are able to explore interactions and effects between different individual and social factors, and how these exploratory findings, using methods that distinguish between between-person, within-person and temporal effects, can be useful in developing new hypotheses.

Finally, Chapter 6 presents a formal modelling framework for substance use that integrates multiple psychological phenomena and hypotheses, modern conceptualisations of psychological constructs, and current verbal psychological theories of substance use into a single formal model. Uniquely, it also integrates social aspects of substance use and is able to explain certain social phenomena, such as differences due to different social norms or the legality of substances. In addition to describing an intuitive way in which these phenomena occur within the context of the model, we show how it can be extended to show certain scenarios, such as the reinforcing effect of combining certain substances. By operationalising verbal psychological theories and constructs, it provides a framework for thinking about these constructs and their relationships. It can be used to develop new hypotheses for interventions, such as the negligibility of the impact of availability on consumption levels.

Finally, the thesis concludes with a discussion of the approach taken, a reflection on the advantages and pitfalls of the approach, and what I believe should be the next steps in advancing psychological knowledge through formal modelling.