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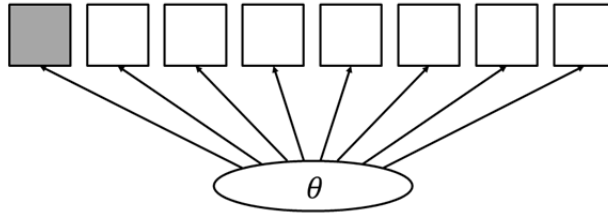
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Chapter 1

Introduction



Prologue

A well-known scientist (some say it was Bertrand Russell) once gave a public lecture on astronomy. He described how the earth orbits around the sun and how the sun, in turn, orbits around the centre of a vast collection of stars called our galaxy. At the end of the lecture, a little old lady at the back of the room got up and said: "What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise." The scientist gave a superior smile before replying, "What is the tortoise standing on?" "You're very clever, young man, very clever," said the old lady. "But it's turtles all the way down!" (Hawking, 1988, pp. 1)

You, the reader, are sitting in a chair somewhere, reading this thesis, out of curiosity, politeness, or perhaps even boredom. You are a psychological being: Using standardized tests and questionnaires; psychologists can describe you along a variety of dimensions and scales. Cognitive scientists can estimate how many random digits you can retain in your working memory (Unsworth & Engle, 2007), the speed at which you can mentally rotate three-dimensional objects (Borst, Kievit, Thompson, & Kosslyn, 2011), how much your performance on a task slows down after making an error (Dutilh et al., 2012) and estimate your general intelligence, known to predict life expectancy, expected income and work performance across decades (e.g., Gottfredson & Deary, 2004). Studying changes in psychological states, it is possible to represent your emotional wellbeing as a dynamic network and, thereby, predict what constellation of psychological symptoms make you vulnerable, or resilient, to adverse emotional states such as depression (Bringmann et al., 2013). In short, you are a psychological entity, one that can be described, measured, quantified, and compared to other individuals and yourself over time, along many dimensions that together form an incomplete and imperfect, yet predictive and informative, picture of you.

Yet at the same time you are a biological entity. You have approximately 1100 grams of brain tissue (Allen, Damasio, & Grabowski, 2002), consisting of 86 billion neurons (Azevedo et al., 2009) interconnected by approximately 3 kilometres of axons per cubic millimetre (Braitenberg & Schuz, 1998) interacting through electrical impulses and neurotransmitters in such a frenzy that, despite representing only 2% of body weight, the brain is

responsible for 25% of the metabolic requirements of the entire body (Mink, Blumenshine, & Adams, 1981). We can measure how much grey matter you have in various brain regions, map how white matter tracts connect various regions of your brain, quantify how cortical subsystems in your brain synchronize their activity over time, and measure localized changes in neurotransmitter levels. In short, you are also a biological entity, made of billions of continuously interacting cells.

One of the biggest scientific challenges of our time is that both these descriptions are in some sense true. Yet at the same time they seem to be, in many ways, irreconcilably different. This raises important questions: Do the psychological processes, states and traits ‘exist’ in the same way at lower (biological) levels, and are brain scanners able to identify these same properties? Or are the biological and the psychological fundamentally different levels of explanation, that each requires a different set of ontological and epistemological tools? The question of how to relate the different explanatory levels is known as the reduction problem, and it will figure centrally in this thesis.

The reduction problem

The reduction problem is concerned with the question of how different explanatory levels in science are connected. One influential proposal has been sketched by Oppenheim and Putnam (1958), based on ‘the working hypothesis of unity of science’. In this perspective, sketched in Figure 1.1, science consists of a hierarchy of explanatory levels that range from those concerned with the ‘large’, or ‘high’ (e.g. social groups) to the ‘small’, or ‘low’ (e.g. atoms or subatomic particles). As entities at a higher level can be said to consist of (be made of) elements at the lower level, science consists of basic, physical building blocks that aggregate to form the hierarchy of sciences. This offers a simplified perspective on the (natural) sciences as running from the highest level of abstraction all the way down to the fundamental physical building blocks of the universe. For instance, sociology considers how people interact in groups, psychologists study the mental workings of people, neuroscientists study the brains of those people, the building blocks of the brain are complex instantiations of biochemistry, and so on, all the way down to the fundamental building blocks of (sub)atomic physics.

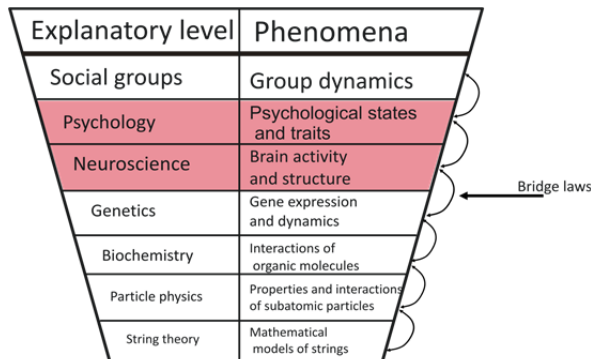


Figure 1.1. The unity of science according to Oppenheim and Putnam (1958). Nagel proposed the development of bridge laws that would translate regularities and laws at a certain level into phenomena at lower levels. This thesis focuses on the relationship between psychology and biology, highlighted in red.

Given this layered perspective on science, the reduction problem is concerned with how these layers could, or should, be related. Oppenheim and Putnam proposed two ways to think about the unity of science. The first is an idealized, meta-theoretical perspective on the ultimate state of affairs in a (hypothetically) completed science. In this view, all scientific knowledge can be, and has been, unified and translated in a single framework such that any describable pattern found in nature can be translated to laws that operate at lower levels. The second perspective on the unity of science is as a description of progress in science, such that the unity of science ‘exists as a trend within scientific inquiry, whether or not unitary science is ever attained’ (Oppenheim & Putnam, p. 3). Oppenheim and Putnam proposed a definition for how one might view the reduction between levels in formal terms. They propose (1958, p. 5) that theories at higher explanatory levels T2 (e.g. psychology) can be reduced to lower order levels T1 (e.g. biology) if and only if:

- 1)! The vocabulary of T2 contains terms not in the vocabulary of T1
- 2)! Any observational data explainable by T2 are explainable by T1
- 3)! T1 is at least as well systematized as T2

Ultimately, the approach by Oppenheim and Putnam left much to be desired. Among other challenges, the precise meaning of what would entail an explanation at lower levels was not cashed out fully. However, their proposal was the inspiration for more developed reductive models such as that put forth by Ernest Nagel (1961). He proposed a formalization of the requirements that must be met in order to say that a theory at a certain level has been, or can be, reduced to a lower level in the hierarchy. Nagel suggested that at every explanatory level, we can discover regularities, or laws, which describe the interaction of entities at that explanatory level (e.g. brain regions interacting). However, as the objects at a certain level (e.g. brains) consist of objects at a lower level (e.g. biochemical molecules), it should be possible to discover law-like statements that *translate* the regularities at one level (brain regions interacting) into the regularities at a lower level (properties of biochemical molecules). Nagel called such statements *bridge laws*. Ultimately, a complete specification of these bridge laws would allow us to do away with any ontological commitments other than of the units at the lowest level: The bridge laws would allow us to analytically translate any scientific regularity either ‘upwards’ or ‘downwards’. Although few, if any, bridge laws have been developed, the sense of reductionist necessity can still be found implicitly, in many scientific approaches (e.g. ‘psychological processes happen in the brain, therefore we must be able to translate psychological theories into theories about the brain’). However, despite its initial appeal, these formal approaches were soon criticized.

Perhaps the most forceful criticism came in a series of papers by Putnam (e.g. 1967) and later Fodor (1974). The argument they developed is known as the multiple realizability thesis. This position states that a particular mental state such as ‘being in pain’ can, or could, be realized by a variety of physical realizations. For instance ‘being in pain’ has been suggested to be identical to C-fibres firing (cf. Hardcastle, 1997; Place, 1956; Smart, 1959, van Rysewyk, 2013). However, Putnam and Fodor argued, there is no reason why C-fibres are the only physical substrate that could serve this purpose: Other

types of neurons (e.g. in other animals such as reptiles) or even non-biological substrates could equally serve this function. Recent successful brainstem transplantations (made of silicon, not neural tissue, Hagan & Wilson, 2013) have allowed congenitally deaf children to hear by incorporating non-neural tissue. Faced with such a patient, someone defending a law-like reduction of 'hearing' would either have to conclude that this patient is not 'really' hearing, or somehow incorporate a disjunction of all possible physical realizations (perhaps future hearing implants will be made of novel substances) into the law-like reduction. This has been seen as a devastating criticism of bridge-law like formalisms of reduction: If a mental state can be realized in a large, possibly infinite, disjunctive set of physical realizations, it is unclear how bridge laws (or any lawlike regularity) could accomplish this one-to-many mapping of the psychological to the physical.

Fodor further argued that for this and other reasons, physicalism (the view that the universe is ultimately made of matter, cf. Stoljar, 2009) does not necessarily entail reductionism. Instead, he argued for the *disunity* of science as a working hypothesis (p. 97). According to Fodor, the ontological and epistemological autonomy of the special sciences (e.g.; disciplines such as psychology, sociology and economics) is not endangered by assuming physicalism. This view, known as non-reductive physicalism, rapidly became popular among philosophers (c.f. Block, 1997). Moreover, Fodor argued that the question of the reduction of sciences is an empirical one, and that empirical evidence for reduction, especially for reduction spanning more than a single level, is sparse (although see Bickle, 1998, for a different perspective). This focus on the empirical fruits of actual reduction was echoed by Daniel Dennett (1995), who distinguished between reductionism in general on the one hand, described as sensible attempts by science to explain larger units as parts of a whole, and greedy reductionism on the other. Greedy reductionism occurs when attempts are made to reduce phenomena at higher levels to lower levels across 'large gaps', without well-established intermediate steps. He uses the metaphor of a crane to represent a scientific or conceptual tool to translate or explain findings at one level from a level 'down'. If one argues, on the basis of a physicalist perspective on the hierarchy of the sciences (Figure 1) that the mind can (or should) be explained by physics or chemistry without establishing the solid intermediate steps required (cranes that can do the 'work'), one is guilty of greedy reductionism. Similarly, we cannot simply proclaim that because the brain is necessary for psychological processes that all psychology can be reduced to the brain: We have to develop the scientific cranes that allow us to do the work of successfully reducing psychological phenomena to (increasingly) lower levels. Clearly, there is much disagreement concerning how to reconcile the premise of physicalism with observable lawlike regularities at various explanatory levels. Within this broader reductionist context, the relationship between the mind and the body, or between psychology and the brain, is perhaps the most contentious of all.

The mind-body problem

The relationship between mind and body has fascinated and troubled scientists and philosophers for centuries. Since its inception as a scientific discipline in the late 19th century, psychology has laboured to justify the reality and scientific relevance of its objects of study: psychological constructs and properties. The status of these psychological constructs has been the topic of much debate in

the psychological literature (e.g., Spearman's 1927 discussions on the nature of intelligence). Such discussions were given renewed impetus in the latter half of the 20th century, when technological advances made it possible to study lower-level (physiological) properties of individuals in tandem with hypothesized psychological constructs (Gazzaniga, 2004). The study of people at biological levels of description (e.g. the structure and activity of the brain, the influence of brain lesions and trauma, the role and function of genes) as it relates to psychological phenomena has had a profound impact on scientific psychology. However, despite technical advances (e.g. measuring activity of the brain during a task), novel paradigms (e.g. temporarily disrupting brain function with magnetic pulses) and a voluminous body of research (e.g. 165,000 hits in scholar.google.com by searching for "cognitive neuroscience"), it is not always clear how we should conceptualize the role of biological psychology with regard to the nature or existence of psychological constructs.

One of the most (in) famous attempts to describe the relationship between the mind and the body is that of dualism. Descartes (1641) concluded that because the mental has different properties than the physical (e.g. all physical things take up three-dimensional space, whereas the mental does not), they must be separate substances. The mental, according to this view, is a separate type of substance that interacts with the physical (brain) via the pineal gland. At the other end of the philosophical extreme, it has been argued that the 'folk psychology' we use in everyday language when speaking of beliefs, memories or desires do not exist, and will ultimately be replaced by the neurosciences. This view has been referred to as eliminative materialism (e.g. Churchland, 1981).

Between these two extremes, a variety of more sensible approaches to the mind-body problem have been proposed by philosophers of mind. Jaegwon Kim argued that the mental supervenes on the physical. The idea of supervenience holds that concepts at higher levels of abstraction are determined by their lower order constituents, such that there can only be a difference in the higher construct (e.g. 'your IQ is higher than mine') if there is also a difference in the brain states ('your brain properties differ from mine'). I will return to this position in detail in chapter two. Another theory is that of emergence, which holds that properties at higher levels of abstraction arise, or occur, because of the complex conjunction of lower features. For instance, a general cognitive property such as 'intelligence' does not exist at the level of individual neurons: it is only when billions of neurons interact that intelligence or intelligent behaviour) emerges¹. The relevance of emergence for cognitive neuroscience is clear: Can psychological processes be understood by studying the building blocks of the brain (e.g. neurons, glia cells and neurotransmitters) in isolation, or do the properties of interest (consciousness, intention, being in pain) only emerge when the lower properties aggregate in the appropriate manner? A final perspective we consider here is identity theory. In identity theory, a psychological state is identical to its neurological realization. Interpretations range from strict forms such as type-type identity theory, in which a type of neural activity (e.g. 'c-fibres firing') is identical to a type of psychological state (e.g. 'being in pain'). Less stringent interpretations hold that a given psychological state at a certain time is identical to a neural realization at

¹Or in the words of Daniel Dennett (2005, p. 2): 'not a single one of the cells that compose you knows who you are, or cares.'

that moment (token-token identity theory), but that there need not be a particular regularity in the neural realization (i.e. it can be different across occasions for the same mental state). A more pragmatic conceptualization, Heuristic identity theory, (e.g. McCauley & Bechtel, 2001) suggests that assuming an identity theoretical relationship between brain and mind is the best way to make empirical progress in relating brain to mind. We return to various forms of identity theory in chapters two, three, four and six.

The dangers of greedy (neuro)reductionism

Far from being purely philosophical deliberation, understanding the relationship between psychology and the brain has direct consequences for society (Miller, 2010). One widely prevalent assumption is the view that the neural level is, in some sense, more tangible, and therefore more real. This point of view has been described as ‘neurorealism’. For instance, Racine, Bar-Ilan and Illes (2005) examined the increased incidence of fMRI-related news, and the often uncritical reporting of neuroscientific findings. They describe the pitfalls of neurorealism, which according to the authors “can make a phenomenon uncritically real, objective or effective in the eyes of the public” (p. 160). They illustrate this tendency by citing examples from popular press such as “Fat really does bring pleasure” and “A relatively new form of brain imaging provides visual proof that acupuncture alleviates pain” (p. 160). An NIMH report offered the following description of schizophrenia ‘Mental illnesses are real, diagnosable, treatable brain disorders.’ (NIMH; Hyman, 1998, p. 38, cited in Miller, 2010) and a majority of people, when interviewed, thought of Major Depression as ‘a chemical imbalance’ (80%) and ‘a neurobiological problem’ (67%) (Pescosolido et al., 2010). Of course, this position is not necessarily wrong; what matters is that the conception we have of the role of biological psychology is sensible, and based on data or sound theory. As Pescosolido and colleagues argue (citing work by Hinshaw, 2006); “Public attitudes matter. They fuel “the myth that mental illness is lifelong, hopeless, and deserving of revulsion” (p. 1324).

Although these types of views are most common in popular reporting, a very similar heuristic also appears in scientific writing. For instance, consider the following descriptions (all italics added) of the role of biological psychology with respect to psychological constructs such as personality; “Temperaments are often regarded as biologically based psychological tendencies with intrinsic paths of development. It is argued that this definition applies to the personality traits of the five factor model”, (McCrae et al., 2000, p. 173); general intelligence, “This evidence of biological correlates of *g* supports the theory that *g* is not a methodological artefact but is, indeed, a fact of nature.” (Jensen, 1986, p. 301) and “Ultimate understanding of *g* must come from the most profound and detailed direct study of the human brain in its purely physical and chemical aspects” (Spearman, 1927, p. 403); and psychopathological disorders such as schizophrenia, ‘One goal of psychophysiological research has been to anchor both diagnosis and symptoms in biological reality’ (Ford, 1999, p. 667). Misinterpreting findings from biological psychology can have adverse consequences. For instance, in India in 2008, a man was convicted on the basis of an EEG-based lie detector (Deceiving The Law, 2008) despite various methodological concerns about neuroimaging-based lie-detection (e.g. Ganis et al., 2011). In Italy, a man convicted of murder had his sentence reduced by 18

months because the defence argued successfully he had ‘the aggression gene’ (Feresin, 2009).

Clearly, a coherent and defensible view on the relationship between mind and brain is not a purely academic exercise. Giving ontological precedence to the biological level of explanation, without establishing a coherent framework of reduction, is a clear case of greedy reductionism, and can have considerable adverse consequences, not just within science but also in society. For this reason, we require a framework that properly integrates the biological with the psychological. Such an approach would have to integrate both levels of explanation, and navigate between the largely unsuccessful extremes of unjustified ‘neurorealism’ and the denial of the relevance of biological explanations in understanding psychology. In the next section I outline such a framework.

A psychometric approach to the reduction problem

As is clear from the above, how to appropriately conceptualize the relationship between explanatory levels in science is far from a settled matter. Nowhere is this question more pressing than when attempting to relate brain to mind: It is this connection that attempts to bridge the seemingly irreconcilable domains of our subjective, first-person perspectives on the world with the billions of firing of neurons and exchanging of neurotransmitters. The fierceness of the debate has led to the unpalatable extremes of either denying that psychological states exist (e.g. Churchland, 1981) or that the findings of neuroscience are irrelevant to psychology (e.g. Fodor, 1999). Neither of these extremes has been well supported by empirical progress. In this thesis I will aim to address this question in a novel way. Drawing on philosophy of mind, theories of reductionism and measurement theory, I will propose that the reduction problem is, at least in part, a measurement problem. That is, to accurately capture the relationship between the brain and the mind, we must get a grip on what it is we are measuring at each explanatory level, and how we can, and should, relate neural measurements of the brain to the behavioural measurements of psychology. As such, the development and application of theoretically guided statistical models are essential in the attempts to tackle this problem.

To do so, we will focus mostly on latent variable models. Latent variable models are models that relate observable measurements (e.g. reaction time measurements, the strength of the signal at a certain point in the brain, or the number of items made correctly) to the hypothesized underlying constructs that either cause (Borsboom, Mellenbergh, & Van Heerden 2003) or summarize (Edwards & Bagozzi, 1991) the observable measurements into latent variables. For our purpose, this means we conceptualize the psychological variable of interest (e.g. intelligence, or working memory capacity), as a latent variable, and attempt to best model the relationship of this latent variable to the observable measurements from both (neural and behavioural) domains. In doing so, we achieve several goals. Firstly, the two domains of brain and behavioural measurements are put, a priori, on equal footing, avoiding assumptions that unnecessarily constrain the outcomes of inquiry. Secondly, by graphically representing hypotheses, implicit causal assumptions become explicit, facilitating scientific debate. Thirdly, the merits of neural versus psychological measurements become purely empirical matters: Their performance (in a

statistical sense) can be directly compared, and evidence for or against theories quantified.

Overview

In this thesis, I approach the reduction problem in a novel way, focusing on the use of statistical models to relate properties of the brain to psychological properties. In chapter two, I examine the nature of reductionism in cognitive neuroscience. I reframe the reduction problem as a measurement problem, arguing that the statistical relationships between the measurements of the neural and psychological domains inform us about the defensibility of theories concerning the mind-body problem. As such, attempting to understand the mind-body problem should be, at least in part, based on empirical data. We take two influential theories from philosophy of mind, identity theory and supervenience, and translate them into psychometric (structural equation) models. These two models, a unidimensional reflective measurement model and a formative MIMIC model, capture the core theoretical predictions that implicitly flow from these two influential theories. Within the framework of structural equation modelling, these two models can then be empirically tested, and the relative evidence for each model for a given certain dataset compared. We compare these models for two datasets, one on intelligence and brain size, and one on personality and localized grey matter density. For both datasets, the formative (MIMIC) model that represents the theory of supervenience better fits the data. We discuss the implications and show that these results converge with recent progress in research on the cognitive neuroscience of emotions.

In chapter 3, I discuss a range of commentaries by scholars from various fields concerning the theoretical framework developed in chapter two. These commentaries focused on, among other things, the mechanistic interpretation of explanatory models, the notion of causality when relating brain to mind, the differences between psychology and naturalistic behaviours and the distinction between data and phenomena. In tackling these challenges, I further develop the framework in chapter 2 along several lines. First, I argue that well-developed measurement models are the best way to achieve the ultimate goal of cognitive neuroscience: A better understanding of the neural mechanisms underlying psychological processes. Secondly, I argue that the justification of choosing the brain as the preferred explanatory level for the mind cannot be based solely on the fact that the brain is physical, but must be based on other criteria such as explanatory coherence, predictive ability or mechanistic insight. Thirdly, I show how behaviour can be integrated in a hierarchical version of a MIMIC model, connecting behaviour, psychology and the brain. Finally, I briefly address the psychometric predictions that flow from additional candidate theories from philosophy of mind, such as emergence.

In chapter 4, I extend the basic tenets of the Structural Equation Modelling approach from chapter 2, and focus solely on the relationship between intelligence and the brain. There are several reasons for the prominent role of intelligence in this thesis (it is empirically addressed in chapters 2, 3, 4 and 7, mentioned as an important example in chapter five). Intelligence has been of central interest in psychology for well over a century, resulting in many interesting findings. For instance, performance on a variety of general ability tasks tends to covary positively (i.e. the positive manifold, Carroll, 1993); IQ test scores have increased steadily over generations in the 20th century (i.e. the Flynn effect, Flynn, 1987); intelligence is related to various aspects of socio-

economic status such as income, education and health (e.g. Gottfredson & Deary, 2004), and intelligence is related to various lower cognitive phenomena such as reaction time variability and perceptual speed (e.g. Jensen, 2006). Yet despite its predictive value, debates concerning the proper understanding of what intelligence is and how it should be measured continue to this day. These debates concern the change in IQ over time (Flynn, 1987), the interpretation of latent variables (Kan, Kievit, Dolan, & Van der Maas, 2011), the role of dynamic models (Van der Maas et al, 2006), the change in factor structure across the range of ability (Molenaar, Dolan, Wicherts, & Van der Maas, 2010) and many other topics. In addition to the statistical and conceptual debates regarding the nature of intelligence, cognitive neuroscientists have studied various ‘biological correlates’ of intelligence. These include brain size (McDaniel, 2005), white matter connectivity and grey matter density (Jensen & Sinha, 1993), lesion studies (Woolgar et al., 2010), brain activity during complex fluid reasoning tasks associated with intelligence (Gray, Chabris, & Braver, 2003) and the estimation of similarity in intelligence scores between monozygotic twins and dizygotic twins (cf. Deary, Penke, & Johnson, 2010). Some have proposed we should search for a ‘neuro *g*’, (Haier et al., 2009), a neurological correlate that would be, or fully capture, intelligence. Yet, despite many studies, the relationship between intelligence and the various proposed ‘neural correlates’ remains unclear. In chapter four, I represent various competing hypotheses concerning the relationship between *g* and the brain as statistical models, in order to empirically compare theoretical accounts. As in chapter two, I find that a formative model, within which a disjunctive sum of brain properties together (partially) determines general intelligence, best represents the data.

The first chapters were concerned with how to best statistically relate brain measurements to psychological measurements, in an attempt to relate two explanatory levels. In chapter 5, I take a broader look at issues that can arise when making inferences that cross explanatory levels. Specifically, I examine the example of Simpson’s Paradox (Simpson, 1951). Simpson’s Paradox occurs when, within the same dataset, a statistical pattern at the group level (e.g. ‘a positive correlation between coffee intake and neuroticism’) is reversed in subgroups (e.g. ‘for both women and men, there is a negative correlation between coffee intake and neuroticism’). Simpson’s paradox occurs when inferences are drawn that cross explanatory levels, such as from groups to subgroups or from subgroups to individuals over time. On the basis of simulations and experimental work (showing that people are not well-equipped to recognize the fallacy) and a review of cases of Simpson’s paradox in psychology and adjacent fields, I conclude that Simpson’s Paradox is, in all likelihood, under diagnosed in the literature. Simpson’s paradox is instrumental in illustrating that our intuitive inferences can easily be led astray, especially when attempting to relate different explanatory levels. I address this problem by providing a variety of solutions for preventing the occurrence of Simpson’s Paradox. I provide a custom-made R-package (Kievit & Epskamp, 2012, see Appendix B) that can automatically detect the presence of subgroups in data and control inference appropriately.

In chapter 6, I discuss a different approach to integrate behaviour and the brain: The study of representational geometry. In the framework of representational geometry, a neural or psychological representation can be considered as a point in a high-dimensional space. This space can be defined

either in terms of inherent properties of the measurement (e.g. the number of voxels measured, or the number of scales a person has to rate a stimulus on) or inferred by means of techniques such as Multi-Dimensional Scaling (Kriegeskorte & Mur, 2012). Within this space, stimuli can be compared and contrasted in terms of various metrics including (dis)similarity and multivariate clustering. By defining representations of stimuli in such a space, a direct comparison between neural and psychological representations becomes possible. This makes it a powerful way to relate brain to mind, by abstracting away from the low-level details whilst retaining relevant information. In this chapter, we review the basis of this technique, show how it has informed various cognitive domains and show how it can be used to compare individuals and groups. Finally, we briefly discuss how representational geometry can be used to test identity theory in a novel way, by abstracting away from the idiosyncrasies of individual brains. We show how the tools of representational geometry can be used to represent type-type, type-token and token-token identity theory in a new way, and that this representation offers a richer picture of identity theory than certain traditional perspectives.

In chapter 7, I examine the relationship between brain function and fluid intelligence. The study of fluid intelligence can focus on two dimensions: Differences between people (in ability) and within people (in difficulty). Many papers on this topic have conflated these two dimensions, despite the fact that they are not necessarily related: The (neural) dimensions that differentiate between people of varying ability need not be similar to the neural networks that are differentially recruited within individuals when performing tasks of increasing complexity. I show how two dimensions of fluid intelligence, the inter-individual differentiating between people and the intra-individual differentiating between more or less challenging fluid intelligence tasks, can be simultaneously modelled using a so-called Rasch model (Rasch, 1960). By using both dimensions as predictors, we show that the neural networks associated with the two dimensions in the brain are quite distinct. However, the two dimensions also show partial overlap in a focal subset of regions. We introduce the term *neural ergodicity* to denote regions of the brain that show differential activity both as a function of individual differences and as a function of intra-individual differences across the same dimension. In the discussion I discuss remaining challenges and further avenues for further statistical modelling of reductive theories.