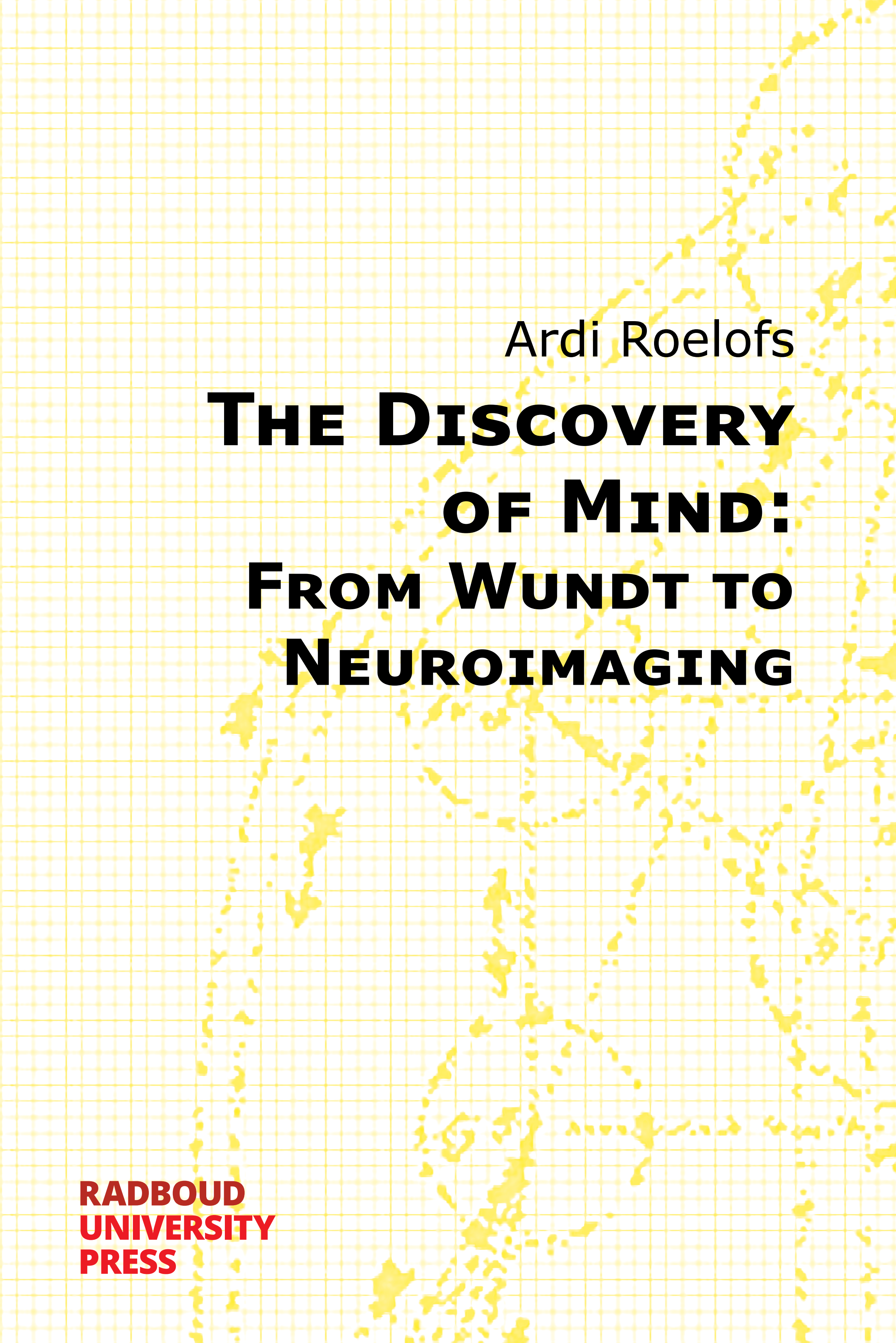

Ardi Roelofs

The Discovery of Mind: From Wundt to Neuroimaging

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Published by RADBOUD UNIVERSITY PRESS
Postbus 9100, 6500 HA Nijmegen, The Netherlands
www.radbouduniversitypress.nl | www.ru.nl/radbouduniversitypress
radbouduniversitypress@ru.nl

Design: Textcetera
Print and distribution: Pumbo.nl

ISBN: 9789493296794
DOI: 10.54195/RAWG9704

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To Herman and Pim,
my teachers regarding history

Preface

This short monograph is a brainchild of 16 years of teaching the Theoretical Psychology course at Radboud University in Nijmegen, taken by approximately 6,500 students. The course focused on the empirical research and psychological theorizing that has been done in scientific societies and universities over the past 200 years, since the philosophical armchair was replaced by the laboratory. The course gave me an alibi to delve into the history of psychology and related fields and to read many original books, articles, manuscripts, letters, and handwritten notes from pioneers. I discovered that, surprisingly, the work of one of the founders of scientific psychology, Wilhelm Wundt, has been largely forgotten, despite its relevance to contemporary psychology. This book is intended to tell the story of the scientific discovery of the mind, recognizing Wundt's groundbreaking work. I synthesize crucial evidence from past behavioral and patient studies to recent neuroimaging to support an integrated account of key aspects of the human mind.

The year 2024 marks the 200th publication anniversary of Pierre Flourens' *Recherches Expérimentales sur les Propriétés et les Fonctions du Système Nerveux, dans les Animaux Vertébrés* and the 150th of Carl Wernicke's *Der aphasische Symptomencomplex: Eine psychologische Studie auf anatomischer Basis* and Wundt's *Grundzüge der physiologischen Psychologie*, which historian Edwin Boring (1950) called "the most important book in the history of modern psychology" (p. 322). Wundt's book is the vantage point for my story about the scientific discovery of the mind. My book's cover shows part of Wundt's diagram of the mind on a pixel array used to create neuroimages.

The book is gratefully dedicated to Pim Levelt and Herman Kolk, who wrote their own history books (Kolk, 1994; Levelt, 2013) and were mentors throughout my career. In 2008 I took over the History of Psychology course from Herman, in which I had once been a student, and which I transformed into Theoretical Psychology. Pim made me aware of the three handshakes between Wundt, Michotte, himself, and me, and much more.

Over the years I have received feedback from students and colleagues about my account of the history of psychology and theoretical view of the mind. The book was written in the inspiring environment of the Centre for Cognition of the Donders Institute for Brain, Cognition and Behaviour in Nijmegen. Irina Chupina, Pim Levelt, Herman Kolk, and two anonymous reviewers read the entire draft manuscript and provided comments. All this has improved my exposition in the book, for which I am very grateful to everyone. I thank my wife Jantine for her encouragement and continued support, and for sitting through all my anecdotes, fun facts, and stories from the book at our breakfast and dinner table.

Ardi Roelofs,
Cuijk,
March 18, 2024

Prologue

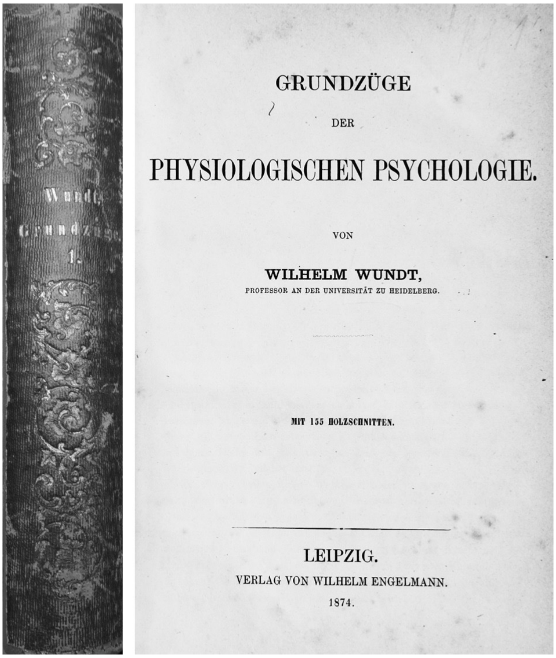
This book briefly describes the history of the scientific discovery of the mind. Although people have speculated about the nature and functioning of their minds for thousands of years, it was only about 200 years ago that they began to investigate the mind scientifically. In this book, I describe the most important empirical and theoretical discoveries that have been made and where we are today in understanding the mind.

In their critically acclaimed book *The Organisation of Mind*, published in 2011, Tim Shallice and Richard Cooper stated: “Sixty years ago, virtually nothing scientific was known about the general organisation of the mind” (p. 2). According to them, “It was in the period 1950-70 that the first major developments occurred” (p. 4). But as I make clear in this book, Shallice and Cooper were wrong by 150 years. They mistook a revival for the beginning.

The scientific study of basic abilities of the mind, such as perception, movement, attention, learning, memory, language, thinking, emotion, and motivation, is called *cognitive psychology*, which is the backbone of psychology. Other branches of psychology, like clinical, developmental, and social psychology, and larger disciplines like *cognitive science* and *cognitive neuroscience* draw on methods and insights from cognitive psychology. Ulric Neisser, who coined the term in his book *Cognitive Psychology* in 1967, discussed visual and auditory perception, attention, memory, and thinking with regard to the adult rather than the developing or disordered mind. However, cognitive psychology has not begun in the 1960s. Rather, Neisser’s book aimed to present an alternative to behaviorism, which dominated American psychology in the first half of the 20th century and repressed an older cognitive psychology that began with Wilhelm Wundt (1832-1920) in the second half of the 19th century.

Figure P.1. Wundt's house in Großbothen, where he completed his memoirs and passed away.

When 88-year-old Wundt dictated the last words of his memoirs to his daughter Eleonore in his country house in Großbothen near Leipzig, a week before his death in 1920, he could look back on a successful life. Half a century earlier, he had laid the foundation for psychology as a scientific discipline, with its own place in the university curriculum, its own laboratories, and its own journals. Together with his 188 doctoral students in Leipzig, he had made important scientific discoveries and developed a comprehensive theory of the human mind. His students had initiated application areas such as clinical psychology and psychological testing and founded new journals such as *Science*. His work was nominated three times for a Nobel Prize. But after his death, Wundt and his work were quickly forgotten, and he came to be seen as an "icon of a dead and failed past", as noted by Blumenthal (2001, p. 142), who went to great lengths to rehabilitate Wundt (e.g., Blumenthal, 1975, 1976). When many of Wundt's findings were rediscovered after World War II, they were associated with the names of the rediscoverers and not with Wundt. His theory has also been redrafted by others, without knowledge of Wundt's original proposal. What is now called cognitive neuroscience includes the field of science at the intersection of physiology and psychology that Wundt proclaimed the birth of 150 years ago, but in which Wundt's name is rarely mentioned.



GRUNDZÜGE
DER
PHYSIOLOGISCHEN PSYCHOLOGIE.

VON

WILHELM WUNDT,
PROFESSOR AN DER UNIVERSITÄT ZU HEIDELBERG.

MIT 155 HOLZSCHNITTEN.

LEIPZIG.
VERLAG VON WILHELM ENGELMANN.
1874.

Figure P.2. Spine and title page of (the author's copy of) the first edition (1874) of Wundt's *Grundzüge*.

In the preface to the first edition of his book *Grundzüge der physiologischen Psychologie* (*Principles of Physiological Psychology*), which appeared in 1874, Wundt stated:

> The work that I am hereby making available to the public attempts to define a new area of science. … In some cases, even the anatomical-physiological foundations of the discipline being studied here are not at all certain, and the experimental treatment of psychological questions is still in its early stages. (p. iii)

In my book, I discuss major empirical discoveries that have been made, and theory building that took place, in the few decades before and in the 150 years after the publication of Wundt's 1874 book, with special emphasis on his work. Compared to previous philosophical speculations about the mind, the new scientific theories were better supported by empirical findings and made new predictions that could be empirically tested and possibly refuted. Theoretical issues were resolved in cycles of empirical research, which is the hallmark of the *scientific method*. The scientific method and ways of discovery are described, for example, in Popper's (1959) *The Logic of Scientific Discovery*, Simon's (1977) *Models of Discovery and Other Topics in the Methods of Science*, and Wundt's (1880a, 1883) *Logik: Eine Untersuchung* *der Principien der Erkenntniss und der Methoden wissenschaftlicher Forschung* (*Logic: An Examination of the Principles of Knowledge and the Methods of Scientific Research*). In a world of uncertainty, superstition, and pseudoscience, the scientific method is the most reliable "candle in the dark" (Sagan, 1997). Importantly, researchers started doing experiments. As Spearman (1923) stated: "The great modern point of vantage is the experimental procedure, long the chief tool of the physical sciences, and now last brought by Weber, Fechner, and Wundt – in rising order of genius – to the aid of mental science also" (p. 34). Replication and extension of empirical findings and the incremental development of theories led to cumulative advances in understanding the mind. The emphasis in my book is on developments in areas central to contemporary cognitive psychology and which were main interests of Wundt and his students, namely the organization of the mind, attentional control, consciousness, and intelligence. Along the way, fundamental mental functions such as perception, movement, attention, learning, memory, language, thinking, emotion, and motivation are discussed.

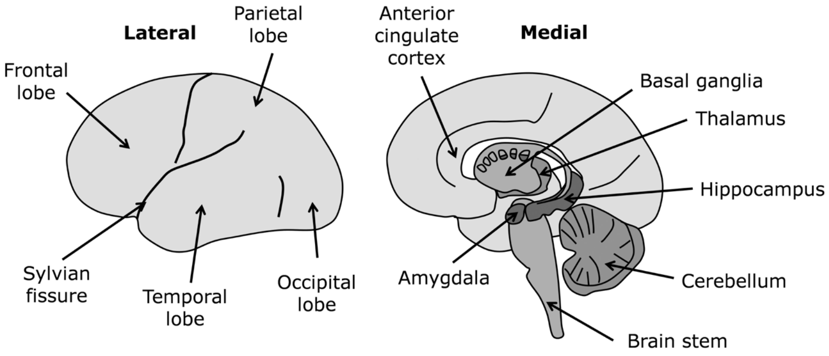


Figure P.3. Lateral and medial views of the human brain, the biological organ of mind, showing the major lobes of the cerebral cortex, the anterior cingulate cortex (part of the frontal lobe), basal ganglia, thalamus, hippocampus, amygdala, cerebellum, and brain stem. A fifth lobe, the insular cortex, is folded deeply into the Sylvian fissure and is not visible from the side. The named parts of the brain are the most relevant ones for this book.

When discussing mental functions, I often make reference to the human brain, the biological organ of mind (Figure P.3). Over the past 200 years, all major theories have been *materialist*, assuming that the mind is what the brain does, in contrast to *dualistic* theories that have dominated the past, such as Descartes' (1664). Dualist theories assume that the mind and brain are fundamentally different substances (e.g., Berrios, 2018). Materialism does not imply that the mind is explicable purely in physiological terms. Instead, a dominant view today is that the mind should be characterized in functional terms (e.g., Dennett, 1981, 2023). Yet evidence from brain anatomy and physiology can be used to constrain and clarify theories in functional terms, as argued by Wundt.

When Wundt used the term ‘physiological’ in the title of his *Grundzüge* in 1874, the intention was clear to his contemporaries, namely to designate an empirical, experimental psychology as an independent scientific discipline rather than as a branch of speculative philosophy, as psychology had been for thousands of years. According to Wundt, physiological psychology wants to utilize physiology as an auxiliary discipline to psychology. In the following decades, however, the adjective ‘physiological’ took on a different meaning, namely reducing psychology to physiology, as, for example, Sigmund Exner (1846-1926) attempted to do in his *Entwurf zu einer physiologischen Erklärung der psychischen Erscheinungen* (*Design for a Physiological Explanation of Psychological Phenomena*) in 1894. Therefore, in the fifth edition of the *Grundzüge* published in 1902, Wundt clarified his use of the term ‘physiological’. He stated that physiological psychology is “primarily psychology … It is neither a branch of physiology nor, as has been misleadingly claimed, does it seek to derive or explain the psychological phenomena from the physical phenomena of life” (p. 2). Instead, the name ‘physiological psychology’ indicates two objectives:

> Insofar as physiological psychology is based on physiology in the development of experimental methods, it is *experimental psychology* … Of the two missions thus indicated in the name of physiological psychology, the *methodological* one, which points to the *use of experiments*, and the *complementary* one, which points to the *physical foundations of mental life*, the first is the more essential for psychology itself. (pp. 3-4)

In line with the Wundtian neurocognitive goal of linking cognitive functioning to structures and processes of the brain, Marr (1982) argued that a complete understanding of cognitive processes requires that they be characterized at three levels. A theory should describe what the mental processes aim to achieve, how the processes are functionally organized, and how the functions are implemented in the brain.

While behavioral measurements in healthy participants and lesion-deficit analyses in patients with brain damage have informed theorizing about the mind since the early days of scientific psychology, the range of techniques has expanded considerably since World War II (e.g., Raichle, 1998). From then on, researchers not only conducted behavioral and patient studies but also began to make use of neurophysiological methods. These methods were designed to measure brain *function* (which was considered a reflection of the mind) rather than structure (i.e., neuroanatomy). Electroencephalography (EEG) was already used in the 1940s and 1950s (Schirmann, 2014) and became an important research tool in the study of mental processes from the 1960s (e.g., Coles, 1989; Meyer et al., 1988). Furthermore, the arsenal of physiological techniques has been expanded even more since the 1980s to include magnetoencephalography (MEG) and hemodynamic methods. EEG measures the brain's electrical activity from outside the skull and MEG records magnetic activity, which has been used since the 1990s. Hemodynamic methods include positron emission tomography (PET), used since the 1980s, and functional magnetic resonance imaging (fMRI), since the 1990s. PET uses radioactive tracer to measure local blood flow, energy metabolism, or specific neurotransmitters. The fMRI method measures the blood oxygen-level-dependent (BOLD) response which reflects local ratios of oxyhemoglobin versus deoxyhemoglobin, indexing neuronal activity.

The spatial resolution of the hemodynamic methods is good (typically a few millimeters in fMRI), but the temporal resolution is limited (a few seconds in fMRI and about 40 seconds in PET). Conversely, the temporal resolution of electrophysiological methods is good (a few milliseconds), but the spatial resolution is limited (several centimeters in MEG and more in EEG). In addition to the functional methods, *structural* methods create images of brain anatomy. For this purpose, computed tomography (CT) uses X-rays (Röntgen) and MRI uses strong magnetic field gradients and radio waves. While for a long time, the 3D course of fiber tracts could only be determined by postmortem microdissection, nowadays, diffusion tensor imaging (DTI) in combination with tractography software can be used in the living brain. DTI measures the movement of water molecules along axons. These functional and structural techniques are collectively called *neuroimaging* (e.g., Banich & Compton, 2023; Gazzaniga et al., 2018; Op de Beeck & Nakatani, 2019). Modern neuroimaging can be seen as an extension of the methods of 19th-century physiological psychology, which aimed to investigate the causal mechanisms of mind and brain.

However, some people have argued that functional neuroimaging results do not show causal involvement but only correlation. For example, R. Sternberg (2005) stated, "Biological approaches seem to have a certain attraction for suggesting a causal mechanism … But they really are not attractive, because the existing data are all correlational" (p. 243). However, the idea that functional neuroimaging studies do not demonstrate causal involvement is incorrect (e.g., Weber & Thompson-Schill, 2010). This is because these studies typically use experimental manipulation, which is the gold standard for testing causal involvement. As Woodworth (1938) put it, "The experimentalist's independent variable is antecedent to his dependent variable; one is cause (or part of the cause) and the other effect" (p. 3). What neuroimaging methods such as fMRI, PET, and MEG cannot show is whether an area or process is necessary, which can only be demonstrated in patient studies (with patients in the acute phase) or by using brain stimulation methods. These methods include direct electrical stimulation (DES) during awake brain surgery in patients and transcranial magnetic stimulation (TMS) applied noninvasively through the skull to the brains of healthy participants.

Empirical research forms the basis for theory development. Today, theory building uses not only diagrams or mathematical formulas, as theorists did in Wundt's time, but also computational modeling. A computer model represents a concrete implementation of a proposed theory that can be rigorously tested to assess whether its assumptions are necessary and sufficient to explain the observed data. For example, while Wundt (1903) *qualitatively* examined frequency distributions of reaction times to evaluate his theory of attention, such distributions can be derived mathematically or approximated stochastically in computer simulations, and it can be statistically determined whether they correspond *quantitatively* to the empirically observed distributions (e.g., San José et al., 2021). While Wernicke (1874) explained aphasia syndromes resulting from brain damage by showing that they can be informally "computed according to the laws of combination" (p. 69) using a diagram, both the symptoms and the amount of damage in different brain areas can be inferred quantitatively for large numbers of individual patients in modern computer models (e.g., Roelofs, 2023a). It should be noted that to be useful, models must simplify reality. Illustrating the necessity of simplification, Borges (1964) described cartographers who constructed a map as large and detailed as the land itself, capturing most of reality but being completely useless. In his seminal *Beiträge zur Theorie der Sinneswahrnehmung* (*Contributions to the Theory of Sense Perception*), Wundt (1862a) emphasized the importance of mathematical tools for psychology. He stated: "Where in a science a large number of facts can be derived from a few axioms through a series of more or less complicated inferences, without the simple procedures of formal logic being sufficient for this derivation, then science is forced to use mathematical symbol language" (p. xix). Such symbol language is at the heart of modern computational modeling.

The goal of my book is threefold. First, I want to describe some of the most important discoveries about the mind over the past 200 years, showing that the first major developments took place in the first half of the 19th century and making it clear that much was known about the general organization of the mind well before the mid-20th century, contrary to what Shallice and Cooper (2011) claimed. Shallice and Cooper are not alone in suggesting that the scientific discovery of the mind began after World War II. In his book *Attention in a Social World* (2012), Michael Posner stated:

> The idea of neural networks as the basic units underlying thought goes back to the work of the Canadian neuropsychologist D. O. Hebb and his 1949 book *The Organization of Behavior*. … In Hebb's time, the idea of a network (cell assembly or phase sequence) was a rather vague verbal abstraction that did not allow for models that could produce specific predictions. (pp. 2-3)

However, several of Hebb's ideas about cell assemblies can already be found in Exner's *Entwurf* from 1894 and his other publications (e.g., Verstraten et al., 2015). Furthermore, in 1874, Wernicke published his epoch-making network model of word production and comprehension, and their breakdown in aphasia, which provided testable predictions. Wernicke's view foreshadowed modern ideas about multiregional cell assemblies (Gage & Hickok, 2005). Similarly, Wundt had put forward a network model of attentional control in the various editions of the *Grundzüge*, also a precursor of modern ideas (Roelofs, 2021). Neither Hebb nor Posner referred to the work of Exner, Wernicke, and Wundt.

Second, I want to show that the physiological approach proposed by Wundt in his *Grundzüge* of 1874 has been and continues to be fruitful (e.g., Dehaene, 2023; Peelen & Downing, 2023). That is, physiological methods can be used to illuminate the mind, contrary to the claims of skeptical voices in contemporary psychology who have argued against neuroimaging as a means of studying the mind in principle or in practice (e.g., Coltheart, 2006, 2013; Page, 2006; Pereira, 2017; Uttal, 2001; Van Orden & Paap, 1997). Knowing the mind's functional neuroanatomy is considered useful, contrary to what Fodor (1999) wrote: "If the mind happens in space at all, it happens somewhere north of the neck. What exactly turns on knowing how far north?" (p. 3). I make clear that knowing the spatial coordinates of mental processes can contribute to their understanding.

Third, I want to demonstrate the feasibility of an integrative theoretical account. Recently, Beller and Bender (2017) argued that theory is "the final frontier" in psychology. Their analyses of all 2,046 articles in *Frontiers of Psychology* in 2015 showed "references to a specific (named) theory in less than 10% of the sample and references to any of even the most frequently mentioned theories in less than 0.5% of the sample" (p. 1). From these and other analyses, it becomes clear that psychology considers empirical findings more important than theory. In contrast to this practice, I argue for a strong role of theory development and testing of alternative theories. Data cannot live without theory. As Gigerenzer (1998) wrote:

> Several years ago, I spent a day and a night in a library reading through issues of the *Journal of Experimental Psychology* from the 1920s and 1930s. This was professionally

> a most depressing experience. …What depressed me was that almost all of this work is forgotten; it does not seem to have left a trace in the collective memory of our profession. It struck me that most of it involved collecting data without substantive theory. Data without theory are like a baby without a parent: their life expectancy is low. (p. 202)

In *The Modularity of Mind*, Fodor (1983) suggested that only perceptual and motor systems can be scientifically understood, while central systems are beyond reach. Against this claim, I show that central abilities of the mind, such as attentional control, consciousness, and intelligence, can be understood theoretically and that an integrative explanation is possible.

In the introduction to his book on attention, Posner (2012) stated: "The present volume is largely a personal statement. It does not seek to review all studies or controversies in the field, but rather to lay out … one [i.e., his] approach to understanding the attention system of the human brain" (p. *xix*). Similarly, John Duncan's *How Intelligence Happens* (2010) is a personal account of what intelligence is and how it is underpinned by the brain. Likewise, in this monograph, I do not intend to provide a comprehensive overview of the history of psychology, but only a selection of crucial discoveries and insights, and a demonstration that an integrated account is possible. I also regularly refer to research done by myself or with colleagues because it is relevant as well as to demonstrate my credentials to write about these topics. In *A History of Modern Experimental Psychology* (2007), George Mandler wrote, "I avoid anything as recent as the last two decades – and it will be some time before a history of this period can be written from a more objective point of view" (pp. 225-226). Mandler's book, therefore, does not describe the modern advances in neuroimaging that illuminated the mind. Now, 20 years later, my book addresses these modern developments.

There are different approaches to historical description (e.g., Donnelly & Norton, 2021). For example, Benjamin (2007, 2024) described how academic psychology emerged and became professionally organized, especially in the US, and how areas of application became established. Mandler (2007) focused more on psychological ideas and the social and political conditions under which they were developed, and Danziger (1990) described the development of psychological methods in their historical context. In my book, I describe the history of the empirical and theoretical discoveries that led to what we know today about the mind, the debates that arose from them, and the different approaches. Decisions about which facts and events to include in the book were based on their relevance to the history of discoveries that led to our current understanding of the mind.

In my historical research, I have used primary sources (i.e., original books, articles, manuscripts, letters, and handwritten notes of pioneers) as much as possible. All translations from German and French were done by myself unless otherwise stated. The original texts can be found in the Open Science Foundation folder for my book at https://osf.io/57za4/.

With a fresh look at historical sources, I explain what has been discovered about how the mind is organized, how it controls itself, what consciousness is, how intelligence arises, and how the mind can deteriorate due to harm, such as stroke and neurodegeneration. In these areas, I also explain what the main modern neuroimaging techniques have taught us about the mind so far. Along the way, I wake up a number of "sleeping beauties", as Levelt (2015) called forgotten discoveries. My story also includes some key characters missing from other books on the history of psychology (e.g., Benjamin, 2007, 2024; Brysbaert & Rastle, 2009; Goodwin, 2011; Leahey, 2017; Mandler, 2007), such as Charles Spearman and Carl Wernicke, or whose work is not substantively discussed, such as Wundt. Boring (1950) described the work of Wundt and Spearman, but not Wernicke. I have economized on names, by often repeating names where other names could have been mentioned. Despite that, there are still a lot of names in the book. There is no index of names and subjects because, in the electronic version of the book, any desired word can be searched for using the standard search function.

Before the 19th century, investigators had explored and described the boundaries of the mind. They moved inland about 200 years ago from different starting points, and their reports on what they discovered were largely in agreement, I argue. In this book, four expeditions and their discoveries are described in each of four chapters, followed by a fifth chapter with an integrated account of key aspects of the human mind.

CHAPTER 1

From phrenology to modularity theory

Theories about the human mind have existed since the ancient Greeks, but a scientific understanding of the mind did not emerge until the 19th century, as a fruit of the 18th century Enlightenment. In the early 19th century, seminal scientific investigations were driven by a controversy over mental localization versus holism in the brain, represented by Gall's phrenology and Flourens' equipotentiality idea, respectively. J. Müller assumed mental holism and maintained that processing proceeds at immeasurable speed. Discoveries such as the localization of mental functions in the brain (Broca), the measurable speed of nerve transmission and mental processing (Helmholtz, Donders), and the nature of the relationship between stimulus strength and sensation (Weber, Fechner) provided a truly scientific approach to the mind. The empirical basis necessary for the formation of psychological theories, such as Wernicke's language model, gradually became available. The battle for scientific respectability was not easily won: Early scientific psychology faced competition from pseudoscientific approaches such as spiritualism (one of the founders of scientific psychology, William James, regularly participated in spiritualist séances). The prescientific ideas of associationism and phrenology have given rise to the modern scientific theories of connectionism (Rumelhart, McClelland) and modularity (Fodor, Kanwisher). Recently, the central role of the frontal lobes of the human brain, described by pioneers (Wundt), was rediscovered.

Figure 1.1. In the study of Wundt's apartment at Goethestraße 6 in Leipzig, opposite the opera house, a bust of Aristotle stood on his desk. Much of the city was destroyed during World War II, but the desk and bust survived and can be admired in the Wundt Museum of the University of Leipzig. The photo comes from a Wundt family album, early 20th century.

Prescientific approaches

Already since the ancient Greeks, theories about the human mind have been formulated. The Greek philosopher Aristotle (384-322 BC), esteemed by Wundt (Figure 1.1), assumed that the mind lacks content at birth, being a *tabula rasa*, and is filled by perception (e.g., Hammond, 1902; Mandler & Mandler, 1964). He maintained that the senses of sight, smell, touch, hearing, and taste provide modality-specific *sensory images* that come together in a supramodal mental faculty, called the *sensus communis* or common sense (Gregoric, 2007). There, associations may be formed between modality-specific images, like the taste and shape of an apple. After this, the associated images may be used for thinking and other mental processes or be put in memory. Thus, Aristotle distinguished between *modality-specific* sensory images and *supramodal* mental faculties, which work on the images and associations. The theory that holds that mental processes proceed via associations is called *associationism*.

Aristotle also formulated a number of fundamental laws about association, the most important of which was called the *Law of Contiguity*: If two things repeatedly occur together, then the occurrence of one thing will remind us of the other.

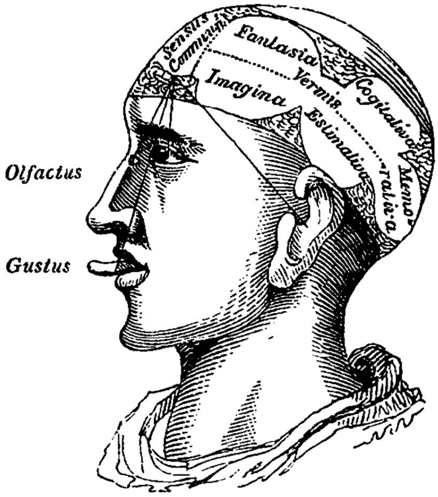


Figure 1.2. Medieval view on the human mind (Dolce, 1562, from *Human Physiology* by John Elliotson, 1840).

Figure 1.2 shows a medieval version of Aristotle's theory of mind. Sensory information about the outside world enters the mind through sense organs such as the eye, ear, nose, and tongue and is combined there by the common sense. As a result, an apple is perceived as a whole consisting of a certain shape and color, and the associated typical smell and taste can be retrieved from memory. Other mental functions can work with the images, for example by using them for reasoning or by storing new associations in memory. The mental functions are of a general nature. Reasoning works the same for apples and faces, and so does memory. Moreover, the functions are localized, here in the brain chambers or ventricles. We now know that these brain chambers are filled with cerebrospinal fluid and serve as cushions (i.e., the ventricles are part of the system that helps protect the brain against trauma, for example during abrupt movements), but at the time it was thought that these chambers housed the mental functions.

The Aristotelian theory of association with serial processing was essentially not elaborated or improved for more than two millennia (e.g., Gregoric, 2007). During this long period of time, thinking about the mind was dominated by religious orthodoxy. But this changed between about 1500-1800 during the Renaissance and the Enlightenment (Jacob, 2019), when the modern scientific method was developed and applied. The *Enlightenment* (which lasted approximately from the mid-17th century to the end of the 18th century) embraced reason and science, typified by the philosopher Immanuel Kant (1724-1804) with the motto "Have the courage to use your own intellect!" (1784, p. 481). Modern scientific psychology is a fruit of the Enlightenment. While some Enlightenment thinkers criticized the ancient theory (e.g., Hobbes, 1651/1909), others built on it (e.g., Locke, 1690).

In his *Leviathan* published in 1651, philosopher Thomas Hobbes (1588-1679) criticized the Aristotelian processing model:

> Some say the Senses receive the Species of things, and deliver them to the Common-sense; and the Common Sense delivers them over to the Fancy, and the Fancy to the Memory, and the Memory to the Judgement, like handing of things from one to another, with many words making nothing understood. (1651/1909, p. 18)

This criticism of a serial processing view of the mind has persisted to this day. The criticism was made by Külpe (1893) on the work of Donders (1868a), which is discussed later in this chapter. More recently, Van Orden and Paap (1997) argued that the success of neuroimaging depends on the seriality assumption, which they rejected, as I discuss in Chapter 2.

Other philosophers built on the Aristotelian view. In 1690, in his *An Essay Concerning Humane Understanding*, the Englishman John Locke (1632-1704) used the ancient association theory as a psychological basis for a philosophical theory on the limits of human knowledge. The philosophical theory that the mind is a *blank slate* (tabula rasa) at birth and that all knowledge is ultimately obtained via the senses is called *empiricism*. The opposing theory that assumes innate knowledge is called *nativism*, which was defended by René Descartes (1596-1650) following the ancient Greek philosopher Plato (427-347 BC).

The association theory of Locke makes four basic assumptions. The first blank slate assumption ("white paper" was the metaphor used by Locke) holds that when we are born, the mind is empty. The second *sensoristic* assumption holds that our senses provide the elementary mental images. The third *atomistic* assumption holds that the elementary sensory images are the building blocks (atoms) for the construction of more complex mental contents. The fourth *associative* assumption holds that this construction is done by association.

Locke's empiricism was criticized by the German polymath Gottfried Leibniz (1646-1716) in a direct response entitled *Nouveaux Essais sur L'Entendement Humain* (*New Essays on Human Understanding*), completed in 1704 but postponed due to Locke's death, and published half a century after Leibniz' own death (Leibniz, 1765/1921). Leibniz' position was summarized in his statement, "*There is nothing in the intellect that was not first in the senses*; except, *the intellect itself*" (p. 70), assuming innate knowledge. Leibniz' book was in French and the statement in Latin. Following Leibniz, Kant (1781) also assumed innate knowledge, including the categories of time and space. Wundt quoted Leibniz' statement in Latin on the title page of his *Beiträge* (1862a), in which he reported on his experimental investigations of sensory perception. However, Wundt did not want to "reintroduce a whole world of innate ideas into the mind, as Leibnitz did" (p. xxxii). Instead, "not the knowledge itself, but only the possibility of obtaining it" was assumed to be innate. Importantly, Wundt's approach was different from that of the philosophers: "When dissecting the processes of perception, I looked for the elementary psychological processes from which they arise, but I did not look for them with the help of metaphysical speculations but with the experimental method of the physiologist" (pp. iv–v). In his philosophical theorizing, Leibniz (1714/1880) made a distinction between unconscious perception and conscious "apperception" (p. 5). In the *Grundzüge* of 1874, Wundt would adopt the term apperception and give it a new psychological twist, which I discuss in Chapter 2. According to Wundt, association as proposed by Aristotle and Locke is supplemented by apperception as a fundamental mechanism of the mind, which he investigated experimentally over the next half-century.

In 1949, Donald Hebb (1904-1985) speculated on the neural basis of the association law of contiguity, that is, Aristotle's observation that the repeated occurrence of things together causes the occurrence of one thing to remind us of another. Hebb proposed that when neurons fire simultaneously, synaptic changes occur. In the 1960s, brain research discovered in the hippocampus of rabbits that such synaptic changes indeed take place. The neural mechanism involved is called *long-term potentiation*, which later appeared to operate throughout the brain (e.g., Eichenbaum & Cohen, 2001).

In modern psychology, associationism is still present under the name *connectionism*, capturing important aspects of the mind, with David Rumelhart (1942-2011) and James McClelland (1948-) as prominent early advocates. An important new addition to the classical associationism of Aristotle and Locke, constituting real progress, is that connectionism formalizes associative networks and processes through mathematical equations in *computer programs*. Computer simulations are run to determine whether the theoretical assumptions explain existing empirical findings and to derive precise predictions that may be tested in new experiments. For example, McClelland and Rumelhart (1981) advanced a computer model of the associative processes that take place when recognizing the visual form of words during reading.

Aristotle and Locke assumed that mental functions are domain-general; that is, they operate in the same way in different content domains. For example, associative memory works the same for domains like language and mathematics. They assumed that perception, memory, and thinking are domain-general faculties of the human mind. The German philosopher Christian Wolff (1679-1754) also posited such faculties in his *Psychologia Empirica Methodo Scientifica Pertractata* (*Empirical Psychology Treated by the Scientific Method*), published in 1732. Domain-general functions are also referred to as *horizontal faculties*, a term coined by Jerry Fodor (1935-2017) in his 1983 book on the faculties of mind. Domain-specific functions are then *vertical faculties*.

In 1927, in his *The Abilities of Man*, Charles Spearman (1863-1945) compiled a list of mental faculties adopted from ancient psychology that continued to be advocated in the literature in the 1920s (33 "prominent publications" had been examined by him). These faculties were, in Spearman's terms:

Sensory perception
Intellect
Memory
Imagination
Attention
Language
Movement

The work and view on the structure of the mind of Spearman (1927) was discussed by Fodor (1983). In reviewing Spearman's list of mental faculties, Fodor wrote:

> Spearman (1927, p. 29) lists seven mental faculties which he claims were traditionally acknowledged: sense, intellect, memory, imagination, attention, speech, and movement. "Any further increase in the number of faculties beyond these seven has, in general, only been attained by subdividing some or other of these." Of the faculties enumerated in Spearman's sensus, only the first five are clearly 'horizontal' in the sense of the present discussion, and 'speech' is a vertical faculty par excellence. This sort of indifference to the horizontal/vertical distinction is … practically universal in the faculty psychology literature, Franz Joseph Gall being … perhaps the only major figure to insist upon it. (p. 130)

In the early 19th century, Franz Joseph Gall (1758-1828) proposed that the mind consists of domain-specific functions only. An early exposition of his theory can be found in Gall (1798), and a full account was published between 1822 and 1825 in the form of six volumes of *Sur les Fonctions du Cerveau et sur Celles de Chacune de ses Parties* (*On the Functions of the Brain and of Each of its Parts*), translated into English in 1835. According to Gall, there is no such function as memory, but there are different memory functions for different domains like language and mathematics. Gall assumed that each domain-specific function has a specific location in the brain (Figure 1.3), the organ of mind, which is called *localizationism*. Gall postulated 27 faculties, including verbal memory, language, number (which was taken to include a "disposition for arithmetic and for mathematics in general"), parental love, location, color, affection, and pride.

All functions were assumed to be bilaterally localized, that is, in a specific location in the left hemisphere and the corresponding location in the right hemisphere. When a function is well developed, it will occupy more space in the brain, that is, the corresponding brain areas are larger. According to Gall, this leads to bumps on the skull. How well a function is developed can be assessed by determining the size of the bump on the skull. This view on the mind and brain is called *phrenology*.

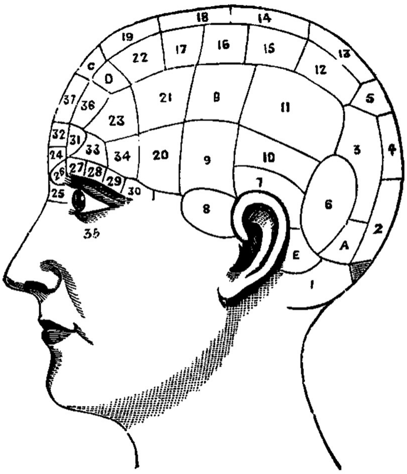


Figure 1.3. Phrenological brain map (from Fowler, 1896). Area 33 houses language and area 28 is the seat of the number sense.

Take, for example, Gall's "Faculty of attending to and distinguishing Words; recollection of Words, or Verbal Memory (Wort-gedächtniss)". Discussing the history of his discovery of this faculty (Gall, 1835, Vol. 5), he tells the story of how, at the age of nine, he noticed that two of his classmates were good at recitation: "Two of my new fellow pupils surpassed even my former companion by their facility of learning by heart. As both had large, flaring eyes, we gave them the nickname of *saucer-eyes*" (p. 8). He then continued:

> I could not have avoided the inference, that eyes thus formed are the mark of an excellent memory. It was not till afterwards, that I said to myself, as I have already mentioned in the introduction to my first volume, if memory manifests itself by an external character, why should not the other faculties have their characters outwardly visible? It was this which gave the first impulse to my researches, and which was the occasion of all my discoveries. (p. 8)

When discussing the "Seat and external Appearance of the Organ of this Faculty", he wrote: "I regard, as the organ of verbal memory, that cerebral part which rests on the posterior half of the roof of the orbit" (p. 11), because growth of this part of the cortex would push the lobe forward and make "the eyeball prominent" (p. 10). However, he also immediately stated a disclaimer, because this same outcome could result from any "considerable development and a great prolongation of this lobe" so that "the form of eyes which results from it, would no longer be the mark of a great memory".

Gall then pointed to a collection of people with good verbal memories, of whom "ninety-nine in a hundred have large, flaring eyes". In the next section, "Of the Memory of Names and of Words, in the State of Disease", he mentioned some cases of illness that affect verbal memory:

> An officer was wounded by a thrust immediately above the eye. He tells me, that since this moment he has had much trouble in remembering the names of his best friends; he had absolutely no knowledge of my doctrine. He does not perceive any debility of his other faculties. (p. 16).

It should be clear from these descriptions that Gall attempted to support his theory with empirical evidence, but the findings remained anecdotal in any case. In addition to a faculty of memory for words, Gall assumed that there existed a "Faculty of Spoken Language; Talent of Philology, etc. (Sprach-Forschungs-sinn)". He wrote:

> When the greatest part of the middle portion of the inferior anterior convolutions, placed on the superior plate of the orbit, or on the roof, is greatly developed … the eyes are at once prominent and depressed towards the cheeks, so that a certain space is found between the ball and the superior arc … Persons who have the eyes thus formed, possess not only an excellent verbal memory, but they feel a peculiar disposition for the study of languages, for criticism; in general, for whatever has relation to literature. (pp. 18-19)

Once again, the evidence Gall discussed in support of this faculty and its seat was collected unsystematically and remained very weak. As a result, Gall's work was generally disapproved by his contemporaries and received a "rotten press", as Fodor (1983, p. 14) put it. Still, the work of Gall can be seen as an early attempt at an empirically based theory of the structure of the mind and its relationship to the human brain (Finger & Eling, 2019).

The discovery of mental localization

The proposal by Gall that domain-specific mental functions are localized in specific areas of the brain was contested by the Frenchman Pierre Flourens (1794-1867), which led to a long-lasting controversy over localization versus *holism*. Working in Paris, as Gall did, Flourens tried to resolve the issue through experimental research. In his book *Recherches Expérimentales sur les Propriétés et les Fonctions du Système Nerveux, dans les Animaux Vertébrés* (*Experimental Research on the Properties and Functions of the Nervous System of Vertebrate Animals*) published in 1824, Flourens described the outcomes of his pioneering ablation experiments in which he made localized lesions to the brains of living dogs, cats, pigeons, rabbits, frogs, and guinea pigs to study their effects on perception, memory, and motor functions. He found functional specialization in that brain stem lesions led to loss of simple movements (*contractions musculaires* and *mouvemens d'ensemble*), lesions to the cerebellum resulted in loss of coordinated movements (*mouvemens coordonnés*), and lesion of the cerebral cortex disrupted higher-level functions, such as voluntary movements (*mouvemens dits volontaires*), perception, and memory. However, he was unable to find specific cortical regions for these functions, which led him to conclude that they are distributed across the entire cerebral cortex (i.e., *cortical* holism), different from what Gall claimed. In Flourens' own words:

> Not only do all sensations, all perceptions, all volitions, all intellectual and sensitive faculties reside exclusively in the cerebral lobes, but all these faculties occupy concurrently and jointly the same seat in these organs: as soon as one of them disappears, all disappear; as soon as one comes back, all come back. The faculty of feeling, of willing, of perceiving, therefore constitutes only one faculty, and resides essentially in a single organ. The cerebral lobes ... can lose a considerable portion, in a specific manner, of their substance, without losing the exercise of their functions: they can reacquire it in its entirety after having lost it completely. (pp. 214-215)

According to Flourens, damage to the cerebral lobes has consequences for all higher mental functions simultaneously, and function recovery does not depend on which part is spared. All parts of the cerebral cortex can perform all mental functions. A century later, in 1929, Karl Lashley (1890-1958) replicated Flourens' observations in maze-learning rats. Like Flourens, Lashley claimed that learning depends on the amount of cortex available, called *mass action*, but not on which parts of it, since any part can take over from any other part, which is called *equipotentiality*.

Approval for Flourens had also come earlier from Berlin. Johannes Müller (1801-1858), one of the founders of modern physiology in the first half of the 19th century, described Flourens' work and also endorsed the holistic view. In his monumental *Handbuch der Physiologie des Menschen für Vorlesungen* (*Handbook of Human Physiology for Lectures*), he wrote:

> Just as it is the property of a specific nerve connected to the sensorium to be able to sense, so it is the property of the brain and the organs of the brain … to become conscious. The mode of becoming conscious is having perceptions, thoughts, and emotions or affections. Nothing entitles us to postulate special organs or regions in the brain for these activities or to assume them as inherent faculties of the soul. … Rather, they are just types of action of one and the same power. (1840, p. 516)

In 1842, in his *Examen de la Phrénologie* (*Phrenology Examined*), dedicated to Descartes, Flourens summarized his case against the phrenological ideas of Gall and others based on the results of his ablation experiments. A major issue, however, was that Flourens' experimental "participants" were nonhuman animals, such as pigeons and rabbits, with different brains and mental functions than humans. This left it unclear to what extent his holistic conclusions applied to the human cortex.

In the 1860s, a key discovery with respect to the localization of higher functions in the cerebral cortex of humans was made by Paul Broca (1824-1880). His seminal observation in 1861 was made on patient Louis Leborgne, who had lost the ability to produce speech after brain damage. In the Bicêtre hospital in Paris, where Leborgne lived for 21 years, he was nicknamed "Tan" because this was all he could say. Speech comprehension was spared. In April 1861, Leborgne was moved to the surgical ward of Broca because of an inflammation of his right leg. When Broca asked him for how many years he had been in the hospital, Leborgne opened his hand four times in sequence and then pointed with a single finger, which would make 21 years. This demonstrated that his speech comprehension was spared. After Leborgne died a week later, Broca examined his brain and discovered damage in the posterior part of the left inferior frontal gyrus, which was apparently responsible for the loss of the ability to produce speech. Based on this observation, Broca rejected Flourens' holism and argued for localization instead, writing that "the localization of a *single* faculty suffices to establish the truth of this principle" (1861, p. 336). Importantly, in the next few years, Broca examined more patients with speech production problems and also patients with no such problem. In only the patients with a speech deficit, damage was in the left inferior frontal lobe; patients with damage to the right frontal lobe showed no speech production impairment. Broca concluded that the ability to articulate speech is localized to a specific area of the human brain, namely the posterior part of the left inferior frontal gyrus, which was later called *Broca's area*. This supported the assumption that higher mental functions are localized in the cortex, different from what Flourens maintained.

Broca did not dissect Leborgne's brain but only assessed observable lesions to the cortical surface. In 1962, the brain of Leborgne, preserved in a glass jar with alcohol, was rediscovered in a cellar of the Paris School of Medicine. Examination of the brain with modern brain imaging by Dronkers et al. (2007) revealed that not only the left inferior frontal gyrus was damaged but also underlying fiber tracts, including the arcuate fasciculus. The same was observed in another patient, Lelong, whose brain was also preserved. Dronkers et al. stated: "Fortunately, Broca had great foresight in preserving these historic brains and in some ways, Leborgne and Lelong can speak to us more eloquently now than they could over 140 years ago" (p. 1441). We now know that damage limited to Broca's area does not lead to long-term impairments in speech production after stroke (Gajardo-Vidal et al., 2021), and that Broca's area can be surgically removed in patients with brain tumors without causing Broca's aphasia (Andrews et al., 2022). Still, direct electrical brain stimulation in 598 patients during awake brain surgery demonstrated speech arrest and word-finding difficulty induced by stimulation of Broca's area (Lu et al., 2021), indicating that the area does play a causal role in production. Given the abundant evidence for a role of Broca's area in normal speech production (e.g., Guenther, 2016; Indefrey & Levelt, 2004; Kemmerer, 2019, 2022), spared brain regions must be able to functionally reorganize to compensate for damage to Broca's area.

While Broca's discovery refuted Flourens' holistic claim about the human cortex, other discoveries disproved it for animals. In 1870, Gustav Fritsch (1838-1927) and Julius Hitzig (1838-1907) published an article about their research on living dogs, in which they applied electricity directly to the exposed cerebral cortex. In doing so, they discovered the motor area of the brain, a vertical strip of cortex at the back of the frontal lobes. Electrical stimulation of different parts of this strip caused muscle contractions of different body parts of the dogs. In a long, convoluted sentence, seen at the time in German science as a virtue but now as a vice, they ended their article concluding:

> It emerges from the sum of all our experiments that by no means, as Flourens and most people after him believed, the mind is a kind of total function of the entirety of the cerebrum, the expression of which can be canceled out as a whole but not in its individual parts by mechanical means, *but rather that certain individual mental functions, probably all of them, for their entry into matter or for their emergence from it are dependent on the circumscribed centers of the cerebral cortex*. (p. 332)

A decade after Broca's seminal observations, Carl Wernicke (1848-1905) discovered in two patients, Susanne Rother and Louise Funke, that *speech comprehension impairment* was associated with damage to the left superior temporal gyrus. Based on his own observation and that of Broca, Wernicke developed an association model of language in the brain.

In 1874, at the age of 26, Wernicke published his model in a 72-pages monograph entitled *Der aphasische Symptomencomplex: Eine psychologische Studie auf anatomischer Basis* (*The Aphasic Symptom Complex: A Psychological Study on Anatomical Basis*). Wernicke wrote his monograph while an assistant physician at the Allerheiligen Hospital (All Saints Hospital) in Breslau, where he would spend much of his career. The monograph was inspired by an earlier six-month stay with Theodor Meynert (1833-1892) in Vienna, where Wernicke was introduced to Meynert's new neuroanatomical work.

Wernicke's model is illustrated in Figure 1.4. Curiously, the model diagram was shown on the brain's right hemisphere in Wernicke (1874) but correctly on the left hemisphere in Wernicke (1880a) and in a reprint of the 1874 monograph in Wernicke (1893). Furthermore, the brain in Wernicke's figure in his 1880a publication was drawn realistically rather than schematically as in his 1874 monograph. My figure shows the model diagram superimposed on the realistically drawn brain. The figure shows the association between the auditory image (A) and the movement image (M) for a word, which are associated with visual (V) and tactile (T) images that form a concept (C). Lichtheim (1885a, 1885b) published a version of the model with the sensory images for concepts (e.g., V and T) combined into a single concept node (C). Lichtheim used the diagram as a teaching tool, as I have done in my Theoretical Psychology course. He wrote: "I have been in the habit of using it for several years past in my lectures, and have found that it greatly facilitates to beginners the mastering of an otherwise very complicated subject" (1885b, p. 438).

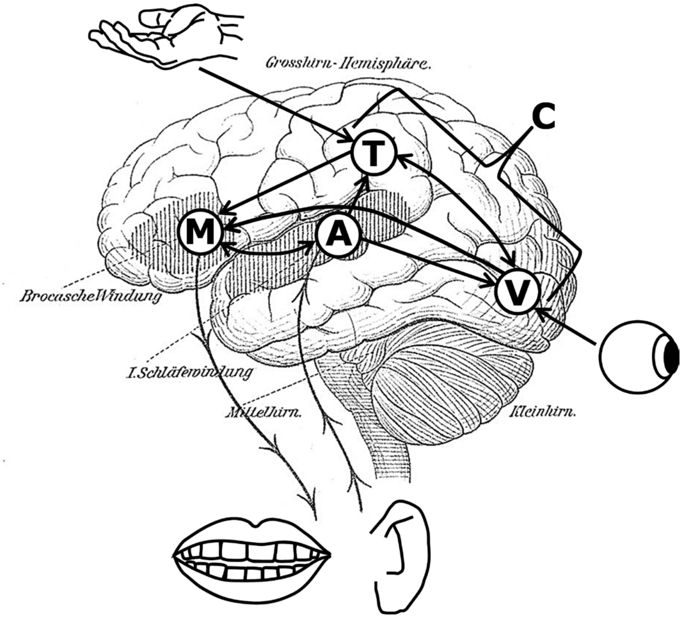


Figure 1.4. Illustration of Wernicke's language model, based on the figure in his 1880a booklet. A = auditory image, M = movement image, V = visual image, T = tactile image, C = concept. Grosshirn-Hemisphäre = cerebral hemisphere; Brocasche Windung = Broca's gyrus; I. Schläfewindung = first temporal gyrus; Mittelhirn = midbrain; Kleinhirn = cerebellum.

At the heart of Wernicke's model are psychological reflex arcs that map sensory images (e.g., A, V, T) in posterior brain areas onto movement images (i.e., M) in anterior areas:

> It suffices ... to explain the spontaneous movement in the manner of a reflex process. Anatomical pathways, which may mediate such psychological reflex actions, exist in abundance; the greater part of the cerebral white matter consists of such bundles of associations, some of which are simple, some of which are more complicated. (pp. 10-11)

Wernicke (1874) held that the only distinction between a reflex movement and a psychological reflex movement, which underlies voluntary action, is that while the former is innate, in the latter there is a learned association between a sensory image and an image of a preformed movement, both of which are memory images (Roelofs, 2024). While a reflex movement immediately follows stimulation, a psychological reflex movement follows the activation of a sensory image. Wernicke assumed that when multiple movement images are activated, the actual movement is determined by the image with the most or strongest associations or associated with the most intense sensory images. He stated: “The only right scientific definition of free will is in perfect agreement with this mechanical view of the origin of spontaneous movement” (p. 12).

According to Wernicke (1874), the left superior temporal gyrus, the posterior part of which was later called *Wernicke’s area*, stores auditory images of words, and Broca’s area stores movement images. The brain areas are connected by a fiber tract, which mediates the association between auditory and movement images so that a person may repeat a heard auditory word. For example, if the word “apple” is heard, the corresponding auditory image for the word *apple* is activated, which in turn activates the corresponding movement image in Broca’s area, so that the word “apple” is pronounced. A heard word also activates its meaning, which is represented by concept images, according to Wernicke. Concept images are the associated sensory images of the object that the word refers to. For example, the concept images of an apple consist of sensory images of its color (e.g., red), taste (e.g., sour), and so forth. For the shape, there are visual and tactile images. This proposal about concepts is nowadays called a grounded view of concepts or *grounded cognition*. According to Wernicke, these concept images are located in different widely distributed areas of the brain (e.g., the color image in visual areas, the shape images in visual and tactile areas, the taste image in gustatory areas), thus the concepts are localized in a distributed fashion across the cortex. In hearing the word “apple”, the auditory image activates the associated concept images, which implies an understanding of the meaning of the word. In having the concept in mind, a person can also produce the corresponding word, which is achieved by activating the movement image that is associated with the sensory images making up the concept of an apple.

Table 1.1. Classic aphasia syndromes according to Wernicke (1886).
A = auditory image, M = movement image, C = concept images.

Aphasia type	Production	Comprehension	Repetition	Disruption
Motor (Broca’s)	X	√	X	$\cancel{M}$
Sensory (Wernicke’s)	√ x	X	X	$\cancel{A}$
Conduction	√ x	√	√ x	$A \cancel{-} M$
Transcortical motor	X	√	√	$C \cancel{-} M$
Transcortical sensory	√ x	X	√	$A \cancel{-} C$

√ = spared, X = impaired

Wernicke (1874, 1886) described how his model explains several types of aphasia, also called syndromes, involving language disorders after brain damage. Aphasia syndromes distinguished by Wernicke and their explanation are listed in Table 1.1. For example, if movement images are disrupted, as in motor aphasia (later called Broca's aphasia), the patient has difficulty producing and repeating words, but word comprehension is relatively spared. If auditory images are disrupted, as in sensory aphasia (later called Wernicke's aphasia), the patient has difficulty comprehending and repeating words, but word production is relatively spared, except that errors (*Paraphasien*) are made. These errors occur, according to Wernicke, because the auditory image no longer sufficiently constrains the selection of the movement image of the word. How exactly the auditory image of a word was activated during word production was unclear from Wernicke's 1874 description, although reverberation of activation between movement and auditory images seemed a likely possibility. This was also Lichtheim's (1885a, 1885b) interpretation of Wernicke's model (for this reason, the relationship between auditory and movement images in Figure 1.4 is bidirectional). In clarifying the issue, Wernicke (1886) proposed a double pathway ("auf doppeltem Wege", p. 373): In word production, concepts activate the corresponding movement image directly as well as indirectly via the auditory images. With disruption of the auditory images, selection of movement images is insufficiently constrained, explaining the paraphasias in sensory aphasia.

If the connection between concepts and movement images is disrupted, as in transcortical motor aphasia, the patient has difficulty producing words, but repetition and comprehension are relatively spared. If the connection between auditory images and concepts is disrupted, as in transcortical sensory aphasia, the patient has difficulty comprehending words, but repetition and production are relatively spared. Errors are made during production, which is to be expected if activation of auditory images from concepts is required to constrain the selection of movement images (Wernicke, 1886), but is now disrupted. Finally, if the connection between auditory and movement images is disrupted, as in conduction aphasia (*Leitungsaphasie*), then errors occur in word production and repetition (done via concepts), but comprehension is spared.

Wernicke (1906) made it clear that tests of the intactness of the association between auditory and movement images require *pseudowords*, which are similar to real words but do not actually occur in the language. This is because a real word can also be repeated by having the auditory image activate the concept, which then activates the movement image. Wernicke's own dissection studies suggested that the fiber pathway connecting the auditory and movement images ran via the insular cortex, but later research revealed that the connection is underpinned by the arcuate fasciculus (e.g., Geschwind, 1972; see Roelofs, 2024, for recent discussion). Wernicke (1874) concluded:

> The proposed theory of aphasia is able to summarize the very different clinical pictures. This diversity itself, which hitherto gave every new observer new riddles to solve, will no longer be noticed; it can even be computed according to the laws of combination. *But what is characteristic of all of them is that they are based on an interruption of the psychological reflex arc used in normal speech processes*. (p. 69)

Following his 1874 monograph on aphasia, Wernicke published two articles, *Ueber das Bewusstsein* (*About Consciousness*) in 1879 and *Nochmals das Bewusstsein* (*Once Again Consciousness*) in 1880, that further explained his ideas about consciousness, which had already been outlined in his monograph. There, he had made it clear that only sensory and movement images are localized, stating:

> The surface of the cerebrum is a mosaic of such simple elements, which are characterized by their anatomical connection with the periphery of the body. Everything that goes beyond these simplest functions, the combination of different impressions into one concept, thinking, consciousness, is an achievement of the fiber masses that connect the different parts of the cerebral cortex with each other. (1874, p. 4)

After linking consciousness to the cerebral hemispheres of the brain with reference to Wundt (1874), Wernicke (1879) rejected Flourens' ideas, stating: "The cerebral cortex is not equivalent everywhere, but circumscribed regions are associated with, say, components of consciousness. As is known, motor and sensory areas have been found" (p. 422). Moreover, he wrote:

> There is no doubt that the content of our consciousness largely comes from the outside world; The impressions that reach us remain stored as memory images at certain end points of the sensory nerves. The first activity of consciousness is that concepts are formed. This assumes that the memory images are linked or, as we usually call it, associated. We also need such associations to understand how spontaneous movements come about. (p. 425)

In Chapter 3, I discuss the discovery in modern neuroimaging studies that activation of sensory areas is necessary but not sufficient for consciousness, contrary to what Wernicke (1874, 1879, 1880c) assumed. Rather, consciousness depends on the activation of specific areas in the frontal and parietal cortex (Dehaene, 2014).

In 1880, Wernicke traveled to Danzig to deliver a lecture *About the Scientific Point of View in Psychiatry* at an annual meeting of German Natural Scientists and Physicians. In this lecture, he discussed his theory of aphasia and placed it in a historical perspective, discussing earlier work by Flourens, Broca, Fritsch and Hitzig, and Meynert. He also proposed extending his anatomical-psychological approach to psychiatric syndromes such as psychosis. Wernicke's lecture has remained under the radar for the past 150 years but was considered important at the time. A written version of the lecture was included in the proceedings of the meeting (Wernicke, 1880b), published as a booklet (Wernicke, 1880a), and simultaneously appeared in five medical journals in the same year (for an introduction and an English translation of the text, see Heckers and Kendler, 2022). In the lecture, Wernicke emphasized the importance of his previous autopsy findings. While it was clear in 1874 that the lesion locus of motor aphasia was Broca's area, the locus of sensory aphasia was still unknown. Referring to the autopsy findings of Rother and Funke, Wernicke (1880a) stated:

> For the second center, which the theory required, the proof that it existed and where one had to look for it, still had to be provided. I have been very fortunate to be able to provide this proof in 1874 in two cases that came to autopsy. (p. 9)

Despite the evidence of localization from Broca, Fritsch and Hitzig, and Wernicke, neurologist Charlton Bastian (1837-1915) remained skeptical of strict localization in his *The Brain as an Organ of Mind*, published in 1880. In contrast, neurologist David Ferrier (1843-1928) was convinced of localization and published a comprehensive review of discoveries in function localization from a wide range of sources, including studies of ablation and electrical stimulation in animals and lesion-deficit analyses in humans. In *The Functions of the Brain* (1886), he reviewed the evidence on the sensory (i.e., visual, auditory, olfactory, gustatory, and tactile) and motor centers in species including cats, dogs, and frogs, as well as monkeys and humans.

Based on literature reports, Exner created quantitative lesion-overlap maps for 167 human patients with brain damage. In his *Untersuchungen über die Localisation der Functionen in der Grosshirnrinde des Menschen* (*Studies on the Localization of Functions in the Cerebral Cortex of Man*) published in 1881, he reported the localizations for movement (i.e., separate for the upper and lower limbs, face, and tongue), sensory perception (i.e., vision and touch), and speech. Figure 1.5 shows the results for patients with language impairment, confirming that aphasic patients often have damage to Broca's area or Wernicke's area. Exner's study is a precursor to modern lesion-overlap examinations that use MRI and voxel-based lesion-symptom mapping (e.g., Forkel & Catani, 2018; Piai & Eikelboom, 2023). This method divides the brain into small volumes (e.g., 2.5 × 2.5 × 2.5 mm), the so-called voxels, and symptoms are related to the damage voxel by voxel.

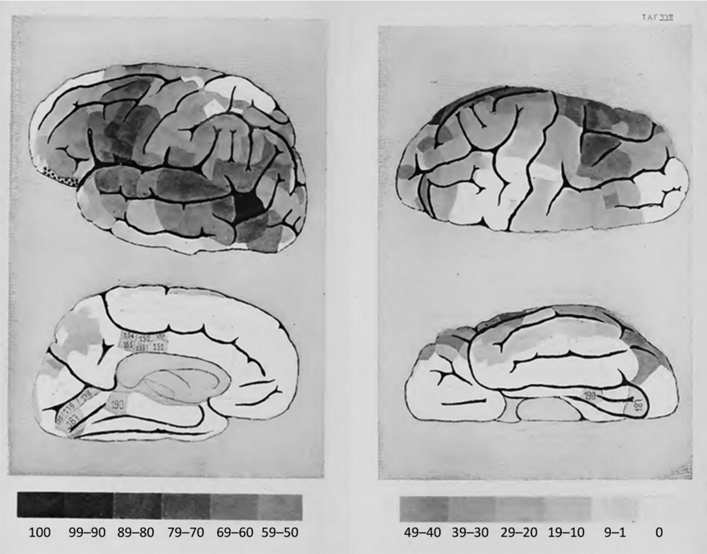


Figure 1.5. Exner's (1881) quantitative lesion-overlap "heat" map for language based on 31 persons with aphasia. The darker the area, the higher the percentage of patients showing damage in that area. For clarity, the numbers on the scale at the bottom have been renewed.

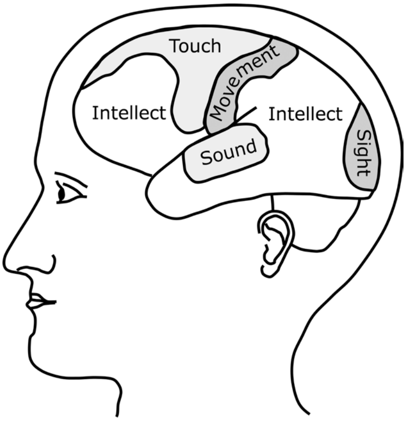


Figure 1.6. Spearman's (1937) diagram of mental faculties and their location in the brain (in Spearman's book shown on the right hemisphere), which aimed to represent the knowledge at the end of the 19th century.

In his *Psychology Down the Ages* (1937), Spearman illustrated the discoveries about the localization of different mental functions in a diagram, shown in Figure 1.6. Of the seven faculties that Spearman (1927) previously distinguished, sensory perception was divided into sight, sound, and touch, and of the other faculties, only intellect and movement were shown. It is unclear what sources Spearman used to construct the diagram. We now know that the movement area (i.e., the primary motor cortex) is in front of the touch area (i.e., the somatosensory cortex) and not the other way around, as the diagram indicates.

The discovery of mental duration

While Broca provided evidence for the localization of aspects of the human mind in anatomical space (i.e., areas of the brain), J. Müller (1835) claimed in his *Handbuch* that processing in physiological time proceeds at immeasurable speed. According to him, "We will probably never gain the means to determine the speed of nerve action, since we lack the comparison of enormous distances from which the speed of a nerve, analogous to the action of light, can be calculated" (pp. 653-654). However, his student Hermann Helmholtz (1821-1894) was skeptical about this claim and tested it empirically (Helmholtz, 1850a, 1850b). To this end, he embedded a motor muscle and nerve of a dead frog in an electrical circuitry that was connected to a clock. Stimulation of the nerve led to contraction of the muscle, which closed the electrical circuitry. The clock indicated the time between stimulation and muscle contraction. By stimulating the nerve at different distances from the muscle, Helmholtz could measure the speed of nerve conduction, which he estimated to be 26.4 meters per second in the frog. Helmholtz concluded that the conduction of the nerve impulse takes time and can be measured, unlike what J. Müller had assumed.

Helmholtz also conducted experiments to measure the speed of nerve conduction in humans. His participants received a weak electrical stimulation at their arm and had to manually respond as soon as they felt the stimulus. By stimulating the arm at various locations from the response finger, he estimated the speed of nerve conduction in humans to be about 61 meters per second. However, he was not very satisfied with this estimate for humans because his results differed from those of others, which ranged between 26 and 94 meters per second. The large variability probably arose because in humans, the stimulus had to be processed by the brain before the finger response could be made, while in frogs, the nerve was directly stimulated and connected to the muscle. In later experiments on humans (Helmholtz, 1867a), the arm was fixed immovable and stimulated in such a way as to evoke an immediate finger response, yielding an estimate of about 34 meters per second, similar to what had been obtained for frogs.

Inspired by the work of his friend Helmholtz, the Dutchman Frans Donders (1818-1889) began a study aimed at measuring the *speed of mental processing*, that is, the processes that so much increased the variance in the experiments of Helmholtz and others. The work was done in Utrecht in the Netherlands. At the beginning of his article about this work, published in 1868, Donders proclaimed:

> We must also recognize that … a complete knowledge of the brain functioning with which every mental process is connected would not bring us any closer to understanding the nature of the connection. … But is any quantitative treatment excluded with regard to psychological processes? Not at all! It seemed that an important factor could be measured: I mean the time required for simple psychological processes. (p. 94)

Donders invented a *subtraction method* to measure the speed of mental processing. He used three types of tasks of increasing complexity. The first task required a *simple reaction*, as in Helmholtz' experiments. The participant had to respond (e.g., by manually moving a lever or making a vocal response) as soon as a stimulus (e.g., a visual or auditory stimulus) was presented. According to Donders, the mental stages involved are sensation and movement. The second task required a *choice reaction*. The participant had to respond by giving one of several responses (e.g., by moving a lever in one of two directions or making one of several vocal responses) as soon as the corresponding stimulus (e.g., one of several visual or auditory stimuli) was presented. According to Donders, the mental stages involved are sensation, discrimination, choice, and movement. The third task required a *go/no-go reaction*. The participant had to respond by giving one response (e.g., by moving a lever or making a vocal response) only when one of several stimuli (e.g., one particular visual or auditory stimulus out of several ones) was presented. The mental stages involved are sensation, discrimination, and movement.

In a crucial experiment, Donders measured the reaction times of speech repetition. For this, he used the *phonautograph* and *noematachograph*, which are illustrated in Figure 1.7. Two participants, A and B, were seated before the mouth of the phonautograph. While the cylinder was rotated by the experimenter, participant A spoke a syllable and participant B repeated it as quickly as possible while trying to make no mistakes. Their speech waves were marked on sooted paper that covered the cylinder. The reaction time is the time interval between syllable onsets (A and B), which Donders deduced by counting the corresponding number of oscillations of a tuning fork recorded simultaneously, irrespective of their length (i.e., a constant speed of rotation of the cylinder is not required). Donders also used the noematachograph to present visual, nonvocal auditory, or tactile stimuli (as he had done in experiments with his daughter and others) and to record the corresponding manual reaction times. To this end, there were two disks on the right side of the cylinder, which were partly covered with brass and partly with ebonite. Pairs of electrodes contacted the discs and induced and stopped an electric current that controlled the presentation of stimuli when the cylinder was rotated.

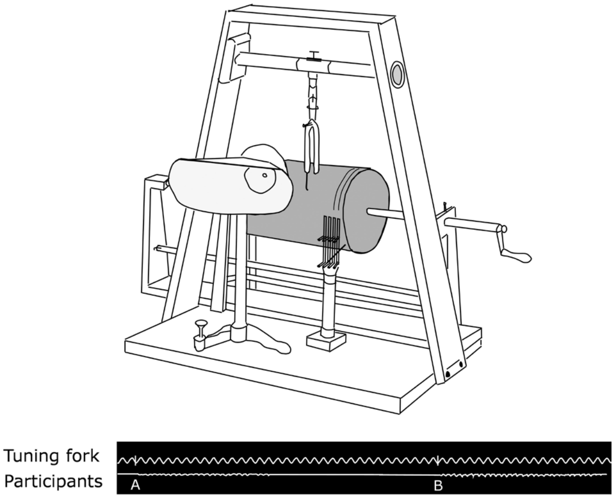


Figure 1.7. Illustration of Donders' phonautograph and noematachograph (top) and the noematachogram (bottom) showing the speech waves of two participants A and B, the sound wave of a tuning fork, and vertical marks indicating the speech onsets for the participants.

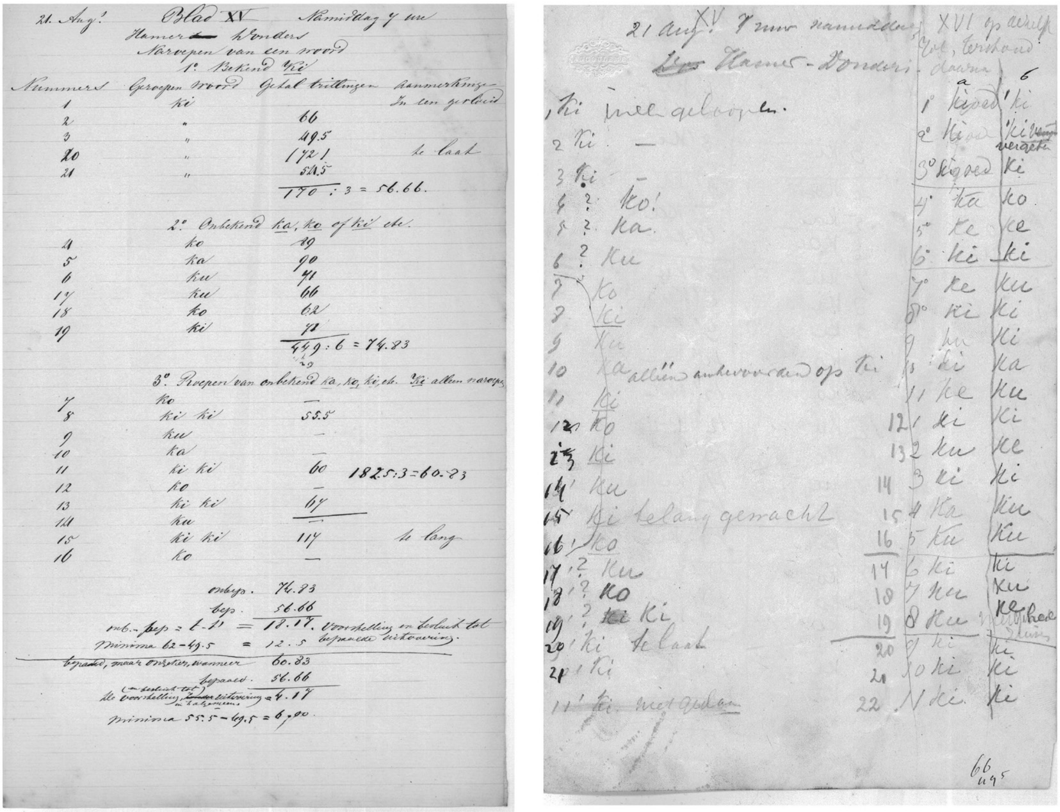
On each simple-reaction trial with the speech repetition task, participant B repeated a known syllable spoken by participant A (e.g., "ki"). On each choice-reaction trial, participant B repeated an unknown syllable spoken by participant A (e.g., "ka", "ke", "ki", "ko", or "ku"). On each go/no-go trial, participant B repeated only a specific syllable spoken by participant A (e.g., "ki"). Donders used lists consisting of 22 stimuli ordered as three simple trials, three choice trials, ten go/no-go trials (with four or five go-trials), three choice trials, and three simple trials. These 22 trials were recorded one after the other on one sheet of sooted paper.

According to Donders, the go/no-go task involves all mental processing stages of the simple task (i.e., sensation and movement) plus discrimination, and the choice task involves all stages of the go/no-go task plus choice. By subtracting the reaction time required by the simple task from that of the go/no-go task, the duration of the discrimination stage was obtained, which was 36 milliseconds. By subtracting the reaction time of the go/no-go task from that of the choice-reaction task, the duration of the choice stage was obtained, which was 47 milliseconds. Based on these observations, Donders made the important conclusion that mental processes take time, which can be measured. Measuring the time required by mental operations to obtain insights into the mind is called *mental chronometry* (Posner, 1978), which is still a dominant method in modern psychology (e.g., Luce, 1986; Medina et al., 2015; Meyer et al., 1988).

At the beginning of 2018, I discovered a complete record of all the reaction time experiments that Donders had conducted in the 1860s in a handwritten notebook of his, dated ca. 1865. The notebook is in the archives of the university museum of the University of Utrecht. Donders' notebook contains not only the raw data and laboratory notes of his classic published experiments but also unpublished raw data of experiments that he had conducted together with his daughter Marie, his good friend William Bowman (as Donders, expert on the human eye), and a number of students. In addition, the notebook contains all the original stimulus lists from the famous "ki–ki" experiments, three of which are illustrated in Figure 1.8 (right).

I decided to replicate the "ki–ki" experiments together with my daughter Sterre (Figure 1.9) using all the original Donders stimulus lists. Instead of Donders' historic device, a microphone and modern software were used for recording the speech and measuring onset latencies. An account of the replication can be found in an article published that same year in the journal *Acta Psychologica* (Roelofs, 2018a). The replication allowed me to examine Wundt's (1874) criticism of the go/no-go task that Donders had used. Wundt's criticism was that, contrary to what Donders had assumed, speech repetition in this task involves a choice, namely whether or not to respond, which is an act of attentional control. If this is the case, this leads to an underestimate of the choice duration when the go/no-go reaction time is subtracted from the choice reaction time.

First, my analysis of unpublished data from Donders (1865) on the repetition performance of his students revealed that the reaction times for the choice and go/no-go tasks may not differ for some participants, supporting the view of Wundt. If the go/no-go task involves a choice, and this choice takes considerable time for some participants, then the reaction times for the go/no-go and choice tasks may be similar for them. Second, my replication of Donders' classic study yielded the same reaction time pattern as Donders obtained for himself (i.e., simple < go/no-go < choice). This indicates that the classic reaction time pattern is replicable. However, my choice



21. Aug. Blad XV Namiddag 7 ure
Hamer ~~—~~ Donders
Naroepen van een woord
1° Bekend Ki

Nummers	Geroepen woord	Getal trillingen	Aanmerkingen
1	ki		In een [illegible]
2	"	66	
3	"	49.5	
20	"	(72)	te laat
21	"	54.5	
		170 : 3 = 56.66.	

2° Onbekend ka, ko of ki etc.

4	ko	89	
5	ka	90	
6	ku	71	
17	ku	66	
18	ko	62	
19	ki	71	
		449 : 6 = 74.83	

3° Roepen van onbekend ka, ko, ki, etc. Ki alleen naroepen

7	ko	—	
8	ki ki	55.5	
9	ku	—	
10	ka	—	
11	ki ki	60	182.5:3=60.83
12	ko	—	
13	ki ki	67	
14	ku	—	
15	ki ki	117	te lang
16	ko	—	

onbep. 74.83
bep. 56.66
onb. – bep. = t – t' = 18.17. Voorstelling en besluit tot bepaalde uitvoering.
minima 62 – 49.5 = 12.5
bepaald, maar onzeker, wanneer 60.83
bepaald. 56.66
de voorstelling, (en besluit tot) ~~zonder~~ uitvoering in 't algemeen = 4.17
minima 55.5 – 49.5 = 6.00

21 Aug. XV 7 uur namiddag
~~[illegible]~~ Hamer - Donders

XVI op [illegible] tot, terstond daarna

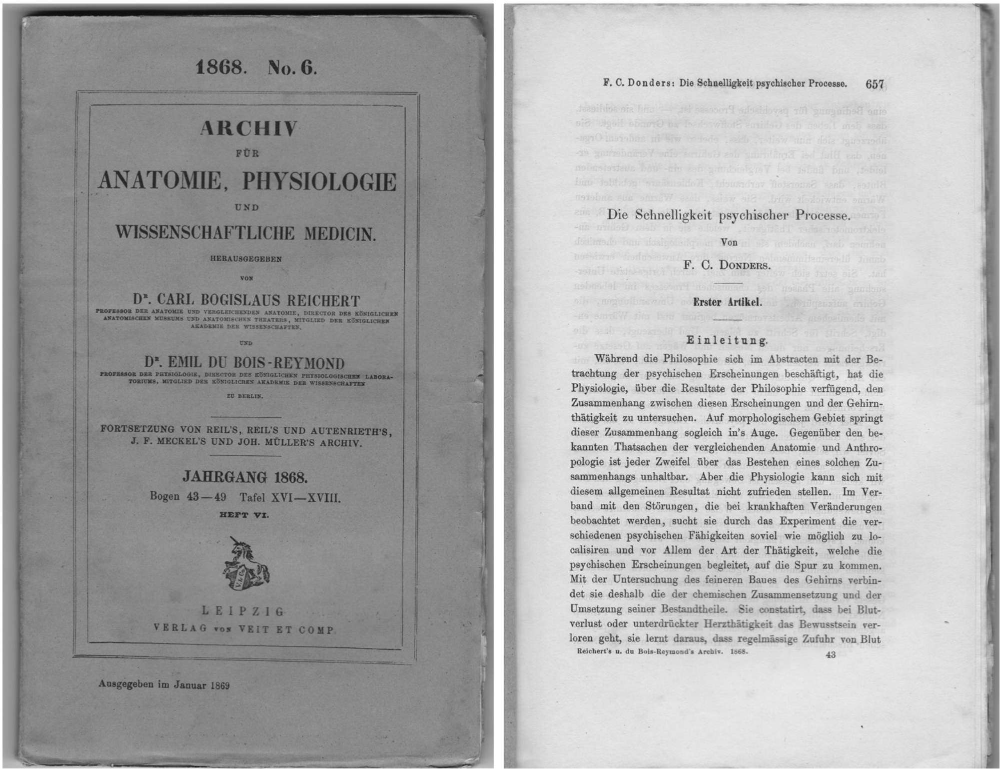
			a	b
1	Ki snel geloopen.	1°	Ki goed	Ki
2	Ki —	2°	Ki goed	Ki vergeten
3	Ki —	3°	Ki goed	Ki
4	? Ko!	4°	Ka	Ko
5	? Ka.	5°	Ke	Ke
6	? Ku	6°	Ki	Ki
7	Ko	7°	Ke	Ku
8	Ki	8°	Ki	Ki
9	Ku	9	Ku	Ki
10	Ka alleen antwoorden op Ki	10	Ki	Ka
11	Ki	11	Ke	Ku
12	Ko	12 1	Ki	Ki
13	Ki	13 2	Ku	Ke
14	Ku	14 3	Ki	Ki
15	Ki te lang gewacht	15 4	Ka	Ku
16	Ko	16 5	Ku	Ku
17	? Ku	17 6	Ki	Ki
18	? Ko	18 7	Ku	Ku
19	? ~~Ki~~ Ki	19 8	Ku	Ke [illegible]
20	Ki te laat	20 9	Ki	Ki
21	Ki	21 10	Ki	Ki
11	~~Ki [illegible]~~	22 11	Ki.	Ki

66
49.5

Figure 1.8. Documentation of reaction times (left) and the associated annotated stimulus list XV (right, leftmost list) in a handwritten notebook by Donders (1865) for an experiment conducted on August 21, 1865 at 7:00 PM.

Figure 1.9. Selfie of the author and his daughter Sterre after repeating Donders' classic experiment in 2018.

duration (choice – go/no-go) was shorter than the discrimination duration (go/no-go – simple), while these were comparable for Donders, suggesting that it took more time for me than for Donders himself to make the go/no-go decision, in line with Wundt's view. Third, my computer simulation using a modern computational model of speech repetition, further discussed in Chapter 5, indicated that the reaction time pattern of Donders (simple < go/no-go < choice) or his students (simple < go/no-go = choice) may be obtained depending on the duration of the go/no-go choice, which was assumed to differ between individuals. Thus, the simulation provided a proof of concept for Wundt's view.


1868. No. 6.

ARCHIV
FÜR
ANATOMIE, PHYSIOLOGIE
UND
WISSENSCHAFTLICHE MEDICIN.

HERAUSGEGEBEN
VON
Dr. CARL BOGISLAUS REICHERT
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ZU BERLIN.

FORTSETZUNG VON REIL'S, REIL'S UND AUTENRIETH'S,
J. F. MECKEL'S UND JOH. MÜLLER'S ARCHIV.

JAHRGANG 1868.
Bogen 43—49 Tafel XVI—XVIII.
HEFT VI.

LEIPZIG
VERLAG von VEIT ET COMP.

Ausgegeben im Januar 1869

F. C. Donders: Die Schnelligkeit psychischer Processe. 657

Die Schnelligkeit psychischer Processe.
Von
F. C. Donders.

Erster Artikel.

Einleitung.

Während die Philosophie sich im Abstracten mit der Betrachtung der psychischen Erscheinungen beschäftigt, hat die Physiologie, über die Resultate der Philosophie verfügend, den Zusammenhang zwischen diesen Erscheinungen und der Gehirnthätigkeit zu untersuchen. Auf morphologischem Gebiet springt dieser Zusammenhang sogleich in's Auge. Gegenüber den bekannten Thatsachen der vergleichenden Anatomie und Anthropologie ist jeder Zweifel über das Bestehen eines solchen Zusammenhangs unhaltbar. Aber die Physiologie kann sich mit diesem allgemeinen Resultat nicht zufrieden stellen. Im Verband mit den Störungen, die bei krankhaften Veränderungen beobachtet werden, sucht sie durch das Experiment die verschiedenen psychischen Fähigkeiten soviel wie möglich zu localisiren und vor Allem der Art der Thätigkeit, welche die psychischen Erscheinungen begleitet, auf die Spur zu kommen. Mit der Untersuchung des feineren Baues des Gehirns verbindet sie deshalb die der chemischen Zusammensetzung und der Umsetzung seiner Bestandtheile. Sie constatirt, dass bei Blutverlust oder unterdrückter Herzthätigkeit das Bewusstsein verloren geht, sie lernt daraus, dass regelmässige Zufuhr von Blut

Reichert's u. du Bois-Reymond's Archiv. 1868. 43

Figure 1.10. Cover of the journal issue and title page of the German publication of Donders' classic 1868 article.

Donders had published his results simultaneously in German, French, and Dutch (i.e., Donders, 1868a, 1868b, 1868c, 1869). The German version appeared in the prestigious *Archiv für Anatomie, Physiologie und wissenschaftliche Medicin* (*Archive for Anatomy, Physiology, and Scientific Medicine*), illustrated in Figure 1.10, a journal founded by J. Müller in 1834. The German article contained a reference to Wundt (a message for him?) in a subordinate sentence that was absent in the Dutch and French versions:

> This was the first determination of the duration of a well-defined psychological process, which seems to me to be missing in Wundt's experiments. It concerned the decision of a dilemma and an act of will corresponding to this decision. (1868a, pp. 665-666)

The Wundt experiments that Donders referred to concerned research into an issue that had troubled astronomers since the end of the 18th century. They had tried to determine the exact time at which a star crossed the wires of a grid in a telescope by relating the crossing to the beats of a clock. One problem was that observers' time estimates did not agree, which was expressed in a "personal equation" that indicated the time discrepancy between two observers. Several researchers attributed this discrepancy to differences in nerve conduction speed between observers, while Wundt argued that it reflected a psychological bottleneck. In an 1862 report of his investigation into the matter (Wundt, 1862b), he wrote:

> Aristotle already asked himself whether we can think two things at the same time. But he was unable to decide this question with certainty, and so it has remained pending for two thousand years. (p. 265)

Using a pendulum that struck a bell upon reaching a preset outer limit, Wundt observed a 1 / 8-second delay between hearing the bell and seeing the pendulum's position on a scale, or vice versa, depending on whether attention was focused on the bell or the pendulum. Wundt concluded that it was impossible to think two things at the same time and that the delay reflected the time of a simple thought.

The manuscript for Wundt's 1862 article has been preserved, as have his handwritten notes (Wundt, 1861/1862). Figure 1.11 (left) shows Wundt's 1861/1862 drawing of a pendulum from his notes, as well as a stylized version that appeared in the 1874 first edition of the *Grundzüge* (right). In closing, Wundt (1862b) quoted Goethe from his *Faust*, in which he compared the mind to a weaver, who is aware of what he makes, but not how: "Where the shuttles dart back and forth, the threads flow unseen" (p. 265). The experiments with the pendulum were mentioned in the *Beiträge* (1862a) and further described in Wundt's (1863) *Vorlesungen über die Menschen- und Thierseele* (*Lectures on the Human and Animal Soul*).

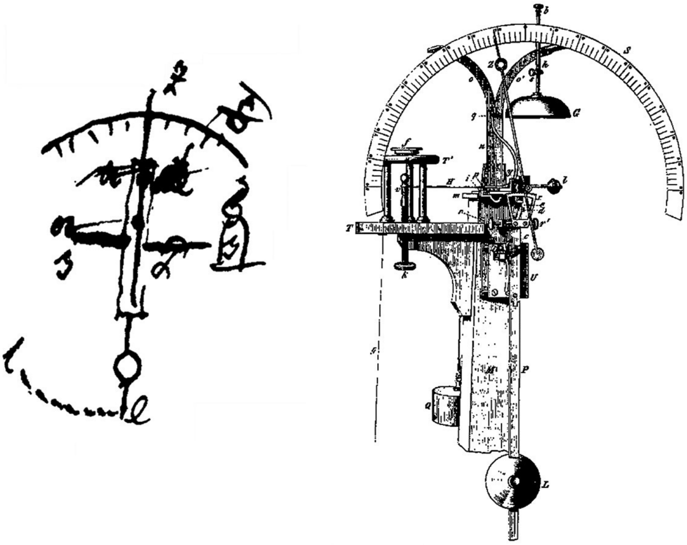


Figure 1.11. Wundt's 1861/1862 drawing of a pendulum from his handwritten notes (left) as well as a stylized version that appeared in the 1874 first edition of the *Grundzüge* (right).

In his handwritten notebook, Donders (1865) rejected Wundt's claim of having measured the time for a simple thought by arguing that "one may wonder whether a thought cannot be broken off in its midst when it is disturbed by a stronger impression. I therefore cannot see Wundt's test as measure for a thought" (p. 40). After reading Donders' 1868 article in the *Archiv*, Wundt adopted the subtraction technique in his research instead of continuing to use the pendulum (for a reaction time study of the pendulum problem in Wundt's lab, see Alechsieff, 1900).

In 1968, on the occasion of the centennial celebration of the work of Donders in the Netherlands, Saul Sternberg (1933-) proposed a related chronometrical method, called the *additive factors method*, that aimed not to estimate the duration of stage durations (as Donders subtraction method did) but to discover mental stages of processing and establish their nature. If different mental stages are involved in performing a task, a combined experimental manipulation of the stages should produce additive effects on reaction time. In support of the method, Sternberg (1969) reported the results of several experiments. In one experiment, participants saw a digit on each of a series of trials and had to decide as quickly and accurately as possible whether the digit was part of a small, memorized set of digits. Set size and response type were manipulated, among other factors. The memorized set consisted of one, two, or four digits, and the response could be positive or negative by pulling one lever or another. It was expected that set size influences the duration of a memory scanning stage and response type the duration of a choice stage. Sternberg observed additive effects of set size and response type. The difference in reaction time between one and four memorized digits was about 100 milliseconds, regardless of response type, and negative responses were about 45 milliseconds slower than positive responses, regardless of set size. For example, negative responses for four memorized digits were approximately 145 milliseconds (i.e., 100 + 45 milliseconds) slower than positive responses for one memorized digit. This result supports the assumption that memory scanning and response choice are separate processing stages.

Sternberg's (1969) additive factors method has been used extensively in subsequent reaction time research (see, for example, Sanders, 1998, for a review). Furthermore, the method has been extended for use in neuropsychology (Coltheart, 2011) and EEG studies (e.g., Anderson et al., 2016; Meyer et al., 1988).

The discovery of psychophysical relationships

Whereas the work of Broca and Donders located the mind in space and time, work by Weber and Fechner precisely described the relationship between physical stimulus strength and psychological sensation. Both researchers worked in Leipzig, Germany. In 1846, Ernst Weber (1795-1878) published the monograph *Der Tastsinn und das Gemeingefühl* (*The Sense of Touch and the Common Sensibility*), in which he reviewed his experimental work and findings on the sensation of touch. To determine the just noticeable difference in the sensation of pressure on the skin, he consecutively and repeatedly placed two small weights in the hands of participants, who were not allowed to look at the weights, until they could indicate which of the two weights was the heaviest. He found that the smallest noticeable difference between two weights is proportional to the weights, later called *Weber's Law*, which is expressed by the formula

$$\frac{\Delta R}{R} = k$$

In this formula, R stands for *Reiz*, the German word for stimulus, and it indicates the first weight. Moreover, ΔR indicates the extra weight that is needed for the second weight so that the difference can be sensed (i.e., the just noticeable difference). Finally, k is a constant (which is different for each sense). $\Delta R / R = k$ can be rewritten as $\Delta R = k \times R$. Weber found that $k = 1 / 30$ for weights. For example, if the first weight is 30 grams, the ΔR needs to be $1 / 30 \times 30 = 1$ gram, so the second weight should be 31 grams. If the first weight is 60 grams, the *ΔR* needs to be 1 / 30 × 60 = 2 grams, so the second weight should be 62 grams. And if the first weight is 90 grams, the *ΔR* needs to be 1 / 30 × 90 = 3 grams, so the second weight should be 93 grams.

In the 1850s, Gustav Fechner (1801-1887) surmised that Weber's observation on how sensed heaviness increases with the weight of the stimulus implies that all just noticeable differences are subjectively equal, which mathematically would produce a logarithmic relation between stimulus strength and sensation. This is called *Fechner's Law*, which is expressed by the formula

$$S = k \log R$$

In this formula, *S* stands for Sensation, *R* for Reiz (stimulus), and *k* is a constant (which is different for each sense). Fechner first published his law in 1860 in the book *Elemente der Psychophysik* (*Elements of Psychophysics*). The law is illustrated in Figure 1.12. The figure illustrates that the difference between 30 and 60 grams (Δa) versus 60 and 90 grams (Δb) is physically the same (Δa = Δb) but psychologically different (Δa > Δb). This is because the difference between 30 and 60 grams corresponds psychologically to 30 × *ΔR* (which for 30 grams is 1 gram), whereas the difference between 60 and 90 grams corresponds psychologically only to 15 × *ΔR* (which for 60 grams is 2 grams).

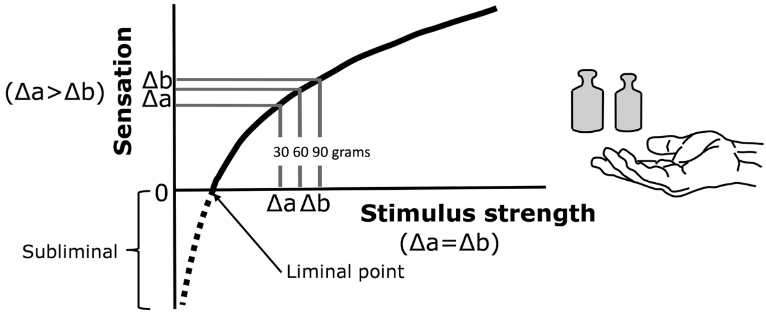


Figure 1.12. Illustration of Fechner's law.

Stimuli need to have a certain minimal strength to be sensed at all. In Fechner's terminology, there is an absolute lower threshold (*Schwelle*, p. 238) on the horizontal physical axis that stimulus strength needs to exceed for the stimulus to be noticed (i.e., for the value on the vertical psychological axis to be larger than zero). Later, the threshold was called the *liminal point* or the *limen of consciousness* (Boring, 1950; Woodworth, 1938). If a weight is too small (i.e., subliminal), a person cannot sense the weight. However, this does not necessarily imply that the brain cannot process the stimulus. Interestingly, the psychophysical curve of Fechner implies subliminal sensation (Boring, 1950), an issue that is further discussed in Chapter 3 on consciousness.

Today, it is believed that the exact relationship between stimulus strength and sensation is not logarithmic, but, as Stanley Stevens (1906-1973) proposed in 1957, a power function, which is closely related. This is a theoretical refinement that does not detract from the contributions of Weber and Fechner.

State of the art in the 1870s

Discoveries like the localization of mental functions in the brain (Broca), the speed of nerve transmission and mental processing (Helmholtz, Donders), and the nature of the relationship between physical stimulus strength and psychological sensation (Weber, Fechner) established the basis for a real scientific approach of the mind. Also, they showed that quantification of the mind is possible. Wundt had personally known several pioneers. After graduating as a doctor of medicine from Heidelberg in 1856, he went to Berlin to study briefly with J. Müller. From 1858 to 1863, back in Heidelberg, Wundt was an assistant to Helmholtz. Weber and Fechner became colleagues of Wundt after he moved to Leipzig in 1875 for a professorship. In his memoirs, Wundt (1920a) wrote:

> That I was privileged to get to know the two men in Leipzig whose work influenced my own psychological studies more than any other I could name, Ernst Heinrich Weber and Gustav Theodor Fechner, I have always viewed as a special favor of fate. … Ernst Heinrich Weber was called by Fechner, who was a few years younger than him, the "father of psychophysics". I am doubtful that this name is accurate. In any case, the creator of psychophysics is Fechner himself. But I would rather call Weber the father of experimental psychology. From the standpoint of our psychology today, this is considerably more, but it is definitely something completely different. (p. 301)

Since the 1870s, psychologists have built on the foundations laid by the pioneers. However, psychology's struggle for scientific respectability was also often undermined by pseudoscientific forces, such as the strong interest in spiritualism of Harvard professor William James, one of the founders of modern psychology (his work is discussed in the next chapter). Spiritualism involves the belief that certain gifted individuals, called mediums, can communicate with the spirits of the dead. In the next chapters, I describe how scientific psychology developed from the 1870s onward in the areas of attentional control, consciousness, and intelligence. But before I indicate what happened to the work of the pioneers in these fields, I discuss the fate of the localization versus holism controversy in modern times.

Modularity of mind

Between 1900 and 1950, psychologists lost interest in the issue of the localization of mental functions in the brain, resulting in a dormant period for this issue. Lashley's holism was the dominant view. In his *The Organization of Behavior* (1949), Hebb expressed this prevailing belief in stating that "about the only localization of a higher function that has so far been achieved is that of the so-called speech area. … No other localization of function in the human cerebrum has been established" (p. 284). Moreover, "although the frontal lobe is the favorite place in which to localize higher functions when one is speculating about these matters, it is still true that there is no proof that any single higher function depends on this part of the brain" (p. 286). However, after World War II, evidence against Hebb's claim accumulated (e.g., Badre, 2020; Dehaene, 2014, 2023; Duncan, 2010; Posner, 2012; Posner & Raichle, 1994; Shallice, 1988; Shallice & Cooper, 2011), pointing instead to a crucial role of the frontal lobes in central processes of the mind. In his *From Neuropsychology to Mental Structure* (1988), Tim Shallice (1940-) provided an extensive discussion.

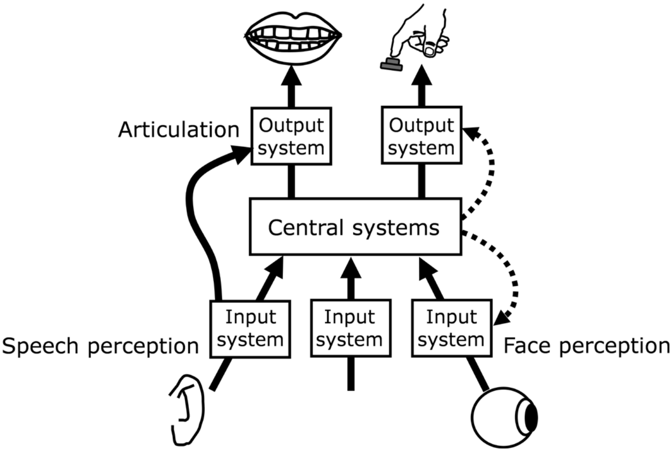


Figure 1.13. A general hybrid horizontal/central and vertical/input-output view of the mind. The dotted lines denote top-down influences, such as attentional control.

Important for the change in view on localization was the revival of Wernicke's work by the neurologist Norman Geschwind (1926-1984) in the 1960s and 1970s (e.g., Geschwind, 1965, 1972), which postulated specific brain localizations for auditory and movement images for words as well as for modality-specific sensory images making up concepts. Consciousness and thought, which operate with the concepts, had been holistically connected by Wernicke (1874, 1879, 1880c) to the "fiber masses" of the entire cortex. In 1983, Fodor published the book *The Modularity of Mind: An Essay on Faculty Psychology*, in which he proposed a similar combination of the historical theories of localization of Gall and holism of Flourens. According to Fodor, the human mind consists of localized modular systems, which were taken to be vertical faculties, and holistic central systems, which are horizontal faculties. A general hybrid mental architecture that combines horizontal and vertical faculties is illustrated in Figure 1.13. In Fodor's own words:

> There is some historical irony in all this. Gall argued from a (vertical) faculty psychology to the macroscopic differentiation of the brain. Flourens, his archantagonist, argued from the unity of the Cartesian ego to the brain's equipotentiality … The present suggestion is that they were *both* right. (p. 118)

According to Fodor (1983), "neural equipotentiality is what you would expect in systems in which every process has more or less uninhibited access to all the available data" (p. 127). Global, holistic computation "comports naturally with neural isotropy (with what Lashley called "equipotentiality" of neural structure) in much the same way that informational encapsulation comports naturally with the elaboration of neural hardwiring" (p. 118). Fodor also noted the similarity between his view on the architecture of the mind and that of Wernicke:

> Wernicke, committed localizationist though he was in respect of the language mechanisms, held that only "primary functions … can be referred to specific areas … All processes which exceed these primary functions (such as the synthesis of various perceptions into concepts and the complex functions such as thought and consciousness) are dependent upon the fiber bundles connecting different areas of the cortex" … Wernicke's picture is not very different from the one that we've been developing here. (p. 138)

However, the assumption that central systems are holistically related to the cortex is not the only theoretical option. An important alternative is for central systems to be localized in circumscribed brain areas that are extensively connected to the rest of the brain, so that information from different content domains and modalities can be shared and used to control thought and action. One such area is the prefrontal cortex, as argued by Wundt (1880b, 1902). From the second edition of the *Grundzüge* onward, published in 1880, Wundt proposed a view of the mind consisting of modality- and domain-general central systems, which he associated with the frontal lobes, and localized modality-specific input and output systems, as Wernicke proposed for language. Wundt assumed that central processes include top-down attentional control over the input and output systems, as illustrated in Figure 1.13. Thus, Wundt, unlike Flourens and Fodor, assumed that the modality- and domain-general central systems are localized, which is consistent with the modern evidence (e.g., Badre, 2020; Dehaene, 2014, 2023; Duncan, 2010; Kanwisher, 2010; Posner, 2012; Posner & Raichle, 1994; Shallice, 1988; Shallice & Cooper, 2011). Fodor's view is discussed below, and Wundt's in the next chapter.

While central systems are nonlocalized domain-general faculties (Flourens), according to Fodor, modules are localized domain-specific faculties (Gall). Fodor mentioned nine characteristics for the domain-specific faculties or modules. He discussed input or perceptual modules, such as modules for face or speech perception, but others like John Marshall (1939-2007) have extended Fodor's view to include output or movement modules (e.g., Marshall, 1984), such as modules for the articulation of speech and manual movements. According to Fodor, modules (1) are domain specific, (2) their operation is mandatory, (3) there is only limited central access to the mental representations that modules compute, (4) modules are fast, (5) they are informationally encapsulated, (6) they have superficial outputs, (7) they are associated with a fixed neural architecture, (8) their development exhibits a characteristic rate and sequence, and (9) they exhibit specific breakdown patterns.

Consider, for example, a face perception module. Reviews of the various basic facts about face perception, which support the modular view, can be found in Dobs et al. (2023), Muukkonen et al. (2020), Simion and Giorgio (2015), Tsao and Livingstone (2008), and Young (2018). The system is *domain specific* because it processes faces but does not process other visual objects like tables or written words. The system works *mandatory* because it is triggered into operation by any stimulus that satisfies the basis properties of a face. There is only limited central access to the intermediate representations that the system computes because people can report on the output, a face, but not on the intermediate processing steps and representations. The system is *fast*; a face is immediately seen as a face, and people do not need to think about this long. The system is *informationally encapsulated* because it only has knowledge about the visual shape of faces. Any other knowledge about the rest of the world is not available. As a result, even though people know that a smiley is not a real face (this is knowledge in their central systems), they cannot help but see it as a face because the system provides that as an output. The system has a *shallow output*, namely a representation of the visual properties of a face, not about who it is (this information may become available in a central system by relating the seen face to other information in long-term memory). The system is associated with a *fixed neural architecture*; namely, it is located in the fusiform gyrus, with the face area usually being larger in the right than left hemisphere of the brain. The fusiform gyrus, also called the lateral occipitotemporal gyrus, is located between the hippocampus and surrounding, and the inferior temporal gyrus. The *development* (ontogeny) of the face perception system exhibits *a characteristic pace and sequencing*. The ability is already present in babies and is fully developed in adolescence. Finally, the system exhibits *specific breakdown patterns*, because damage of the system or its connection with the central systems gives rise to a specific impairment called *face blindness or prosopagnosia*.

The neurologist Oliver Sacks (1933-2015) reported on face blindness in his book *The Man Who Mistook His Wife for a Hat* (1985). The title of the book refers to a patient who no longer could distinguish between faces and other objects, like hats. This suggests that in this patient, the face perception module itself (computing the "what") was damaged. Sacks himself suffered from another type of face blindness: He could distinguish faces from other objects but could not identify persons by their faces (Sacks, 2010). This suggests that he had a weak connection between his face perception module and the central systems, where the face could be associated with other information in long-term memory (computing the "who"). When Sacks gave a party, he asked his friends to wear name tags so that he could still identify them by reading their names. The distinction between a disturbance of perception versus that of the association of percepts with other knowledge was first made by Wernicke's student Lissauer (1890), who described a patient with the second, association disorder.

Regarding Donders' simple, choice, and go/no-go tasks, input systems are concerned with sensation and discrimination, while central systems are concerned with choice (necessary for choice and go/no-go tasks, but not for the simple task), and output systems deal with movement, such as a vocal or manual response. Input and output modules may be directly linked with each other (as illustrated in Figure 1.13). For example, as Wernicke claimed (Figure 1.4), a module for speech perception is directly linked to a module that deals with articulation. With this direct link, and without mediation by central systems, a person may repeat the speech that is perceived as a sort of mental reflex, or parroting, without understanding what is said – being a speaker of English only, it can be used to repeat, for example, Russian or Chinese speech. Direct links between modules can also be learned in an experiment, such as a link between face perception and a button-press reaction, which can be used in a simple-reaction task.

Fodor (1983) assumed that modules are autonomous in an *informational* sense, leaving open whether they are autonomous in a *computational* sense. Processing components are informationally encapsulated if they operate only with limited knowledge, being narrow-minded experts in linking specific inputs to specific outputs. Processing components are computationally autonomous if they run entirely on their own resources and do not compete for shared (i.e., horizontal) means, such as attention and memory. Fodor wrote:

> For Gall, if I read him right, the claim that the vertical faculties are autonomous was practically equivalent to the claim that there are no horizontal faculties for them to share. … Now, it is unclear to what extent the input systems *are* autonomous in *that* sense. … In a nutshell: one way that a system can be autonomous is by being encapsulated, by not having access to facts that other systems know about. I am claiming that, whether or not the input systems are autonomous in Gall's sense, they are, to an interesting degree, autonomous in this informational sense. (pp. 72-73)

The properties of mandatory operation and informational encapsulation of Fodorian modules are reminiscent of an earlier account of perception by Helmholtz. In his *Handbuch der physiologischen Optik* (*Handbook of Physiological Optics*), Helmholtz (1867b) argued that perception involves "inductive inferences carried out unconsciously" ("unbewusst vollführte Inductionsschlüsse", p. 449). He proposed

> to describe the psychological acts of ordinary perception as unconscious inferences. … these unconscious analogical inferences occur with compelling necessity, precisely because they are not acts of free conscious thinking, and their effect cannot be cancelled out by better insight into the context of the matter. (p. 430)

According to Helmholtz, unconscious inferences can, therefore, lead to perceptual illusions that cannot be corrected by conscious reflection:

> That we cannot get rid of the illusion despite our better insight … is because the induction is formed by an unconscious and involuntary activity … appearing to our consciousness as a foreign, compelling natural force. (p. 450)

According to Fodor (1983), the involuntary operation of modules makes it likely that we can gain a scientific understanding of them, which is supported by research over the past 150 years (from Fechner, Donders, Wernicke, Wundt, and many others, to Dehaene, Duncan, Kanwisher, Posner, Shallice, and countless others). In contrast, Fodor believed that central systems are not really open to scientific inquiry, stating:

> I should like to propose a generalization; one which I fondly hope will some day come to be known as 'Fodor's First Law of the Nonexistence of Cognitive Science'. It goes like this: the more global (e.g., the more isotropic) a cognitive process is, the less anybody understands it. *Very* global processes, like analogical reasoning, aren't understood at all. (p. 107)

However, in assessing the scientific progress made in understanding central processes in the 35 years since the publication of Fodor's book, Murphy (2019) showed that Fodor's claim has been falsified by advances in areas such as decision-making and analogical reasoning.

In fact, in 1983, the same year that Fodor's *Modularity* book was published, John Anderson (1947-) already proposed a theory of central systems, implemented as computer programs, in his book *The Architecture of Cognition*. Anderson (1983) assumed that central processing involves cooperation between three memory systems called declarative, procedural, and working memory. These memory systems are further discussed in Chapter 2. Retrieval of factual knowledge from declarative memory ("knowing that") in the form of structured symbolic representations is achieved by applying knowledge from procedural memory ("knowing how") in the form of IF-THEN (condition-action) rules. These rules refer to symbolic representations and goals in working memory, such as: IF the goal is to add $x + y$ THEN retrieve $x + y = z$ from memory and answer z. These assumptions together characterize a *production system*. The theoretical properties of production systems are further discussed in Chapters 2 and 3. In 2013, Chris Eliasmith, in his book *How to Build a Brain: A Neural Architecture for Biological Cognition*, provided a theoretical account of how structured symbolic representations and IF-THEN rules can be realized by networks of spiking neurons.

In contemporary psychology, Nancy Kanwisher (1958-) argued, based on functional activation in neuroimaging studies, that there are modules for the perception of places, faces, visual words, body parts, and for attributing thoughts to others (e.g., Kanwisher, 2010). She claimed that in autism, the thought attribution module is disrupted. Kanwisher also assumed the existence of domain-general central systems, which she argued are localized in specific areas of the frontoparietal cortex, as she made clear in an article with Ev Fedorenko and John Duncan (Fedorenko et al., 2013). According to Kanwisher, and in contrast to Fodor, central systems are not holistically distributed but localized in specific parts of the brain. Evidence for a modular organization also comes from modern research using various graph-based clustering methods that examined functional and structural connectivity in the brain (e.g., Bullmore & Sporns, 2012; Meunier et al., 2009). Compared to global connectivity, modularity reduces the cost of neural wiring and increases processing efficiency. Analyses by Bullmore, Meunier, and colleagues showed that local modules are linked via "connector hubs", predominantly in frontal cortex, supporting the view that the mind is composed of localized modular and central systems. Cole et al. (2012) provided evidence that the "global connectivity of prefrontal cortex predicts cognitive control and intelligence". In particular, lateral prefrontal cortex "is a global hub with a brainwide influence that facilitates the ability to implement control processes central to human intelligence" (p. 8988), which was further supported by evidence from Cole et al. (2015).

In *What Babies Know* (2022), Elizabeth Spelke (1949-) argued that the mind is equipped at birth with localized systems of core knowledge about objects, places, numbers, shapes, agents, and social partners. These domain-specific systems of encapsulated knowledge provide the basis for later learning and, using the unique human capacity for language, for integration in support of domain-general knowledge.

Other theorists in modern psychology, such as Carruthers (2006), defended the Gallian view that the mind consists only of a large number of semi-independent modules (the brain as a "Swiss army knife"), known as *massive modularity*. In his bestseller *The Language Instinct* (1994), Steven Pinker (1954-) also defended massive modularity, proposing a list of putative innate modules, somewhat similar to Gall's inventory. In addition to language and perception, Pinker's list included intuitive mechanics, biology, and psychology, number, mental maps, habitat selection, danger, food, contamination, monitoring of well-being, a mental Rolodex, self-concept, justice, kinship, and mating.

At the other end of the continuum of theoretical possibilities, some theorists, such as Uttal (2001) in his book *The New Phrenology*, have argued for domain-general processing distributed throughout the brain, claiming that "the brain represents cognitive processes in a highly distributed and interactive manner. The idea that these processes can be precisely localized … is fundamentally incorrect" (p. 217). Uttal maintained that the attempt to locate cognitive processes in the brain is fraught with philosophical and methodological problems and lacks a taxonomy of mental processes. However, in a book review, Rees (2002) argued that

"Uttal has a tendency to generalise inappropriately; specific problems with interpretation of a single experiment become general assertions that the technique is unable to provide any useful information" (p. 555). The generalization is inherently asymmetrical. As Broca (1861) argued, a single successful localization is sufficient to support the principle, while a failed attempt does not rule out successful others. Moreover, as cognitive neuroscience textbooks demonstrate, good taxonomies of mental processes exist (e.g., Banich & Compton, 2023; Gazzaniga et al., 2018). The *Cognitive Atlas* project by Poldrack and colleagues provides an inventory of correspondences between mental and neural entities and cognitive tasks (Poldrack et al., 2011; Poldrack & Yarkoni, 2016).

Mental faculties are the different functions of the mind that involve fundamentally different mechanisms and are, therefore, expected to be associated with different neural substrates. For example, the modern discovery that attentional control is supported by the frontal cortex, basal ganglia, and cerebellum (e.g., Badre, 2020; Posner, 2012), while declarative memory is supported by the lateral temporal cortex and hippocampus (Eichenbaum, 2012), discussed in the next chapter, indicates that they are different capabilities that cannot be reduced to each other or take over each other's functionalities. Neuroimaging can be expected to illuminate mental faculties.

Candles in the dark

In his memoirs, Wundt (1920a) wrote of his time in Heidelberg that "in the age when there was neither gas nor electric lighting, there was a custom for the lecturer to give each of his attending listeners a candle, which was planted in their place" (p. 239). So, how well the lecture hall was lit indicated the popularity of the lecturer. In the 47 years since 1871, including four years in Heidelberg (1871-1874), one year in Zürich (1875), and 42 years in Leipzig (1876-1917), approximately 11,500 students attended Wundt's psychology lectures (my estimate from a graph in Schlotte, 1973). Wundt was Leipzig's most popular lecturer, filling the university's largest auditorium. For example, the roll sheet of Wundt's course on the history of modern philosophy in the winter semester of 1901/1902 lists about 400 names (Wundt, 2018). "The tall and slender Wundt, clad in black, would deliver his lecture in 'an easy and abundant bass, somewhat toneless' … Titchener remembered. Others remembered his chiselled language and well-prepared experimental demonstrations", wrote Pim Levelt in his 2013 *A History of Psycholinguistics*.

Wundt's voice was recorded in 1918 on an analog shellac disc, which has recently been digitally restored. To hear his voice, listen to Wundt (1918). The recording concerned the closing words of Wundt's inaugural speech for a philosophy professorship in Zurich in 1874. Wundt's repetition of his earlier speech made it clear that philosophy had always remained close to his heart. In his memoirs, Wundt wrote about his life, but he also digressed into long philosophical discussions. This makes Wundt's book fit well on the bookshelf next to the memoirs of philosopher of mind Dennett (2023), entitled *I've Been Thinking: Adventures in Philosophy*. In the 1918 recording Wundt said that awareness of the

> connection between philosophy and science has sometimes been lost in recent times. The individual areas deserve the lesser blame, because it is up to philosophy to maintain the good relationship between the two, between philosophy and science, by taking from the individual areas what they need, the basis of experience, and giving them themselves, which is no less necessary for them, knowledge of the general context of our knowledge.

A year after these words were originally spoken, in 1875, Wundt accepted a professorship in Leipzig, where he began his program of scientific psychology. The next chapter describes some of Wundt's teachings on the mind.

Summary

Ancient speculation (Aristotle and followers) held that information from the various senses is associated with each other in a supramodal mental faculty, from which it can be used for thinking, imagination, and other processes, or stored in memory. In the 19th century, beginning with a controversy over mental localization (Gall) versus holism (Flourens), researchers discovered that mental abilities are localized in the brain (Broca, Wernicke, Fritsch and Hitzig), that the speed of nerve conduction and mental processing can be measured (Helmholtz, Donders, contra J. Müller), and that the relationship between stimulus strength and sensation follows mathematical rules (Weber, Fechner). Today, a dominant view of the mind is that it consists of modality- and domain-general central systems (e.g., thinking, attention, memory) and modality-specific modular input and output systems (e.g., face perception, articulation), all of which are localized in circumscribed areas of the brain (Wundt, Kanwisher, contra Fodor).

CHAPTER 2

Control, a legacy of Wundt and James

According to historians of psychology (Benjamin, 2024; Boring, 1950), scientific psychology began with the founding of Wundt's laboratory in Leipzig in 1879. Inspired by the psychophysical discoveries (Weber, Fechner) and the discoveries on reaction time (Donders), he embarked on an extensive research program investigating the structure and operation of the mind. Wundt's 188 doctoral students, J. Cattell, Külpe, Titchener, and Spearman among them, and their students, such as Woodworth and Thorndike, shaped the formation of modern psychology according to his example. Wundt's descendants not only performed important experimental and theoretical work (Cattell, Titchener, Thorndike, see Chapter 3) but also initiated clinical psychology (Witmer, see Chapter 3) and intelligence tests (Cattell, Spearman, see Chapter 4). Simultaneously with Wundt, significant experimental and theoretical work was performed in Germany by Ebbinghaus and G. Müller, as well as by Külpe and his Würzburg student Watt. Wundt's American counterpart was William James, who published an immensely influential textbook that summarized what was known at the time of writing in the field of psychology. In contrast with Wundt, James had only a few disciples, like Calkins and Hall. In 1913, Watt's work on attentional control gave rise to a significant theoretical controversy between G. Müller and Selz, which is still unresolved in contemporary psychology.

Wundt and the birth of a new discipline

“Experimental psychology began gradually; it did not come about all at once. But there is one event at which experimental psychologists like to set $t = 0$. That was the establishment by Wundt of a physiological psychology laboratory at the University of Leipzig in 1879” (Bolles, 1980, p. 715). It all started with one room but quickly expanded (Figure 2.1). Very much inspired by the psychophysical discoveries of his Leipzig colleagues Weber and Fechner, and Donders’ discoveries on reaction time, Wundt began an extensive research program investigating the structure and operation of the conscious mind. Over the next half-century, he would lay the foundation for psychology as a scientific discipline, with its own place in the university curriculum, its own laboratories, and its own journals.

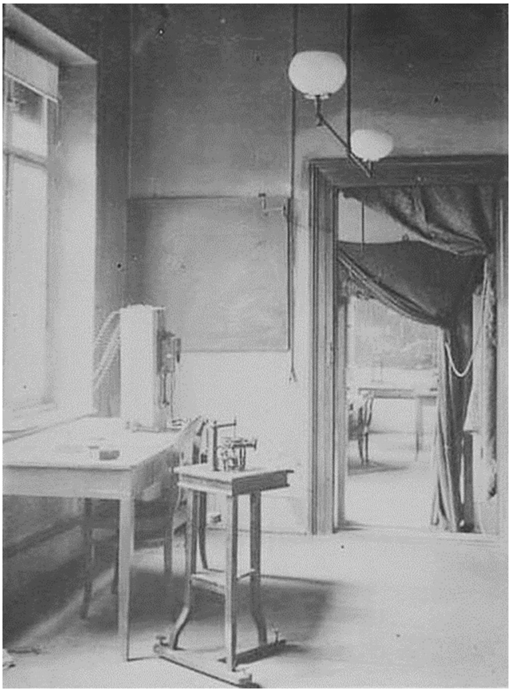


Figure 2.1. Experimental rooms in the Institute for Experimental Psychology of Wundt.

From 1878 to 1911, Wundt and his family lived in Weber’s former apartment in a large university building on Goethestraße in Leipzig. Many colleague professors lived in that building, just a few minutes away from the main classrooms. Wundt’s years in Leipzig are described in detail in David Robinson’s dissertation (1987). Wundt had arrived in Leipzig in 1875 with plans for experimental psychological research, a few pieces of equipment, and a new textbook, namely the first edition of his *Grundzüge*. He was assigned a small unused classroom in the refectory to store his instruments, which he used for demonstrations during his psychology lectures in a lecture hall near the storeroom. From 1879 onward, the room was used to actually conduct experiments, starting with experiments for Max Friedrich's dissertation on the duration of apperception, a notion further explained below. This work was published in 1883 in the first volume of Wundt's own new journal *Philosophische Studien*. That year, Wundt turned down an offer for a professorship in Breslau (where he would otherwise have later become a colleague of Wernicke), and because he agreed to stay in Leipzig, he was granted additional new space for his institute and the listing of a seminar for experimental psychology in the university catalog. From then until Wundt's death in 1920, the institute flourished and dominated scientific psychology. Spearman (1904) described the success:

> To-day, it is difficult to realize that only as recently as 1879 Wundt first obtained from the authorities of Leipsic University one little room for the then novel purpose of a "psychological laboratory". In twenty-four years, not only has this modest beginning expanded into a suite of apartments admirably equipped with elaborate apparatus and thronged with students from the most distant quarters of the globe, but all over Germany and in almost every other civilized country have sprung up a host of similar institutions, each endeavoring to outbid the rest in perfection. The brief space of time has sufficed for Experimental Psychology to become a firmly established science, everywhere drawing to itself the most vigorous energies and keenest intellects. (p. 202)

According to Wundt, experiments were not the only way to scientifically investigate the mind. In studying it, he distinguished between *experimental* and *nonexperimental* approaches (e.g., Wundt, 1896), as he had already done in the *Beiträge* of 1862. In his opinion, an experimental approach based on simple introspection (Weber, Fechner) and measurement of reaction time (Donders) was suitable for elementary mental processes, which he described, together with the knowledge of the brain at the time, in his *Grundzüge* in 1874. A nonexperimental approach involving comparative and logical analyses of the products of the mind, such as language, myth, and custom, was suitable for complex mental processes, which he described in his ten volumes *Völkerpsychologie* (*Cultural Psychology*), published between 1900 and 1920. Figure 2.2 illustrates Wundt's distinction in a diagram from his own handwritten lecture notes for his teaching on psychology.

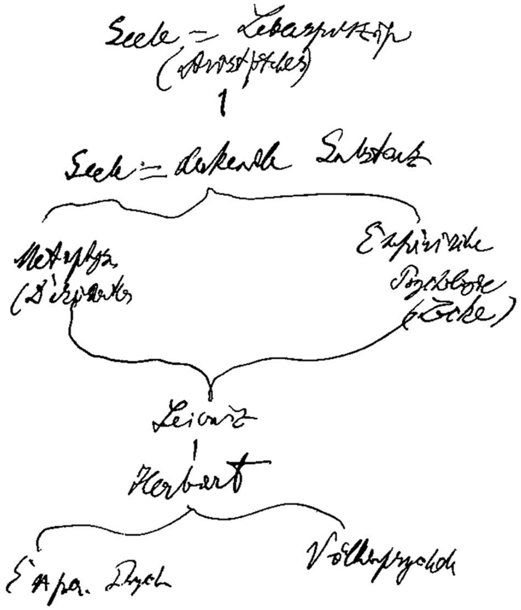


Figure 2.2. Wundt’s drawing of the history of theorizing on the mind from his handwritten lecture notes for (experimental) psychology, around 1900. From top to bottom, translated: Soul = life principle (Aristotle), Soul = Thinking substance, Metaphysics (Descartes), Empirical psychology (Locke), Leibniz, Herbart, Experimental psychology, Cultural psychology.

In the first two volumes of the *Völkerpsychologie*, which dealt with language (*Die Sprache*, 1900), Wundt criticized Wernicke’s model of language for assuming only associative processes. The critique was repeated in the *Grundzüge* of 1902. According to Wundt, mental processes not only proceed via association, as had been the prevailing view for over 2,500 thousand years (from Aristotle to Locke to Wernicke), but there are also nonassociative mechanisms, which he called *apperception*. This notion was introduced in the first 1874 edition of the *Grundzüge* and further elaborated in later editions. Wundt’s notion of apperception involved a modification of earlier notions put forward by philosopher Leibniz (1714/1880) and philosopher-psychologist Herbart (1839). According to Wundt, association is a passive process and apperception an active process, which has been argued to be a key distinction in the history of psychology (Kolk, 1994). The term apperception is no longer used today but a similar contemporary notion is *attentional control*, also called executive or cognitive control.

Whereas Wernicke (1874) maintained that voluntary movements are psychological reflexes that have developed from real reflexes (Chapter 1), Wundt (1896) assumed that drive actions (*Triebhandlungen*) constitute the basis for voluntary movements, which he called *voluntarism*. The drive actions may later automatize through practice and become reflex-like. A drive action links a motive consisting of ideational and affective aspects (i.e., a moving reason [*Beweggrund*] and a driving force [*Triebfeder*]) to an action, which may be internal or external. An act of apperception concerns a motivated action that operates internally on mental contents. The motivated actions were believed to be rooted in the brain system for controlling overt movements, later extended to support internally motivated actions. Motivated actions can be linked, with one act providing the motive for the next. They were considered essential for intellectual processes. During intellectual development, the affective aspect was believed to be weakened in internally motivated acts that direct thinking. The motivated actions of Wundt bear some resemblance to IF-THEN (condition-action) rules in modern psychology, discussed later.

Moving reason (*Beweggrund*)
Driving force (*Triebfeder*) → Act (*Handlung*)

If only one motive is present in the mind, the volitional movement was called an *impulsive act* by Wundt, and if several motives are present involving a choice, it is a *selective act*. Wundt (1896) clarified the distinction using Donders' different tasks, where the impulsive act corresponds to a simple reaction and the selective act to a choice reaction. When simple acts are repeated many times, they become automatic movements.

Wundt (1896) distinguished between simple and complex apperceptive functions. The simple functions are relating and comparing (*Beziehung* and *Vergleichung*, p. 294), which are involved, for example, in the psychophysical tasks of Weber and Fechner and the reaction time tasks of Donders (Chapter 1). Apperceptive enhancement (Wundt, 1880b) and inhibition (Wundt, 1902) are also simple functions. The complex functions are synthesizing and analyzing (*Synthese* and *Analyse*, p. 305), which, in addition to the simple functions, are specifically involved in more intellectual tasks (Chapter 4). Wundt (1902) wrote:

> If you want the complex phenomena, which are summarized under the indefinite collective name of 'intelligence', to be broken down into elementary processes, such that a clear and simple psychological notion can be connected to it, and possibly the relationship to an appropriately simple physiological correlate be made, such an elementary notion would be the apperception of a psychological content. (p. 322)

Wundt (1900) argued that Wernicke's (1874) assumption of association as a psychological reflex is insufficient to explain aphasic language performance. Wundt's examples concerned strategies that persons with aphasia may use to compensate for their problems, which later became a topic of research in its own right (e.g., Isserlin, 1922; Kolk & Heeschen, 1990). Here, I provide an example that illustrates a problem more inherent to Wernicke's model. Take, for example, Wernicke's patient Seidel, who responded appropriately to a question like "Is your name Seidel?" by saying "Yes" (taken from Wernicke, 1874, p. 61). When hearing the question, Wernicke's model assumes that the auditory and movement images of the words that make up the question are activated, including the movement image for "Seidel". This raises the issue of why the patient did not repeat the question or part of it, like "Seidel", as patients with transcortical aphasia often do (Kemmerer, 2022). According to Wundt (1874), correct responding occurs because the "laws of association, too, are entirely subject to the control of attention" (p. 793), which "expresses itself not only in the elicitation of certain movements but also in the perception of sense impressions and the reproduction of ideas" (p. 830). Assuming a mental act of apperceptive inhibition (Wundt, 1902), selective responding in answering a question, as in the Seidel example, can be achieved by inhibiting the connection between the auditory image and the movement image, or between the movement image and the articulation organs, for the inappropriate response "Seidel" and other words so that the correct answer "Yes" can be produced. Modern functional neuroimaging has confirmed Wundt's assumption that attentional control is supported by the frontal lobes (see Posner & Raichle, 1994, for a review of the early evidence, and Badre, 2020, and Posner, 2012, for recent reviews). Pathological repetition or echolalia is associated with damage to the medial frontal cortex (Berthier et al., 2017).

Wundt's ideas on motivated acts and attention were anticipated in a more speculative form by J. Müller in his *Handbuch*. Whereas Wundt experimentally tested his psychological theory, Müller did not. Müller (1840) hypothesized:

> One could imagine that the voluntary movement depends on the intensity of a conscious representation of the purpose and the necessity of its immediate execution. Every time this representation reached a maximum intensity, the movement necessary to achieve the purpose would occur. … However, we can also let the intention work arbitrarily on the sensory impressions. … If two people say different things to us in both ears, we can pay attention to the words of one while ignoring those of the other. … In short, the will acts just as strongly here as it does on the motor nerves. … Arbitrary intention is also not limited to motor nerves and sensory nerves; it also works on mental actions. (pp. 93 and 96)

The concept of attention became increasingly important from J. Müller to Helmholtz to Wundt. This can be seen from a simple word count. While the word "attention" (*Aufmerksamkeit*) appeared 50 times in J. Müller's *Handbuch* (1835, 1840), it was used 128 times in Helmholtz' *Optik* (1867b), and "attention" or "apperception" occurred 290 times in Wundt's *Grundzüge* (1874). While J. Müller and Helmholtz used the term as a one-word explanation, a surrogate for theory (Gigerenzer, 1998), Wundt proposed and tested a detailed processing model, which I discuss later.

The role of attention in mental processing was a central research topic in Wundt's laboratory, beginning with Friedrich's dissertation on apperception in the early 1880s. During this research, Wundt and his American student James McKeen Cattell (1860-1944), his first student assistant, began to disagree on an important issue. Supported by several studies in his lab (e.g., Lange, 1888), Wundt claimed that apperception of a stimulus prolongs processing, but Cattell's own studies suggested that this is not always the case (Cattell, 1893). As a doctoral student in Wundt's laboratory in Leipzig in the 1880s, Cattell conducted many experiments, not only on attention but also on naming and reading. In these experiments, he made some groundbreaking observations about the speed at which objects, colors, and words are named (e.g., Cattell, 1885), which inspired Stroop's famous experiments with colors and words in 1935. Instead of using a graphical method to measure vocal reaction times, as Donders (1868a) did, Cattell introduced lip and voice keys, which are devices that stop a chronoscope (i.e., timer) when opening the mouth or detecting a speech sound, respectively. Back in America, Cattell founded a number of important journals, including *Psychological Review* (now the most prestigious theoretical journal in psychology) and *Science* (now the most prestigious journal in all sciences, together with *Nature*). Cattell was the owner and editor-in-chief of *Science* for 50 years, from 1894 till his death in 1944 (Sokal, 1980).

By the early 20th century, Wundt thought he had definitive data on the question of the reaction time reflection of apperception. A photograph from a photo shoot that took place in 1912 shows Wundt, 80 years old, surrounded by his collaborators (Figure 2.3). He pretends to be engaged in a reaction time experiment, holding one finger on a left-hand button and another finger on a right-hand button. In the background hangs a poster with the reaction time data that answered the question.

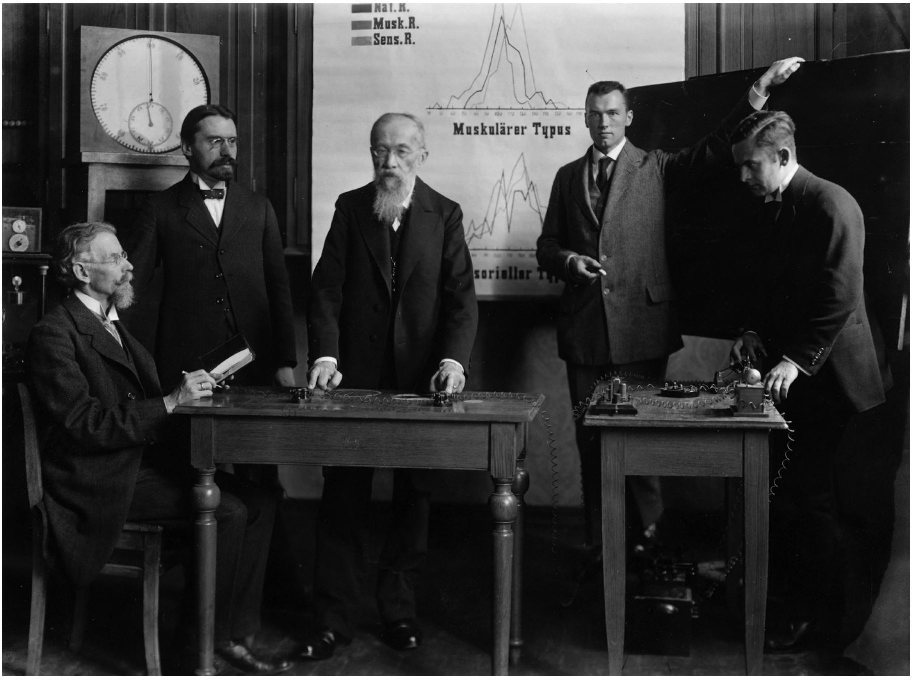


Figure 2.3. Wundt surrounded by his collaborators in 1912.

To demonstrate that apperception prolongs processing, Wundt’s poster shows *frequency distributions* of reaction times, with the horizontal axis representing the reaction times (in bins of four milliseconds) and the vertical axis their frequency. There are two graphs on the poster. The top graph is called *Muskulärer Typus* (muscular type), which I reconstructed and show in Figure 2.4, and the bottom graph (not shown in my figure) is called *Sensorieller Typus* (sensorial type), with similar reaction time patterns. The types refer to individual differences in the tendency (*Neigung*) to respond reflexively or with more deliberation. According to Wundt (1903), practice and instruction have the same effect on the frequency distributions across these individual tendencies, which is what the two graphs on the poster were intended to show.

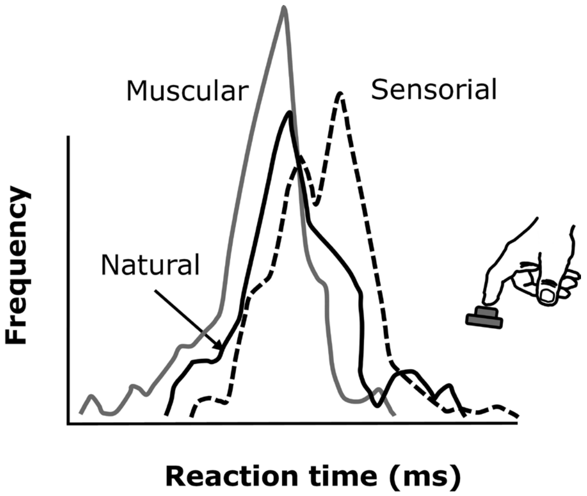


Figure 2.4. The reaction time distributions on the poster of Wundt, reconstructed using Wundt (1903, p. 421). The natural distribution is based on 205 trials, the muscular on 291 trials, and the sensorial on 590 trials.

The reaction times on the poster came from an experiment conducted by Bergemann in Wundt's laboratory. Participants had to perform a simple-reaction task consisting of pressing a button when hearing a sound. According to Wundt (1903), the "natural" distribution (indicated as "Nat. R." on the poster in Figure 2.3) consists of a mixture of "muscular" or *automatic* reactions (indicated as "Musk. R." on the poster) and "sensorial" or *apperceptive* reactions with attention paid to the stimulus (indicated as "Sens. R."). In terms of Fodor's modularity theory (Chapter 1), the automatic reactions happen by proceeding directly from perception (input module) to movement (output module), whereas the apperceptive reactions proceed via the central system (apperception is a central process). The natural distribution is obtained early in the experiment. As more trials are performed later, the automatic responses will dominate, and the frequency distribution curve will shift to the left toward shorter reaction times. However, when the participant is instructed to attend to the stimulus and not respond until it is identified as the stimulus sound, apperception will occur. The apperceptive function here is the relating function, which is involved in recognizing the identity between a stimulus and the image that is stored in memory. As a result, the apperceptive reactions will dominate, and the frequency distribution curve will shift to the right toward longer reaction times. According to Wundt, participants may differ in their tendency to respond more automatically or attentively (i.e., the top versus bottom graphs on the poster), but with the appropriate practice and instruction, all participants will behave similarly, and the researcher will observe that apperception prolongs the reaction times.

Wundt (1874) also initiated the investigation of interference, which requires the allocation of attention, through reaction time experiments involving manipulation of stimulus onset asynchrony (SOA). For example, he conducted an experiment in which he examined the influence of a distracting sound (*störender Klang*, p. 748) on the reaction time of manually responding to a target sound (*Haupteindruck*). By manipulating the SOA (the exact SOA was not reported), the time course of the interference could be investigated. Wundt noted that reaction time was longer with preexposure of the distractor (*vorher*) than with postexposure (*nachher*) or simultaneous presentation (*gleichzeitig*). A century later, Glaser and Glaser (1982) and Glaser and Düngelhoff (1984) studied attentional control by examining the time course of interference in color-word Stroop and picture-word interference through SOA manipulation, which I discuss later.

The experiments with responses to sounds show that Wundt not only proposed the theoretical concept of apperception, but also investigated it experimentally. Danziger (2001) stated:

> The reaction time studies conducted during the first few years of Wundt's laboratory constitute a unique early example of a coherent research program ... Wundt's apperception concept provided a theoretical framework that transformed what would otherwise have been a collection of isolated studies. (p. 111)

Later experiments in the laboratory not only measured reaction times but also made physiological recordings, including measurements of blood pressure, respiration, heart rate, and vasomotor responses. Furthermore, Emil Kraepelin (1856-1926) studied in the laboratory the influence of psychoactive drugs on simple, choice, and go/no-go reaction times (Kraepelin, 1883). The multi-method approach characterizes Wundt's research strategy. EEG recording and computational modeling did not yet exist. Kraepelin, a lifelong friend of Wundt, would later become the founder of modern scientific psychiatry and psychopharmacology, with Alzheimer among the researchers he hired for his research institute. Kraepelin had not been the first to study the effect of psychoactive drugs. Ribot (1898) noted that "[a]lready in 1873, Exner (in *Pflügers Archiv*), showed that after having drunk two bottles of Rhine wine in quick succession, the reaction time rose for him from 0.1904″ to 0.2969″, although he subjectively had the feeling of reacting in the latter case with much greater speed" (p. 344).

Wundt's neurocognitive processing model

Beginning with the second of the six editions of his *Grundzüge*, Wundt described a detailed neurocognitive processing model for apperception in naming, listening, reading, and writing (the first edition appeared in 1874, the second in 1880, and the sixth in 1908-1911). A woodcut figure, shown in Figure 2.5 (adapted from Wundt, 1902), displayed a hierarchical network with subordinate processing centers (*untergeordneten Centren*) with sensory, movement, and higher nodes for words, which are connected to nodes in a superordinate apperception center. Connections to (i.e., bottom-up), from, and within the subordinate processing network are excitatory, while top-down connections from the apperception center are excitatory (as proposed in the second, third, and fourth editions of the *Grundzüge*) or inhibitory (as presented in the fifth and sixth editions).

Apperception can optionally operate at sensory and corresponding higher-level nodes (i.e., perceptions), movement and corresponding higher-level nodes (i.e., responses), or both. As Wundt put it: "We then have, according as these impulses are transmitted to sensory or motor centres, either the apperception of sensations or the execution of voluntary movements" (1904, p. 318, English translation by Titchener). Wundt (1902) presented his model as an alternative to Wernicke's (1874) model of normal and impaired word production and comprehension (Chapter 1), which had no top-down control mechanisms (Wundt, 1880b, already applied his model to aphasia and acquired dyslexia, with reference to Kussmaul, 1877).

In simple tasks such as picture naming or word reading, apperception was taken to exert "a regulative influence" (*regulirenden Einfluss*, Wundt, 1902, p. 325) on associative processes. While Wundt (1880b) assumed that apperception enhances (*verstärken*, p. 219) the subordinate spread of activation (*Erregung*), from Wundt (1902) onward, it was assumed that inhibition (*Hemmung*, p. 326) was the mechanism. He stated that "the substrate of the simple apperception process may be sought in *inhibitory processes* which, by the very fact that they arrest other concomitant excitations, secure an advantage for the particular excitations not inhibited" (1904, p. 317). Furthermore, "the inhibitory influence, in this special case, is not exerted directly upon certain excitations in progress within the sensory centres, but rather upon the conduction of the excitations to the higher centres" (p. 317), creating an inhibitory gate or filter. The apperceived perceptual content is brought to the foreground and other content to the background in consciousness. In all editions of the *Grundzüge*, Wundt described in some detail how apperception works in voluntarily naming a visual target among distractors. His proposal for the attentional control of perception is similar to Broadbent's (1958) filter theory and Treisman's (1960) attenuation theory, which were put forward sixty years later (Chapter 4).

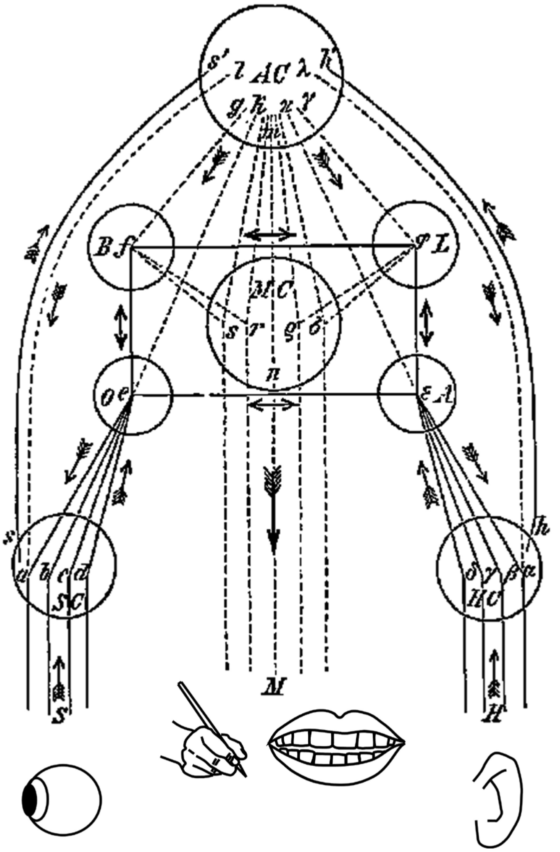


Figure 2.5. Diagram of Wundt's apperception model for the top-down control of naming, listening, reading, and writing. Solid lines denote "centripetal" connections and dashed lines "centrifugal" connections. The top-down connections from the apperception center (AC) are excitatory (Wundt, 1880b) or inhibitory (Wundt, 1902), while all other connections are excitatory. The eye, ear, hand, and mouth have been added to denote the sensory and motor organs. SC = seeing center; HC = hearing center; MC = motor center; O = optical; B = writing; A = auditory; L = articulation.

Modern evidence indicates that the involvement of top-down inhibition in perception is reflected in the power of evoked oscillatory brain activity in the alpha frequency band (8-12 Hz). Alpha oscillations were discovered and dubbed by Hans Berger (1873-1941) in 1929. The oscillations are currently obtained using high-density EEG and MEG recordings. These methods have high temporal resolution, allowing assessment of the timing of changes in oscillatory power, and their high sensor density allows for the localization of the neural source in the brain. Ole Jensen and Ali Mazaheri (2010) stated: “From a physiological perspective, the alpha activity provides pulsed inhibition reducing the processing capabilities of a given area”. As a result, “information is routed by functionally blocking off the task-irrelevant pathways: gating by inhibition” (p. 1). This is similar to what Wundt (1902) proposed. When alpha power increases in a brain region, its activation decreases. Resting-state alpha band activity has been shown to be correlated with measures of intelligence, including scores on the Raven test, discussed in Chapter 4. Resting-state alpha power reflects individual differences in inhibitory capacity (see Roelofs, 2021, for a review).

The discovery of consolidation

While Wundt criticized the 2,500-year-old classical association theory of the mind, others wanted to make it more precise. After reading Fechner’s (1860) *Elemente*, Hermann Ebbinghaus (1850-1909) was so impressed by the meticulous mathematical procedures that he wanted to do for associative memory what Fechner had done for psychophysics. To study the formation and forgetting of new associations, he constructed approximately 2300 *nonsense syllables* (i.e., meaningless pronounceable consonant-vowel-consonant combinations, like *wak*, *tif*, *pok*, and so forth) that were free of existing associations. The syllables were placed in lists for memorization and recitation (e.g., saying out loud “wak, tif, pok, …”), with several variables manipulated. In 1885, after many years of investigation, in Berlin, he documented his results in the book *Über das Gedächtnis: Untersuchungen zur experimentellen Psychologie* (*On Memory: Investigations into Experimental Psychology*). The book was translated into English in 1913.

Using himself as the only participant, Ebbinghaus (1885) first learned a list of nonsense syllables for a number of minutes until he could recite the list from memory without mistakes (e.g., “wak, tif, pok, …”), and then relearned the list to perfection for a number of minutes sometime later (i.e., “wak, tif, pok, …”). In one of the studies, the interval between first learning and relearning was manipulated, and it could be 19 minutes, 63 minutes, 9 hours, 1 day, 2 days, 6 days, or 31 days. Ebbinghaus recorded how many minutes the initial learning (e.g., 15) and the relearning took (e.g., 6), and determined the percentage saving (e.g., 15 − 6 = 9 / 15 = 60% retention). He observed that most forgetting occurred in the first few hours after learning and then leveled off, as illustrated in Figure 2.6.

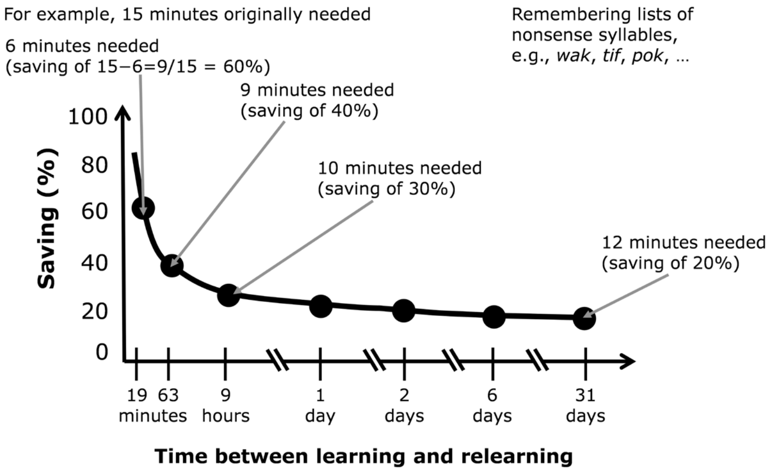


Figure 2.6. The curve of forgetting of Ebbinghaus (1885), constructed from the tables in section 28 of his book.

According to Ebbinghaus, the *forgetting curve* has a logarithmic form (just like Fechner's psychophysical curve, but reversed), which implies that *the rate of forgetting decreases with time*. Instead, if the rate of forgetting had been constant (e.g., a drop by a factor of 0.5 every hour indefinitely), the curve would have been exponential (e.g., retention would drop in the first hour after learning from 80% to 40%, and from 40% to 20% in the next hour, etc.). Different from this, Ebbinghaus observed that the rate of forgetting decreased with time. Thus, for example, retention would drop from 80% to 40% in the first hour but only from 40% to 37% in the next hour (and by a lesser amount each hour after that). In 2015, Jaap Murre and Joeri Dros repeated the original experiment of Ebbinghaus (i.e., also with only a single participant) and obtained a similar forgetting curve (Murre & Dros, 2015).

The formula that Ebbinghaus proposed for the forgetting curve shown in Figure 2.6 is

$$b = \frac{100\,k}{(\log t)^c + k}$$

Here, *b* denotes the saving (*Besparung*) and *t* indicates the learning time in minutes. The constants *k* and *c* were estimated by Ebbinghaus to be 1.84 and 1.25, respectively. This predicts, for example, 57% saving after 19 minutes where 58.2% was observed, which is really close.

It is now clear that the forgetting curve is not a logarithmic function but a power function of time, as Wixted (2004) argued. For both logarithmic and power functions, the rate of forgetting decreases with time, unlike the constant rate of an exponential function.

Ebbinghaus' work was a milestone in the history of the study of the mind. Woodworth (1909) described the importance of what Ebbinghaus had done as follows:

> He had devised a method by which quantitative experiment could be extended, beyond the sphere of sense impressions and reaction times to which it had mainly been confined, to the memory, and by which so apparently inaccessible a thing as the degree of retention of matter which had once been learned but passed beyond recall could be measured. His demonstration that so central a process as memory could be studied by exact methods added greatly to the courage of the young science, and his work was the starting-point for a large and steadily increasing literature. (p. 254)

How can the decreasing rate of forgetting, as evidenced by the Ebbinghaus curve, be explained? The answer came from the work by Georg Müller (1850-1934) and his student Alfons Pilzecker in the 1890s in Göttingen, Germany. They asked participants to learn lists of nonsense syllables, whereby pairs of syllables were cues and responses. For example, in the list {*buf, dek, gom, jap*, ...}, *buf* would be a cue and "dek" a response, and *gom* would be the next cue and "jap" the next response. Lists of 12 syllables were mounted on a twelve-sided prism of a "memory drum", which was rotated along its horizontal axis by an electrical device at a constant speed (e.g., 8.90 seconds per side). Participants saw each syllable through a small window, one syllable per prism side. The window showed the cue and response syllables sequentially during learning and showed the cue syllables only during testing. The percentage of correctly recalled responses was recorded, and reaction time was measured using Cattell's lip key. Müller and Pilzecker (1900) called this the hit and time method (*Treffer- und Zeitmethode*, p. 3). There were two conditions. In the interference condition, a participant first learned a list of cues and corresponding responses (e.g., list A) for a fixed number of trials, then learned another list (e.g., list X), and finally was tested on the original list (i.e., list A). In the control condition, the participant first learned a list (e.g., list B) and was later tested on the list without the intervening learning of another list.

Müller and Pilzecker (1900) observed that recall was worse, and reaction time was longer, in the interference condition than in the control condition. For example, in Experiment 32 (pp. 182-184), accuracy was 27% in the interference condition and 55% in the control condition, and reaction times were 3230 and 3070 milliseconds, respectively. Thus, learning a second list decreased accuracy and increased reaction time. This implied that retroactive interference (from learning X upon first learning A) had occurred.

To explain the retroactive interference (*rückwirkende Hemmung*, p. 194), Müller and Pilzecker (1900) proposed that "physiological processes, which serve to strengthen the associations created, … continue for a certain time", referred to as *consolidation* (*Consolidirung*, p. 197). Learning (list A) requires consolidation in memory, which is weakened (*geschwächt*, p. 196) by new learning (list X).

Consolidation also explains the mathematical shape of Ebbinghaus' forgetting curve. If memories consolidate over time, they become more resistant to forgetting with time. As a consequence, the rate of forgetting decreases over time, as observed by Ebbinghaus. Moreover, consolidation explains the temporal gradient in retrograde amnesia, described by Théodule Ribot (1839-1916) based on clinical reports in his book *Les Maladies de la Memoire* (*Diseases of Memory*), published in 1881. He observed that how much memories formed prior to brain damage are impaired depends on the age of the memories, with more recently formed memories suffering the most, later called *Ribot's Law*. If memories consolidate over time, they become more resistant to the effect of damage as they age, as observed by Ribot.

The discovery of multiple memory systems

Evidence from later research indicated that memory consolidation was done by the *hippocampus*, which is a sea-horse-shaped organ buried in the medial temporal lobe. The evidence came from neurodegeneration and from surgical removal of the hippocampus.

In 1906, in the laboratory of Wundt's disciple and friend Kraepelin in Munich, Alois Alzheimer (1864-1915) discovered abnormal protein plaques and tangles that led to atrophy (cell death) in the brain of his patient Auguste Deter. She had died earlier that year after a decade of dementia, first showing a loss of the ability to form new memories and later also losing existing memories. In a brief article, Alzheimer (1907) reported on the case. Shortly afterwards, Kraepelin (1910) named the new disease Alzheimer's in the eighth edition of his textbook on psychiatry: *Alzheimerschen Krankheit* (p. 627). In the 1990s, it was discovered that Alzheimer's disease starts in the entorhinal cortex, then spreads into the hippocampal formation, and later progresses to the lateral temporal cortex and other brain regions (Braak & Braak, 1991). The atrophy of the hippocampus hampers consolidation, which explains the memory problems of patients with Alzheimer's dementia.

At the end of the 1990s, the patient records of Deter and the slides with neural tissue prepared from her brain by Alzheimer were rediscovered in Munich (Graeber et al., 1997). Because Deter was only 56 years old when she died, familial influences to her early-onset disease may be expected. To assess this, in the 2010s, DNA was extracted from her brain tissue. However, genetic analyses revealed no known familial mutations (Graeber et al., 1998).

In 1953, Henry Molaison, long known as patient H. M. in the literature, underwent a bilateral hippocampus removal as a last-ditch effort to alleviate severe epileptic symptoms through neurosurgery. After the operation, Molaison could no longer form new memories (anterograde amnesia), which indicates that the hippocampus is necessary for the consolidation of memories. He also showed retrograde amnesia spanning a period of about three years prior to the surgery. After Molaison's death in 2008, his brain was preserved for posterity by making a digital atlas of it (Annese et al., 2014).

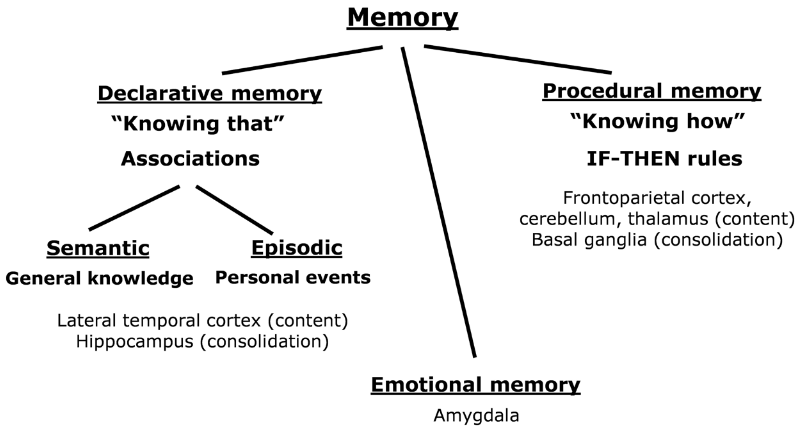


Figure 2.7. The multiple long-term memory systems.

Studies in the 1960s showed that H. M. still could learn procedural tasks, like mirror drawing, as documented by Brenda Milner (1918-) and her colleagues (e.g., Milner et al., 1968). Mirror drawing involves drawing a figure by looking at its reflection in a mirror. H. M. exhibited the same learning curve as control participants, although he had no explicit memory of the learning trials. The same has been observed in people with Alzheimer's disease (Gabrieli et al., 1993). This finding indicates that there are *multiple long-term memory systems*, associated with different parts of the brain, which may be selectively affected by surgical removal or neurodegenerative disease. Subsequent patient studies (e.g., Cavaco et al., 2004) and modern neuro-imaging have provided converging evidence (e.g., Eichenbaum & Cohen, 2001;

Eichenbaum, 2012). The memory systems are summarized in Figure 2.7. Since the 1970s, a distinction has been made between *declarative memory* ("knowing that"), associated with lateral temporal cortex storing the memory contents and the hippocampus consolidating new contents, and *procedural memory* ("knowing how"), associated with the frontal and parietal cortex storing the procedures and the basal ganglia consolidating new procedures. Conscious recollection is associated with declarative memory, while the contents of procedural memory remain outside of consciousness. This is further discussed in Chapter 3. Declarative memory is further subdivided into semantic memory for facts and events (e.g., what a cat is) and episodic or autobiographical memory for personal experiences (e.g., that our house cats Hobbes and Guna caught mice and frogs in our garden in the summer). A third type of memory is *emotional memory*, storing emotional evaluations and responses, which is associated with the amygdala.

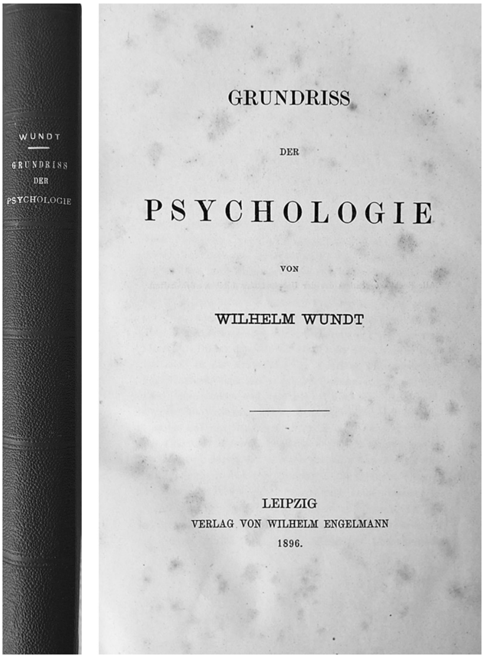
Whereas *Alzheimer's disease* is associated with degeneration of the hippocampus and impairment of declarative memory, *Parkinson's disease* specifically affects the basal ganglia and disrupts procedural memory (e.g., Heindel et al., 1989). Disturbances of emotional memory have been linked with *depression* (e.g., Weniger et al., 2006), which is a serious mental illness characterized by long periods of low mood.

The discovery of mental set and imageless thought

The discovery of multiple memory systems in the brain supported Wundt's earlier distinction between mental content (declarative memory) and mental acts (procedural memory), as well as his emphasis on feelings (emotional memory) in driving mental processes. Wundt had supplemented classical association theory with nonassociative mechanisms, such as apperceptive functions involving motivated mental acts, and by adopting abstract concepts (*abstracte Begriffe*), he went beyond the classical assumption that all mental content is sensory in nature (e.g., Wundt, 1880c). Wundt had experimentally studied elementary mental functions, such as simple perception and movement, and their attentional control. In the early 20th century, his student Külpe's research group began to conduct experimental investigations into the assumptions of classical association theory about *complex* mental functions, in particular thinking (Külpe, 1912, 1922). While Külpe's notions of mental set (*Einstellung*) and task (*Aufgabe*) echoed Wundt's idea of moving reason (*Beweggrund*) as an important factor in steering mental processes, Külpe's notion of imageless thought had an equivalent in Wundt's earlier notion of abstract thought ("das abstracte Denken").

Oswald Külpe (1862-1915) had studied with G. Müller in Göttingen before he went to Leipzig to work in Wundt's laboratory. There, he followed Wundt's suggestion to write an introduction to psychology for students. In this book, the *Grundriss der Psychologie* (*Outlines of Psychology*), published in 1893, Külpe advocated an almost exclusive experimental approach and a ban on purely psychological notions in theorizing. This represented a radical departure from Wundt's own view on psychology. In 1896, after Külpe had moved to Würzburg, Wundt therefore published his own *Grundriss der Psychologie*, which would provide students with another conception of theorizing and the methods and their scope in psychology (Figure 2.8).

Wundt's *Grundriss* is perhaps the best and most comprehensive introduction to his general views on psychology written by Wundt himself. The first edition of 1896 was translated into English by former student Charles Judd in collaboration with Wundt, and the translation appeared in 1897. The 14th edition is the last one revised by Wundt himself and appeared in 1920 (Wundt, 1920b). The break between Wundt and Külpe concerned their view on psychology but did not extend to the personal domain, also not when Külpe began to study complex mental processes (i.e., thought) using experimental methods in Würzburg, again deviating from Wundt's own view. In 1902, Külpe was among Wundt's close friends invited to celebrate his 70th birthday (Figure 2.9).



GRUNDRISS

DER

PSYCHOLOGIE

VON

WILHELM WUNDT

LEIPZIG
VERLAG VON WILHELM ENGELMANN
1896.

Figure 2.8. Spine and title page of the first edition (1896) of Wundt's *Grundriss*.

Figure 2.9. Group photo taken on the occasion of Wundt's 70th birthday in 1902. Back row: his daughter Eleonore (left) and Oswald Külpe (third from left). Middle row from left: Emil Kraepelin, Wundt himself, his wife Sophia, and Carl Reinecke. Front row from left: Wundt's son Max and Wilhelm Wirth.

In the 1896 *Grundriss*, Wundt also proposed his three-dimensional theory of feeling, which would be tested using physiological methods in the following decades. The theory states that feelings vary in three dimensions, with the first being *pleasant – unpleasant* (*Lust – Unlust*), the second being *straining – relaxing* (*erregend – beruhigend*), and the third being *excitement – calmness* (*spannend – lösend*, p. 98). Feelings were believed by Wundt to guide all mental processes and play an essential role in driving voluntary action, which I discuss further below.

While Wundt maintained that complex mental processes such as thinking cannot be studied experimentally (e.g., by asking for introspection and measuring reaction times), Külpe and his Würzburg students, including the Scotchman Henry Watt (1879-1925), thought otherwise. They were interested in the issue, already addressed by Wundt, how associative processes are directed. According to classical association theory (Aristotle, Locke), the strongest association with a stimulus is always retrieved from associative memory. If a person sees an apple and wants to name it, the strongest association will be the response "apple". This raises the question of how the person can retrieve a less strong association if this is required. For example, if the person is instructed to say to what category an apple belongs, the response will be "fruit", but this is clearly a weaker association than "apple". What, then, is controlling the retrieval process such that it is goal-dependent? Wundt's answer was that control is achieved through mental acts of apperception, and Külpe and his students assumed, less clearly, that control somehow arises from a mental representation of the task instruction.

Watt examined directed retrieval from associative memory by giving his participants a retrieval instruction and asking them for introspection, and he reported the results in his dissertation (Watt, 1904). On each trial, his participants were given simple spoken instructions like “Name a part” or “Name the category”, and then they were shown a written word, like *apple*. The participants responded by saying for example “skin” or “fruit”, respectively. In their introspections, the participants stated that the task instruction (Aufgabe) steered them toward an appropriate response. This came to be called *mental set*. Moreover, the participants stated that, in many trials, there were no sensory images mediating the response. This came to be called *imageless thought*. Both observations seemed problematic for classical association theory. Contrary to what this theory would predict, the participants did not produce the strongest association, but the association that was appropriate to the instruction, a point already emphasized by Wundt. Moreover, according to association theory, all mental contents are made up of sensory images. Thus, the theory predicts that images should always mediate responding, which is different from what Watt empirically observed. A further detailed description of the work of Watt and other Würzburg researchers can be found in Humphrey (1951).

Subtraction in neuroimaging

Almost a century later, in 1988, Watt’s directed association task was revived in the seminal PET neuroimaging experiments of Michael Posner (1936-) and Marcus Raichle (1937-) in St. Louis in the United States. They also revived Donders’ subtraction method, now not applied in the temporal domain (i.e., to determine the duration of mental processing stages) but in the spatial domain, to determine the location of mental processing stages in the brain.

Although David Ingvar (1924-2000), Niels Lassen (1926-1997), and their Scandinavian colleagues reported on measurements of regional blood flow in the brain during task performance since the 1960s, the tasks used did not allow localization of subprocesses. For example, they compared watching motion, listening to words, or counting with resting as a baseline. The task could be even more complex. For example, other researchers compared cerebral blood flow between imagining walking along a route and resting. The complexity of the tasks made it impossible to tell how subprocesses related to the brain regions that were activated. The crucial insight of psychologist Posner and neurologist Raichle in the late 1980s was that success required Donders' subtraction technique and tasks that allowed for the isolation of subprocesses.

Figure 2.10. Marcus Raichle (fourth from left) next to Donders' noematachograph exhibited at the Donders Institute in Nijmegen (on temporary loan from the Utrecht University Museum) on the occasion of the 200th anniversary of F. C. Donders.

In a now classic study, Posner and Raichle, together with Petersen and several other colleagues (Petersen et al., 1988), subtracted the PET image with brain activation obtained when participants looked passively at a fixation cross (+) from the PET image obtained when they read words silently (e.g., the noun *apple*). This led to a localization of the perceptual processing of visual words (by the corresponding input module) to bilateral striate and extrastriate occipital cortex. Next, the PET image for reading words silently (e.g., the noun *apple*) was subtracted from the PET image for reading words out loud (i.e., say "apple"). This led to a localization of the articulatory planning of words (by the corresponding output module) in left premotor and motor areas in frontal cortex. Finally, the PET image for reading words aloud (e.g., say "apple" to the noun *apple*) was subtracted from the PET image for giving a verb expressing a use for the noun (e.g., say "eat" to *apple*), comparable to Watt's directed association task. In this verb response task, later often called *verb generation*, participants do not produce the strongest association (i.e., say "apple" to *apple*) but the association that is appropriate to the instruction (e.g., say “eat” to *apple*). This led to a localization of the attentional control of association in the frontal lobes, including left lateral prefrontal cortex and the anterior cingulate cortex. Thus, the PET brain imaging study supported Wundt’s claim about the frontal location of attentional control. The attentional control is needed to sequence the processes in verb generation and to prevent inadvertent reading of the noun (as in the earlier Seidel example, to comprehend and respond instead of repeating a word), which would be a predominant response. Similar results were obtained when participants passively listened to auditory words, repeated them, or uttered a verb expressing a use for the auditorily presented noun, except that the perceptual processing of the word now occurred in the superior temporal cortex.

In his 1893 *Grundriss*, Külpe criticized Donders’ subtraction method, arguing that a certain processing stage need not remain exactly the same when the task changes. For example, while complete discrimination is required for choice responses, partial discrimination may be sufficient for go/no-go responses. This problem was also noticed by Donders himself and became known as the problem of *pure insertion* (e.g., Luce, 1986). Importantly, Raichle (1998) noted that pure insertion does not challenge neuroimaging, in which changes at each processing stage are directly signaled by changes in observable neural measures. If partial discrimination is sufficient for go/no-go responses, while full discrimination is required for choice responses, this will be reflected in changes in these measures. Then, the brain areas involved in discrimination will be more active in the choice task than in the go/no-go task. Processes taking place in the brain are not hidden from the researcher, as in purely behavioral experiments. In an interview with Gazzaniga and colleagues (2002), Raichle described another way in which a violation of pure insertion can be revealed, namely when

> areas of the brain that are active in the control state are not active in the task state. Now the subtraction image reveals not only areas of increased activity relative to task state but also areas of decreased activity, reflecting areas that are used in the control state but not in the task state. (p. 141)

Not everyone was convinced that violation of pure insertion is not a problem for neuroimaging. Van Orden and Paap (1997) argued that

> subtractive neuroimaging necessarily requires a true, feed-forward, modular theory as the basis for reliable subtractions. If feedback occurs, however, then any change in a laboratory task reverberates through the entire system, which invalidates the

> subtraction. Because the nervous system employs recurrent feedback … subtractive methods and the entailed modularity hypothesis have failed. (pp. 93-94)

However, this reasoning is flawed. Take the PET imaging study by Petersen et al. (1988). They used a hierarchy of tasks for subtractions. Their initial subtraction compared passive reading of a word with viewing a fixation cross, revealing activation in striate and extrastriate occipital areas involved in visually identifying the word. The next subtraction compared reading the word aloud with reading the word passively, showing activation in premotor and motor areas in frontal cortex involved in articulatory planning and motor control. Now suppose that in reading aloud, there is feedback from articulatory planning to visual perception, and that the feedback facilitates perception, resulting in less activation. Then, subtracting passive reading from reading aloud would not only have revealed activation in the frontal areas but also deactivation in the occipital cortex. Whether pure insertion is violated can, therefore, be deduced from the subtractions. Rather than being invalidated by feedback, neuroimaging can be used to assess whether feedback is present. Henson (2011), S. Sternberg (2011), and Shallice and Cooper (2011) provided extensive discussions of pure insertion and other issues in neuroimaging.

Mechanisms of attentional control

While Watt (1904) believed that his results on directed association challenged classical association theory, others were not convinced. In 1913, G. Müller (who also proposed the notion of consolidation) argued for an associative account. He discussed the work of Watt as part of a monograph entitled *Zur Analyse der Gedächtnistätigkeit und des Vorstellungsverlaufes* (*On the Analysis of Memory Ability and the Flow of Ideas*), which made up a complete issue (over 500 pages) of the *Zeitschrift für Psychologie* (*Journal of Psychology*). According to Müller, Watt's observations do not really challenge association theory. Instead, a task instruction such as "Name the category" will activate all corresponding associations in memory, including the responses "furniture", "clothing", "fruit", and so forth. Moreover, the stimulus word *apple* will activate the directly associated response "apple" but also the indirectly associated responses "fruit", "skin", "eat", and so forth. One of these responses, namely "fruit", was also activated by the instruction "Name the category", and therefore, the association "fruit" will receive double activation (from the instruction and stimulus) and will be produced as response.

Also in 1913, the associative account of G. Müller was rejected by Otto Selz (1881-1943), who worked with Külpe in Bonn (Külpe went there after his time in Würzburg). In a monograph entitled *Über die Gesetze des geordneten Denkverlaufs: Eine experimentelle Untersuchung* (*On the Laws of the Orderly Course of Thought: An Experimental Investigation*), Selz critically discussed Müller's account and proposed an alternative symbolic-procedural theory. Selz's account was consistent with Wundt's earlier conceptualization of attentional control as a mental act, although Selz seemed unaware of Wundt's proposal. According to Selz (1913), the stimulus word (e.g., *apple*) and the task (e.g., "Name a part" or "Name the category") work together to produce a schematic anticipation ("die schematische Antizipation", p. 119) of the searched word. This initiates a mental operation aimed at completing the schema (*Operation der Komplexergänzung*, p. 119) by finding the missing word. For example, *apple* and "Name a part" create the schematic anticipation HAS-A(APPLE, ?), which initiates an operation that yields "skin" as response word, and *apple* and "Name the category" trigger an operation that produces "fruit" as response. A particularly clear, brief summary of these ideas can be found in Selz (1924).

A mere associative link between two nodes in an associative network says nothing about the relation between the entities represented. For example, the concept APPLE is strongly associated with both FRUIT and SKIN, but the relationship between APPLE and FRUIT is very different from the relationship between APPLE and SKIN. Therefore, Selz's proposal implies that associative declarative memory explicitly represents the relation between nodes by labeling the links. That is, declarative memory contains *symbolic* associative information. For example, the symbolic label IS-A between APPLE and FRUIT indicates that APPLE is a member of the category FRUIT, and the label HAS-A between APPLE and SKIN indicates that an APPLE has a SKIN as a part.

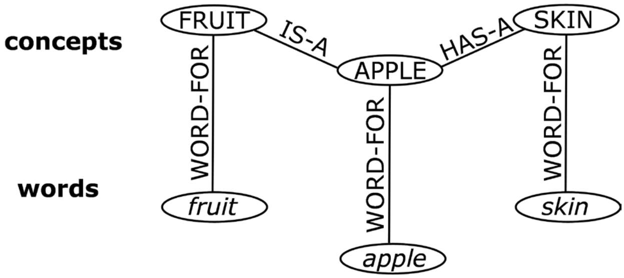


Figure 2.11. Illustration of a labeled associative network, where category membership (IS-A) and properties (HAS-A) of concepts are made explicit, as well as the associated word.

Moreover, according to Selz, the goal-directed retrieval is achieved by *procedural* knowledge, similar to the IF-THEN rules in modern psychology, which are stored in procedural memory for the many tasks that people have learned to perform. The IF (condition) part always specifies the task goal so that a rule is only retrieved from procedural memory when its particular task needs to be performed. For example, the rule for the task "Name the category" specifies this task in its IF (condition) part. Moreover, the IF part also tests for the presence in declarative memory of the appropriate symbolic label between nodes, which is the IS-A label for the task "Name the category". The IF part schematically anticipates the searched word, as in Selz's (1913) proposal. Thus, we have a rule like

IF the task is to name the category of *x* AND *x* IS-A *y* is in declarative memory
THEN select the word for *y*

Note that *x* and *y* are variables, just like in a mathematical equation. If the stimulus is the word *apple*, then this rule will find, in declarative memory, the symbolic associative information IS-A(APPLE, FRUIT), whereby *x* is bound to the concept APPLE and *y* to the concept FRUIT. This rule will thus lead to the correct response "fruit". A similar rule exists for the task "Name a part" with instead *x* HAS-A *y* as one of the conditions, which will produce "skin" in response to the stimulus word *apple*.

Selz's (1913, 1922, 1924) work foreshadowed several developments in modern theorizing and research into thought and its control (e.g., Frijda & De Groot, 1981; Proctor & Ridderinkhof, 2022). Yet, a century later, the theoretical controversy between G. Müller and Selz still exists in psychology. In 1990 and 2001, Jonathan Cohen (1955-) and Earl Miller (1962-) proposed an associative theory of goal-directed retrieval from associative memory (Cohen et al., 1990; Miller & Cohen, 2001), which was similar to the proposal of G. Müller. And in 2003, I proposed a symbolic-procedural theory of goal-directed retrieval from associative memory (Roelofs, 2003), along the lines of Selz. While the theories of G. Müller and Selz were only specified verbally, modern theories have been implemented as computer models so that precise predictions can be derived and empirically tested. For example, using categorization tasks (e.g., saying "fruit" in response to the written word *apple* or a picture of an apple), I tested modern Müllerian and Selzian models by examining reaction time distributions and simulations thereof (Roelofs, 2008a), the results of which supported Selz's position. Other experimental tests are discussed below.

Selz's life had a tragic end. Just before the outbreak of World War II, Selz fled Germany to the Netherlands, where he taught and conducted research in Amsterdam until his deportation in 1943 to Auschwitz, where he died. In Amsterdam, Adriaan de Groot (1914-2006) did his PhD research into the thinking of chess players based on the ideas of Selz, who gave him advice. De Groot's dissertation *Het Denken van den Schaker. Een Experimenteel-Psychologische Studie* (*The Thinking of the Chess Player. An Experimental-Psychological Study*) was published in 1946 and was dedicated to the memory of Selz. In the 1950s, Herbert Simon (1916-2001) became acquainted with Selz's work through De Groot's dissertation (Simon, 1981) and saw the similarity between Selz's ideas and his own work with Allen Newell (1927-1992) on human problem solving, which I discuss later.

Fractionation of motivational control

In his research on directed association in Würzburg at the beginning of the 20th century, Watt had divided each trial into four periods: the period of preparation for the task (Aufgabe) to be performed on the stimulus word, the presentation of the stimulus word, the search for the response word, and the occurrence of the response word. Participants were required to limit introspection after each trial to one of the four periods. Historian Boring (1950) referred to this procedure as "the introspective method of fractionation" (p. 404). Wundt and others criticized this method for relying too much on immediate memory. A century later, however, direct objective evidence about the periods of a trial can be obtained using modern neuroimaging. For example, event-related fMRI can measure the BOLD response during the different trial periods.

Wundt had assumed that a voluntary movement, such as pressing a left or right button in response to a stimulus, involves an action conditioned by a motive consisting of ideational and affective aspects (i.e., a moving reason and a driving force, respectively). In modern terminology, voluntary action involves both cognitive and *motivational* control. One way to study the latter is to use rewards. To be effective, the reward must influence the procedural system, including the basal ganglia and the frontal cortex. Modern research has shown that the ventral striatum is the region within the basal ganglia that processes input information about reward, while the frontal cortex implements the action.

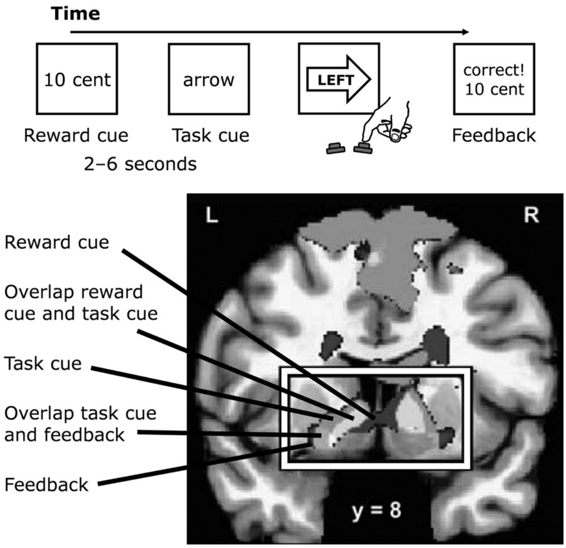


Figure 2.12. Trial periods (top) and corresponding activations in the ventral striatum (bottom) in the study of Aarts et al. (2010). y = 8 indicates the front-to-back position of the image in the brain according to the coordinate system of the Montreal Neurological Institute.

In 2010, Esther Aarts (1980-) and colleagues, including myself, examined the effect of reward anticipation and receipt during different periods of a trial by examining activation in the ventral striatum in response to a reward cue, task cue, arrow-word stimulus, and feedback, as illustrated in Figure 2.12. On each trial, a reward cue indicated whether the participant could earn one or ten cents for a correct and quick response. The task cue told the participant to respond to the arrow or to the word of an incongruent arrow-word stimulus, which was then presented. Finally, after pressing one of two buttons for the “left” or “right” response, feedback was provided regarding the amount of reward the participant had earned during the trial. There was a variable delay of two to six seconds between the reward and task cues and between the task cue and the stimulus, and a response-speed-dependent delay between stimulus and feedback.

Anticipating and receiving rewards produced a medial-to-lateral gradient of activation in the ventral striatum as a function of the trial period, shown in Figure 2.12. The effect of anticipating reward during reward cues was found in the ventromedial region; during task cues, it was observed more laterally, and the effect of reward receipt during feedback occurred in the most lateral region. During task cues, there was also activation in the medial frontal cortex in preparation for the task to be performed on the arrow-word stimulus.

The medial frontal activation included the anterior cingulate cortex, which Tomáš Paus (2001) called the area "where motor control, drive and cognition interface" (p. 417). Extensive projections from the thalamus and brainstem nuclei to the anterior cingulate indicate a role for drive and arousal. Extensive reciprocal connections between the anterior cingulate and the dorsolateral prefrontal cortex indicate a role for working memory. The motor areas of the cingulate sulcus project densely to the brainstem, spinal cord, and motor cortex, pointing to a role of the anterior cingulate in higher-level motor control.

The outcomes of the brain imaging study of Aarts and colleagues illustrate the power of neuroimaging to examine mental processing events during different periods of a trial without having to rely on questionable introspection practices. Furthermore, the results clarify and support Wundt's contention that voluntary action involves both ideational and affective control, or what is now called cognitive and motivational control.

The beginnings of American psychology

Wundt trained several students from America (for their memories of Wundt, see Hall et al., 1921), who, back in America, applied the experimental methods learned from Wundt but did not continue his psychological theorizing. Worse still, while Wundt had emphasized the importance of both mental content and operations, the students and others started schools that focused on either content (Titchener's structuralism) or operations (Angell's functionalism). Blumenthal (1977) stated:

> Quite literally, Wundt trained the first generation of American experimental psychologists; hence he may be counted as one of the major roots of American psychology. Yet in spite of this rather considerable contribution, it would appear today, in retrospect, that very little of Wundt's actual system of psychology ever survived the return passage back across the Atlantic. (p. 13)

Wundt's American counterpart was William James (1842-1910), who spent much of his academic career at Harvard University in Cambridge, Massachusetts. James wrote about a great many topics in psychology and reviewed the existing knowledge at the time magnificently in his best-seller *The Principles of Psychology* (1890). According to James, the content of consciousness is never stable but flows like a river, which he referred to as the stream of consciousness. The stream is directed by *selective attention* and *habit*, which basically amounts to a control mechanism and the strongest association. Inspired by the work of Charles Darwin (1809-1882), James argued that psychological functions like selective attention have a survival value; that is, the functions help us to survive in a complex environment. In *The Descent of Man*, Darwin (1871) had stated that "Hardly any faculty is more important for the intellectual progress of man than the power of *Attention*. Animals clearly manifest this power, as when a cat watches by a hole and prepares to spring on its prey" (p. 44). The survival value of selective attention is that it helps guide behavior in accordance with goals, and the value of habits is that they enable rapid response at low metabolic cost.

However, unlike Wundt, James (1890) did not further specify the exact mechanisms of selective attention, but his theorizing remained descriptive. In a famous paragraph, reproduced in many textbook chapters about attention, he stated:

> Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called *distraction*, and *Zerstreutheit* in German. (pp. 403-404)

James showed a strong interest in spiritualism, which holds the belief that the mind can exist independently of the brain after death. He was vice president of a spiritualist organization for almost twenty years and an avid hypnotist. James often took part in spiritualistic séances, where mediums suggested making contact with the spirits of the dead. Wundt thought that spiritualism and séances were *Blödsinn* (nonsense). In September 1879, he wrote an open letter (translated into English) to *The Popular Science Monthly*, in which he argued against spiritualism in general and against the American medium 'Mr. Slade' in particular, who had held séances in Leipzig. Wundt's student Cattell was also skeptical of spiritualism and had a debate about the medium 'Mrs. Piper' with James in Cattell's own journal *Science* in 1898.

Together with his friend Frederic Myers, a pioneer in the field of parapsychology, James decided to do the ultimate test, the 'deathbed experiment' (Draaisma, 1988): whoever died first had to immediately send a message from the afterlife to the other. In 1901, as Myers was on his deathbed, James was called to come to his friend. In his memoirs, Myers' doctor Munthe (1929) told what happened:

> William James told me of the solemn pact between him and his friend that whichever of them was to die first should send a message to the other as he passed over into the unknown – they both believed in the possibility of such a communication. He was so overcome with grief that he could not enter the room, he sank down on a chair by the open door, his note-book on his knees, pen in hand, ready to take down the message with his usual methodical exactitude. ... The dying man asked to speak to me. ... "I am going to know at last. Tell William James, tell him ..." (pp. 371-372)

After Myers died, Munthe left the room and saw James waiting: "When I went away William James was still sitting leaning back in his chair, his hands over his face, his open note-book still on his knees. The page was blank" (p. 372). Unfortunately, not much can be concluded from one null result, although a message from the afterlife is extremely unlikely given everything else we know about the world. Still, my wife and I are going to try it again and have agreed to repeat the experiment (consider this statement as pre-registration).

In his *Principles*, James (1890) expressed strong opinions about the work of others. About Wernicke, James wrote: "Wernicke was the first to discriminate those cases in which the patient can *not even understand* speech from those in which he can understand, only not talk; and to ascribe the former condition to lesion of the temporal lobe" (p. 54). However, he did not describe the model of Wernicke. Instead, James came up with his own version, assuming that "In our minds the properties of each thing, together with its name, form an associated group" (p. 55), with lesions knocking out specific parts of the network – exactly as Wernicke had proposed. Nevertheless, James concluded that "There is no 'centre of Speech' in the brain any more than there is a faculty of Speech in the mind. The entire brain, more or less, is at work in a man who uses language" (p. 56). Although a review of Wundt's (1874) *Grundzüge* by James (1875, reprinted in Bringmann and Tweney, 1980) had been positive, he was now highly critical. About Wundt, James wrote: "I must confess to finding all Wundt's utterances about 'apperception' both vacillating and obscure. I see no use whatever for the word, as he employs it, in Psychology" (p. 89). He stated: "The frontal lobes as yet remain a puzzle. Wundt tries to explain them as an organ of 'apperception' ... but I confess myself unable to apprehend clearly the Wundtian philosophy so far as this word enters into it" (p. 64).

James also discussed reaction time in the *Principles*, although he did not refer to the work of Donders, even not when explaining Donders' graphic method for registering them (p. 86). James described the simple reaction method only, arguing that the duration of the psychological stage translating the perceived signal into a motor response cannot be properly measured because "the data for calculation are too inaccurate for use" (pp. 89-90). In discussing the psychophysical work of Fechner, James ventured even a personal attack: "Fechner himself indeed was a German *Gelehrter* of the ideal type, … and as loyal to facts as to his theories. But it would be terrible if even such a dear old man as this could saddle our Science forever with his patient whimsies, and … compel all future students to plough through the difficulties, not only of his own works, but of the still drier ones written in his refutation" (p. 549).

The history of psychology has proven James to be wrong: Processing components of language are localized, frontal lobe attentional control (apperception) has been well established, reaction time can be measured precisely and reliably, and the work of Fechner has not been refuted. Unlike Wundt (see Tinker, 1932), James had only a few disciples, such as Mary Calkins and Stanley Hall. His theoretical ideas were also not carried forward by his students. Calkins (1930) recalled the early seminar in James's home when the other male students withdrew because of her, a female student (Benjamin, 2007):

> I began the serious study of psychology with William James. Most unhappily for them and most fortunately for me the other members of his seminary in psychology dropped away in the early weeks of the fall of 1890; and James and I were left … quite literally at either side of a library fire. The *Principles of Psychology* was warm from the press; and my absorbed study of those brilliant, erudite, and provocative volumes, as interpreted by their writer, was my introduction to psychology. (p. 31)

Mary Calkins (1863-1930) did important experimental work in the field of associative memory. In everyday life, people often want to remember items in pairs, such as objects and places (where did I put my keys) and faces and names. Rather than testing the recall of a series of nonsense syllables (Ebbinghaus), Calkins (1896) pioneered the use of paired associates, which were tested individually and randomly rather than serially in a list, as G. Müller and Pilzecker (1900) later did. Participants were first shown pairs of prompts and responses, for example consisting of combinations of colored rectangles and numbers (e.g., green – 47, brown – 73, violet – 61), and then were presented with the prompts, one at a time (e.g., brown) in random order, and wrote down the corresponding responses (e.g., 73). This is still a commonly used method to study memory today (e.g., Buck et al., 2021). Note that the type of memory Calkins studied (in terms of the multiple memory systems of Figure 2.7) is episodic memory, also studied by Ebbinghaus and G. Müller. By learning paired associates or nonsense syllables, participants do not expand their knowledge of the world (semantic memory), but rather learn specific information for an experiment, which is usually forgotten after the experiment. Calkins (1930) summarized her achievement as follows:

> Concretely stated – in showing series of colors paired with numerals I found that a numeral which had repeatedly appeared in conjunction with a given color was more likely than either a vividly colored numeral or than the numeral last paired with the color, to be remembered, on a reappearance of the given color. Perhaps more significant than these results is the method, since known as that of right associates, which I employed. For I discovered presently, to my unbounded surprise, that I had originated a technical memorizing method. G. E. Müller, who sharply criticized and greatly refined, but in essence adopted the method, calls it the *Treffermethode*. (p. 34)

Stanley Hall (1844-1924) was the founder of the first psychological laboratory in America, at Johns Hopkins, and also a co-founder and the first president of the American Psychological Association (APA) in 1892 – Calkins became the first female president in 1905. To celebrate the 20th anniversary of Clark University in 1909, of which he was the president, Hall organized a conference that was attended by James, Cattell, Titchener, Freud, and others. Wundt could not come because of the celebration of the 500th anniversary of the University of Leipzig. Freud's speeches in German at this conference in America gave his scientific career an enormous boost. They were published, translated into English, in Hall's *The American Journal of Psychology* (Freud, 1910). Hall also sparked an interest in childhood studies, the *child study movement*. He called for collecting as much data as possible on children's minds, with the ultimate goal of improving education. However, the movement failed to achieve its goal, presumably because it involved data collection without a guiding theory. For example, in his monograph *The Contents of Children's Minds on Entering School*, Hall (1893) reported on the results of questionnaires sent to teachers about the conceptual knowledge of children in their classrooms. He provided tables that indicated, among other things, how many children out of 10,000 knew clouds (5925 children), sunrise (3052), harvest (2368), and so on.

Modern research has been successful in discovering the properties of the minds of babies and children, as well as their development. Based on more than four decades of empirical research, including her own, Spelke (2022) argued in her *What Babies Know* that the human mind is equipped from birth with a number of core knowledge systems. These cognitive systems, shared by a range of other animals, represent core knowledge of objects, places, numbers, shapes, agents, and social partners. The systems are innate, remain present throughout life, and support learning. Spelke maintained that the unique human capacity for language allows the child's mind to go beyond core knowledge and integrate knowledge from different systems, which starts after the first year of life. Although the core knowledge systems contain encapsulated knowledge like Fodorian modules, they still depend on attention to function.

Modern research into the development of attention is documented in the book *Educating the Human Brain* written by Posner and his colleague Mary Rothbart, which was published by APA Press in 2007. The book describes a theory and supporting empirical data on the development of attention in the first six years of life of a child. The theory of attention was based on some 40 years of theory-driven empirical research in adults by Posner and colleagues, summarized in his book *Attention in a Social World* in 2012. A recent discussion can be found in Posner (2023).

According to Posner, attention is an umbrella term covering three abilities related to different networks of brain regions: *alerting*, *orienting*, and *control*. The brain networks were initially identified in neuropsychological studies with patients and later confirmed by neuroimaging in healthy individuals (e.g., Posner & Raichle, 1994). More recently, the networks have been related to different neurotransmitter systems and genes (e.g., Posner, 2012). Alerting is the ability to achieve and maintain alertness, either briefly or for an extended period of time, also called sustained attention or vigilance. This ability is supported by a brain network that includes the locus coeruleus in the brainstem and right frontal and parietal cortex. Orienting is the ability to shift the locus of perceptual processing to a particular location, either overtly with eye movements or covertly without eye movements. This ability is supported by the superior colliculus in the midbrain, the pulvinar nucleus of the thalamus, parietal cortex, and the frontal eye fields. Control is the ability to regulate mental processes to remain goal-oriented despite distractions. This ability is supported by the frontal lobes, including the anterior cingulate cortex, the anterior insula, and the basal ganglia. Attentional control also regulates overt and covert orienting, and its capacity depends on the state of vigilance, as documented by Daniel Kahneman (1934-2024) in his *Attention and Effort* (1973). Kahneman also discussed the allocation of attentional capacity.

The alerting ability is present from early childhood, although the ability to sustain alertness develops in late childhood. The ability to orient attention to external stimulation is also present very early in life and improves during childhood. Attentional control begins to develop in the second half of the first year of life and also shows significant development during the preschool years. When children begin formal education around the age of six to learn reading, arithmetic, and other mental skills, most children have basic capacities for alerting, orienting, and attentional control (Posner & Rothbarth, 2007; Rueda & Posner, 2013).

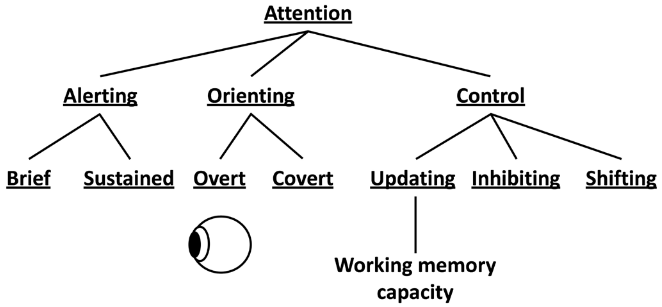


Figure 2.13. Varieties of attentional abilities according to Posner (2012) and Miyake et al. (2000).

Miyake et al. (2000) provided evidence that attentional control itself also consists of three abilities: *updating*, *inhibiting*, and *shifting*. Updating is the ability to maintain and manipulate the contents of working memory, inhibiting is the ability to reduce the activation of irrelevant representations, and shifting is the ability to alternate quickly between mental sets or tasks. The updating ability determines *working memory capacity* (e.g., Schmiedek et al., 2009). Figure 2.13 summarizes the attentional abilities. Inhibition was central to Wundt's model, and control more generally was central to Watt's research and the theories of G. Müller and Selz and those of their modern counterparts, J. Cohen and E. Miller and myself. Attentional control not only concerns the control of cognition (like controlling the retrieval from declarative memory, associated with lateral temporal cortex) but also the control of emotion (controlling the retrieval from emotional memory, associated with the amygdala).

It should be mentioned that in the *Grundzüge*, Wundt already discussed the varieties of attention distinguished by Posner, such as sustaining attention over time, the orienting of attention through overt eye movements or covert shifts, and the top-down regulation of mental processes. For example, Wundt (1911) discussed fluctuations of attention over time (*Schwankungen der Aufmerksamkeit*, pp. 345-352). Moreover, Wundt (1910) addressed the orienting of attention (*Orientierung*), assuming that, as a rule, there is a correspondence between attention and eye fixation (*Gesetz der Korrespondenz von Apperzeption und Fixation*), although it is possible to shift attention while maintaining eye fixation (pp. 560-565). Finally, Wundt (1908) discussed attentional control (pp. 378-385), including top-down inhibition. Numerous modern studies, including neuropsychological examinations, have confirmed the existence of these separable attentional abilities. Wundt's seminal proposal, however, appears to be unknown to many authors. As Fahrenberg (2019) put it: "Neuropsychology appears to have begun during the 1960s in the US for these authors, with the exception of the old problem of attention, for which they refer to William James (1890), but not to Wundt" (p. 47).

Structuralism, functionalism, and eclecticism

While Wundt was interested in both the structure and processing of the conscious mind, his English student Edward Titchener (1867-1927) sought to mainly understand the content of the mind, called *structuralism*. Titchener tried to analyze consciousness into elementary sensations by using introspection (e.g., Titchener, 1898). To formalize and standardize how to do introspection exactly (such that different investigators and participants would do it in exactly the same way and produce the same results), Titchener wrote manuals entitled *Experimental Psychology: A Manual of Laboratory Practice* (1901, 1905), which played an important role in teaching psychology to students. There were two volumes, one covering qualitative experiments using introspection and another covering quantitative experiments using reaction time and psychophysical methods (Weber, Fechner). One part of each of the two volumes was for the students (*Part I. Student's Manual*) and the other for the instructors (*Part II. Instructor's Manual*). Introspection aside, this is still how experimental research techniques are taught to psychology students. For example, I gave research practicums to second- and third-year psychology students for several years, using one manual for students and one for teachers.

An opposing school of psychological theorizing is called *functionalism*, which is associated with James Angell (1869-1949) in Chicago. Angell placed emphasis on mental operations rather than contents, sought to understand the survival value of mental functions (i.e., what purpose they served, see James), and wanted to understand the relation between mental functions and their neurobiological underpinnings (e.g., Angell, 1907).

An eclectic position was taken by Robert Woodworth (1869-1962). Winston (2006) wrote: "Woodworth articulated an inclusive, eclectic vision for 20th-century psychology: diverse in its problems, but unified by the faith that careful empirical work would produce steady scientific progress" (p. 51). In 1938, Woodworth's textbook *Experimental Psychology* was published, which he had worked on for almost three decades at Columbia University in New York. When the book appeared, popularly known as the "Columbia Bible" (Winston, 1990), Woodworth was already in his late sixties. The book summarized the field of experimental psychology, of which he witnessed the beginnings and rise, and it popularized the notions of *independent* and *dependent variables*. An experiment was defined as a study manipulating one or more independent variables and measuring the effect of this on one or more dependent variables. For many generations of (American) psychology students, this bestseller was the textbook on experimental psychology and thereby had a great influence on research in psychology. In 1954, a revision of the book (together with

Schlosberg) was published when Woodworth was in his mid-eighties but still taught at Columbia.

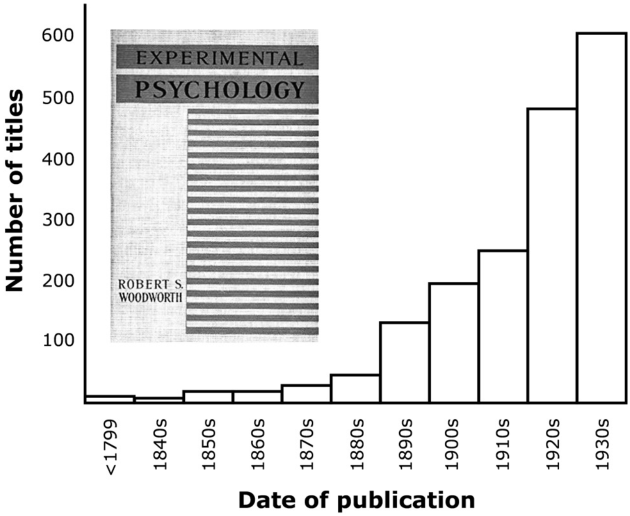


Figure 2.14. Cover of Woodworth's (1938) *Experimental Psychology* and his graph showing the distribution of the publications mentioned in the book based on their publication dates. Adapted from the graph in the book.

In the preface to the 1938 book, Woodworth provided a graph showing the rapid expansion of laboratory research in psychology since the mid-19th century, shown in Figure 2.14. The most frequently referenced authors in the book were G. Müller and Wundt. Woodworth wrote:

> It is interesting, now that the bibliography is fully assembled, to distribute the titles according to their dates of publication. The graph pictures the rapid expansion of laboratory research in psychology. A few scattering titles date from the earlier centuries and from the first half of the nineteenth, and there would have been more references to this early period if the chapters on the senses had been treated historically. But the upswing began about 1850 and still continues. (p. iii)

Regarding attention, Woodworth and Schlosberg (1954), echoing Darwin (1871), wrote:

> Consider a cat, poised at the entrance to a mousehole (*an effective determiner of attention*). This cat illustrates most of the problems we meet in the field of attention. In the first place, her eyes and ears are directed to get the maximum stimulation (*clearness,*

> *attensity?*) from the hole. Breathing is modified to sniffs, which will give maximum smell stimulation. Partly as a result of these adjustments, and probably also because of lowered thresholds or raised levels of activity of certain neural centers, any stimulus which emerges from the mousehole will be potent in determining a response. The corollary to these lowered thresholds for certain stimuli is an increase in other thresholds; the cat is not *distracted* from the job at hand by people moving around the room, or calling her name. However, she may stop looking to scratch, which might illustrate *division* of *attention* (or better, alternation). Periods of greater alertness are at least analogous to *fluctuations of attention*. Anything comparable to *span* is less obvious. (pp. 105-106)

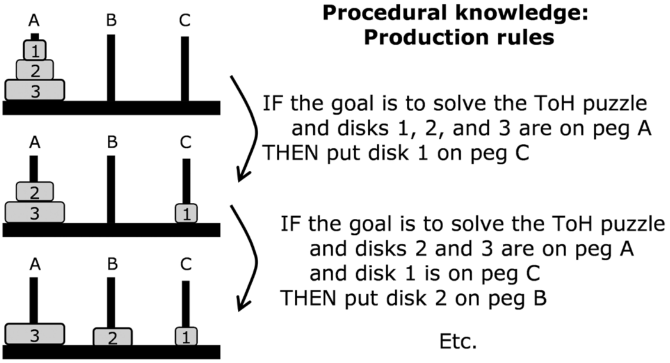
Woodworth (1938) also discussed the pioneering reaction time experiments of Donders, Cattell, and Wundt and pointed out the problem of pure insertion discussed earlier. He asked, “If we cannot break up the reaction into successive acts and obtain the time of each act, of what use is the reaction time?” (p. 310). And then, he immediately gave the answer: “It affords a means of studying the *total reaction* as dependent on the stimulus, the task, and the conditions in which the task is performed. Variations in the total RT throw light on the dynamics of performance.” (p. 310). This is how reaction times were used in psychology after World War II.

Interestingly, Woodworth foreshadowed in his book the use of electrophysiological methods such as EEG and MEG to study the mind: “We may be able in the future to use ‘brain waves’ as indicators of the beginning and end of a mental process” (p. 298). As earlier indicated, these methods measure the electrical or magnetic activity of many neurons over time using respectively electrodes placed on the scalp or arrays of sensors positioned around the head.

In a final chapter on *Thinking*, Woodworth (1938) discussed Watt’s work at length, including the notions of imageless thought and mental set as a factor in thinking, as well as the theories of G. Müller and Selz. He also described research on thinking from the 1910s to the 1930s involving controlled association, syllogistic reasoning, and concept formation. After World War II, additional tasks were used for studying thought, such as the Tower of Hanoi puzzle.

Solving the Tower of Hanoi puzzle

While the introspection method was used to study simple forms of thought by Watt in Würzburg in 1904, the method was used to study complex forms of thinking by Simon and colleagues at Carnegie Mellon University in Pittsburgh in the 1970s and 1980s (e.g., Simon & Hayes, 1976). For example, they asked participants to think aloud while trying to solve the *Tower of Hanoi* puzzle (Kotovsky et al., 1985; Simon, 1975). This puzzle consists of a number of disks of increasing size placed like a pyramid on one of three pegs. The task for participants is to place the disks of increasing size on the far-most peg by moving the disks one at a time, but never to place a bigger disk on a smaller one. Clearly, this task requires thinking, involving the dynamic management of goals and subgoals. Moreover, it requires attentional control to resist temptations because certain easy moves should be avoided in favor of less obvious moves; otherwise the puzzle cannot be solved (Miyake et al., 2000; Simon, 1975). While the Tower of Hanoi puzzle is used in research on thinking in healthy participants, another version of the puzzle, called the *Tower of London*, is used as a test of planning ability and attentional control in clinics (Shallice, 1988). The London version has differently colored balls instead of disks, and the pegs are of different lengths. This way several puzzles of increasing difficulty can be created, and it may be assessed at what level of difficulty a patient fails. Most patients with frontal lobe damage fail already at low levels.



Procedural knowledge:
Production rules

IF the goal is to solve the ToH puzzle
and disks 1, 2, and 3 are on peg A
THEN put disk 1 on peg C

IF the goal is to solve the ToH puzzle
and disks 2 and 3 are on peg A
and disk 1 is on peg C
THEN put disk 2 on peg B

Etc.

Figure 2.15. Procedural knowledge for the Tower of Hanoi (ToH) puzzle.

As indicated earlier, G. Müller (1913) proposed that goals and instructions bias the activation of one association rather than another. According to another view, originating with Selz (1913), goal-directed processing arises from procedural knowledge, which is now regarded as consisting of IF-THEN rules. With a goal in working memory (a notion that is further discussed in Chapter 3), processing is focused on those rules that include this goal among their conditions. The idea that procedural knowledge directs processing thrived in the work of Simon and his colleague Newell, among others, on higher-level cognitive processes like playing chess, proving logic theorems, and solving puzzles such as the Tower of Hanoi (e.g., Anderson, 1983;

Newell, 1990; Newell et al., 1958; Newell & Simon, 1972). Figure 2.15 illustrates how the application of procedural knowledge solves the Tower of Hanoi puzzle.

Attentional control in the Stroop task

Following Donders and Wundt, psychologists also continued to study attentional control in basic reaction time tasks. The "gold standard of attentional measures", as MacLeod (1992) called it, in modern psychology is the color-word test published by John Stroop (1887-1973) in 1935. Stroop used three cards with 100 stimuli each. Card 1 contained color words like *blue*, *green*, and *red*, printed in black ink, Card 2 contained rectangles in different colors, and Card 3 contained color words printed in incongruent colors, like the word *red* in green ink. Participants had to read aloud the words on Cards 1 and 3, and the card completion time was measured with a stopwatch. It took about 43 seconds to read aloud each card. Other participants had to name the presentation colors on Cards 2 and 3, which took about 58 seconds for Card 2 and 110 seconds for Card 3. Clearly, reading (Card 1) went faster than naming colors (Card 2), as Cattell already observed in the 1880s in Wundt's lab (Cattell, 1885). Moreover, there was interference from incongruent words in color naming (naming took much longer for Card 3 than Card 2) but not from incongruent colors in word reading (there was no difference between Cards 1 and 3).

Cattell had not only observed that naming colors is slower than reading words, but also that naming pictures takes more time than reading. Measuring picture naming and word reading times on individual trials using a voice key (Cattell, 1886a, 1886b), he observed that it took some 100 milliseconds longer to name a picture than to read aloud a word. Most of the pictures and words were not referring to the same objects, but a 100-millisecond difference was also observed for the subset of pictures with corresponding words (my analysis of Cattell's data). Cattell's seminal findings on the difference between naming and reading times have been replicated in modern experiments using colors and pictures and their printed names (e.g., Glaser & Düngelhoff, 1984; Glaser & Glaser, 1982).

A PET imaging study of Stroop color naming conducted by Pardo, Raichle, and colleagues (Pardo et al., 1990) showed that the anterior cingulate cortex is more active during a block of incongruent color-word Stroop trials (e.g., the word *red* in green ink) than a block of congruent trials (e.g., the word *red* in red ink). This is in line with the PET imaging finding from the verb generation task, indicating that the anterior cingulate cortex is an attentional control area in collaboration with lateral frontal cortex (Petersen et al., 1988). Recall that in verb generation, participants are presented with nouns and generate an appropriate verb for each noun (e.g., they see or hear the noun *apple* and respond by saying "eat" or another verb). Later research has shown that different parts of the anterior cingulate cortex underlie cognitive and emotional control (Bush et al., 2000). The dorsal (upper) part of the anterior cingulate is involved in the control of cognition, like in the color-word Stroop task (e.g., the word *red* in incongruent green color versus congruent red color), whereas the ventral (lower) part of the area is involved in the control of emotions, like in the emotion Stroop task (e.g., the emotional word *murder* versus the neutral word *house* in red ink).

In Stroop's (1935) original study, participants named the colors of incongruent color words or neutral rectangles on cards, with the classic finding being that the completion time for the incongruent card was much longer than for the neutral card. Moreover, there was no difference in completion time between reading the words on the incongruent and neutral cards. In modern computerized versions of the task (e.g., Glaser & Glaser, 1982), the stimuli are presented in individual trials, following Cattell (1886a, 1886b). Participants are instructed to vocally name the presentation color of printed incongruent or congruent color words (e.g., the words *green* or *red* printed in red ink; say "red") or the color of neutral stimuli, such as rows of *x*'s. Alternatively, participants are instructed to read aloud printed color words in incongruent or congruent colors, or in neutral black ink. Vocal reaction times are measured using an electronic voice key. The mean time for color naming is typically longer on incongruent trials than on neutral trials, and the naming time is often slightly shorter on congruent trials than on neutral trials. There is no difference in mean time for word reading on incongruent, congruent, and neutral trials.

The same pattern of results is obtained in the picture-word analog of the Stroop task (e.g., Glaser & Düngelhoff, 1984), in which participants name pictured objects (e.g., a picture of a cat, say "cat") while trying to ignore superimposed printed distractor words, which may be incongruent (e.g., *dog*) or congruent (*cat*), or neutral *x*'s. Alternatively, participants read aloud printed words that are incongruent or congruent with the picture name, or they read words surrounded by a neutral, empty picture frame. In picture naming, there is interference from incongruent words and facilitation from congruent words relative to neutral *x*'s, and in word reading, there is no difference between incongruent and congruent pictures relative to neutral frames.

A long-standing issue concerned the functional locus of color-word and picture-word interference (e.g., Roelofs, 2003). Does the interference arise during color or picture recognition, during the planning of the color or picture name, or during the articulatory buffering of the motor program for the name? Note that this is a question about the mind. I discuss how this question has been answered by research using both behavioral and neuroimaging measures, demonstrating the power of neuroimaging to solve cognitive problems and illuminate the mind.

Some researchers argued that the interference arises during color and picture recognition (Hock & Egeth, 1970). According to this explanation, visual processing of the incongruent word interferes with the processing of the color or picture by distracting attention from it, which would explain the naming delay caused by the word compared to the *x*'s. However, this view cannot explain why congruent words (which are also words) often help in naming the color or picture. Furthermore, EEG measurements by Shitova et al. (2017) showed that event-related brain potentials began to differ for incongruent and congruent stimuli approximately 350 milliseconds after stimulus onset for the color-word Stroop and picture-word tasks, but not earlier. The onset of the effect at approximately 350 milliseconds in both tasks links the effect to word planning or later rather than to perceptual recognition, which is estimated in the literature to complete approximately 200-250 milliseconds after stimulus onset.

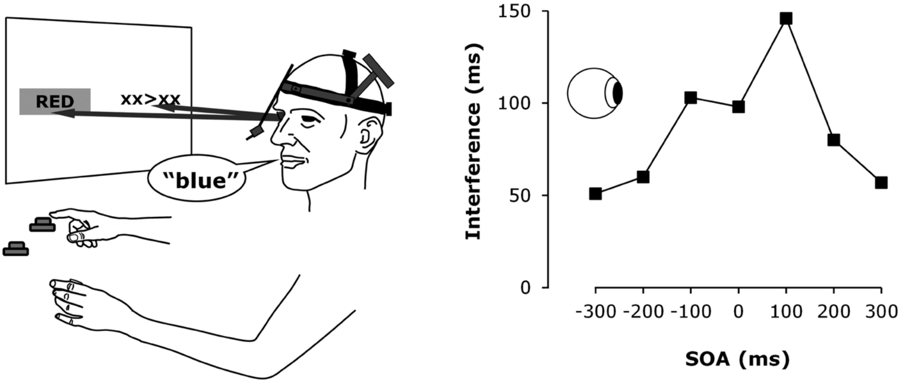


Figure 2.16. Procedure to measure gaze shift latencies in the color-word Stroop task (left) and the time course of Stroop interference in gaze shifts (right) in Roelofs (2014a). ms = milliseconds. SOA = stimulus onset asynchrony, the difference in presentation onset between color rectangle and word. Preexposure of the word is indicated by a minus sign (e.g., –300).

According to the explanation of articulatory buffering, the printed word is automatically processed into its articulatory program and temporarily buffered. The interference is explained as the extra amount of time required to clear the output buffer from this program so that the color or picture name program can be buffered instead (Finkbeiner & Caramazza, 2006). The account is challenged by several findings, including evidence from eye movements. Research on color and picture naming has shown that shifting gaze from one stimulus to another (i.e., overt orienting of attention) occurs before reaching the articulatory buffer in spoken word planning. In eye-tracking experiments that I performed (Roelofs, 2014a), participants were shown color-word Stroop stimuli and left- or right-pointing arrows on different sides of a computer screen (see Figure 2.16, left). A color-word stimulus consisted of a colored rectangle combined with a printed word. To measure the time course of interference, the SOA between a color rectangle and a word was manipulated. The word was presented 300, 200, or 100 milliseconds before color presentation onset (denoted by a minus sign, e.g., −300 milliseconds), simultaneously with (zero SOA), or 100, 200, or 300 milliseconds after color onset. Participants named the color and shifted their gazes to the arrow to manually indicate its direction by pressing a left or right button. If Stroop interference occurs in the articulatory buffer, the interference should be present in the times for color naming (which engages the buffer) but not in the times for gaze shifting (which happens before the buffering) and manual responding. Contrary to these predictions, Stroop interference occurred in all three behavioral measures (shown for the gaze shifts in Figure 2.16, right). These results indicate that Stroop interference occurs during spoken word planning rather than articulatory buffering.

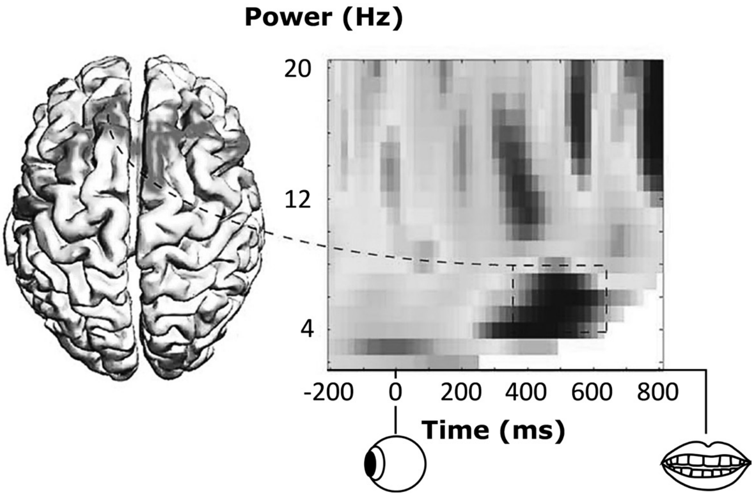


Figure 2.17. Picture-word interference increased theta power (4-8 Hz) in the superior frontal lobe on incongruent compared to congruent trials (left) between 350-650 milliseconds after picture onset (right). Observations of Piai et al. (2014).

If the interference does not occur during perceptual recognition and articulatory buffering, it must occur during color or picture name planning. Direct evidence for this came from an MEG study of picture-word interference by Vitória Piai and colleagues, including myself (Piai et al., 2014). According to time estimates from the literature, a picture is perceptually identified within 200-250 milliseconds, and picture name planning reaches the articulatory buffer no earlier than approximately 145 milliseconds before the onset of articulation, when the average reaction time is about 600 milliseconds (Indefrey & Levelt, 2004). Average picture naming times obtained by Piai et al. were approximately 900 milliseconds. Linear rescaling of the duration of perceptual recognition and reaching the articulatory buffer to account for this difference in mean reaction time (900 vs. 600 milliseconds) indicates that perceptual recognition must have occurred approximately during the first 300-375 milliseconds and articulatory buffering after 700 milliseconds. The MEG findings revealed that the frontal attention system was active between 350 and 650 milliseconds after picture onset, as reflected by an increase in theta power (4-8 Hz) in the superior frontal lobe (Figure 2.17). This corresponds to the time window of word planning.

Computer simulations with Wundt's model

Digital computers and their programming did not exist in Wundt's time, and consequently, he could not investigate his model computationally. Therefore, I did this for him a few years ago (Roelofs, 2021). In particular, I created a possible computer implementation of his apperception model (shown in Figure 2.4) called Wundt 2.0. Next, I tested the model using the classic data on the time course of distractor effects in naming and reading obtained for the color-word Stroop task by Glaser and Glaser (1982) and for the picture-word task by Glaser and Düngelhoff (1984). I examined eight model versions that assumed apperceptive enhancement or inhibition (as discussed by Ribot, 1889, and Pillsbury, 1908), where inhibition was applied at both the perceptual and response levels, at the perceptual level only, or at the response level only (as distinguished by Broadbent in 1958), and where color and picture naming differed from reading either in automaticity or in functional architecture (Cattell, 1886c, versus W. Brown, 1915). The latter means that color and picture naming and reading words occur via different functional routes, such as naming colors and pictures from visual to auditory to articulatory representations and reading words directly from visual to articulatory representations.

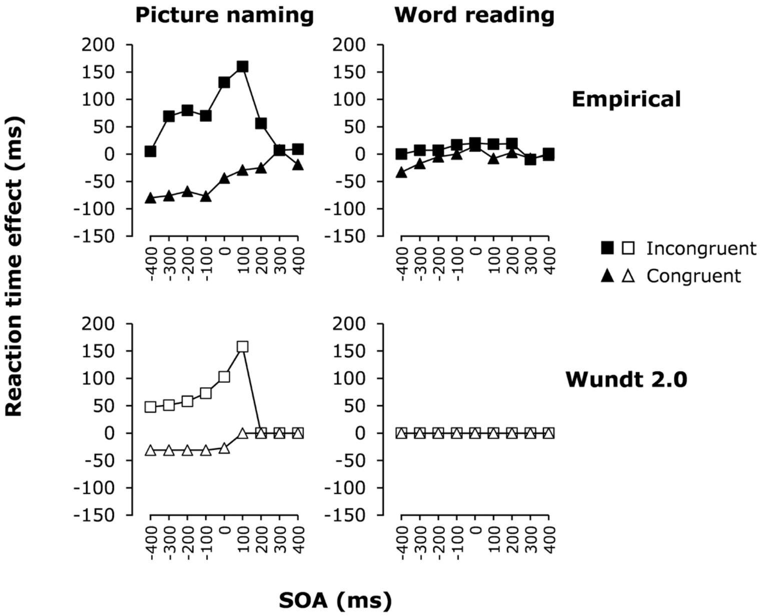


Figure 2.18. The effect of incongruent and congruent distractor words relative to neutral *x*'s in picture naming, and of incongruent and congruent pictures relative to an empty frame in word reading, as a function of stimulus onset asynchrony (SOA) observed empirically by Glaser and Düngelhoff (1984) and in Wundt 2.0 simulations (Roelofs, 2021). ms = milliseconds.

Glaser and Glaser (1982) investigated the time course of the Stroop effect in color naming and word reading by presenting words and colors at a wide range of SOAs. One group of participants had to name the colors and another group had to read the words aloud. The words were displayed in white and the colors were displayed as colored rectangles. The background was dark. The SOAs ranged between 400 milliseconds preexposure and postexposure, with values differing by 100 milliseconds. Stroop interference by incongruent words in color naming increased as the preexposure and postexposure time of the word decreased (as shown for gaze shifts in Figure 2.16). No interference was observed at any SOA during word reading. The same pattern of effect across SOAs for naming and reading was obtained in the picture-word analog of the Stroop task used by Glaser and Düngelhoff (1984). The empirical results for picture-word interference are shown in the top graphs of Figure 2.18.

My computer simulations with the Wundt 2.0 model showed that a perceptual inhibition assumption is necessary to account for the time course of the color-word Stroop and picture-word effects in naming and reading, and together with the architectural difference assumption works best in light of other evidence (Roelofs, 2021). The bottom graphs of Figure 2.18 show the simulation results for the model version with perceptual inhibition and an architectural difference between naming and reading. Although modern computer models in the literature, such as J. Cohen and E. Miller's model (Cohen et al., 1990; Miller & Cohen, 2001), clarify many aspects of color-word Stroop and picture-word interference, they fail to explain its time course, while Wundt's apperception model explains the findings (see Roelofs, 2021, for extensive discussion). Thus, Wundt's model has stood the test of time (pun intended).

Frontal control, a return of phrenology?

The neuroimaging findings of Petersen et al. (1988) on controlled association (i.e., verb generation) and Pardo et al. (1990) on the Stroop task showed that attentional control is supported by the frontal lobes. This has been further corroborated by research over the past few decades. Thus, modern evidence supports Wundt's position. However, not everyone agreed. Uttal (2001) argued that "it is incorrect to think of attention, like many other mental activities ... as a potentially localizable entity" (p. 137). Does frontal control revive phrenology, as Uttal maintained?

When discussing his frontal lobe theory of attentional control, from the second to sixth editions of the *Grundzüge*, Wundt made it clear that he rejected any phrenological interpretation. In 1880, he wrote:

> All these observations only prove that there must be elements in the frontal region of the brain that provide essential intermediate links in the physiological processes that accompany the intellectual functions. ... We would then assume that the sensory impressions only reach *perception* as long as the central excitations remain limited to the actual sensory centers, but that their capture through attention or *apperception* is always connected with a simultaneous excitation of elements in the frontal region. (pp. 217-218)

In the next chapter, I further discuss Wundt's distinction between activation that remains in sensory areas (reflecting perception) and frontal activation (reflecting apperception) and their hypothesized relationship to consciousness. Wundt (1880b) continued:

> After this, there is hardly any need for special remark that, according to this hypothesis, we by no means think of the physiological process accompanying apperception

> as being concentrated in a specific brain region, but that the elements of the "organ of apperception" are viewed in a similar sense as merely indispensable intermediate members, as this happened at the language centers. ... But the dominant importance of this area rests solely on the fact that its elimination abolishes all of those processes, while the elimination of any other contributing center always only makes a part of the apperceptions impossible. For example, elimination of the sensory speech center abolishes the apperception of words, while the perception of faces and even simple sound impressions is still possible. (p. 221)

Not everyone was convinced of Wundt's proposal that the frontal lobes play a crucial role in the attentional control of perception. For example, in an article in the journal *Brain* in 1892, Bastian presaged Uttal (2001) by claiming:

> I should not think of attempting to localise the process known as attention in any one definite part of the brain, but should regard it as having its loci in cell and fibre mechanisms in each one of the cortical sensorial centres – that is, as being concerned with mechanisms scattered all over the cortex, according as we are, with more or less predominance, attentive to visual, auditory, tactile, olfactory, gustatory, or kinaesthetic impressions. (p. 16)

And then Bastian launched an attack on Wundt's supposed phrenology. Bastian (1892) stated:

> Wundt, however, does postulate a distinct organ for apperception (attention) which he also is inclined to localise in the convolutions of the frontal lobe. But it should be said that his theories concerning apperception, its localisation, and the modes of cerebral activity with which it is associated are entirely speculative and fanciful. ... nor can I regard attention, whether called by its own name or by that of 'apperception,' as a 'faculty' which, somewhat in the old phrenological sense, is to be definitely localised in this or that portion of the cortex. (pp. 15-16)

Wundt (1893) was clearly irritated by these words of Bastian. He responded:

> If Charlton Bastian (Brain, Vol. XV, 1892, p. 16) finds something of the meaning of the old phrenology in these assumptions about the organ of apperception, then I need not tell the attentive reader that the knowledge that this distinguished neurologist has gained from the above discussions can hardly extend to more than the word 'Apperception organ'. (p. 232)

Roelofs’ Law

In this chapter, I described discoveries about the attentional control of perception and movement, as well as retrieval from associative declarative memory. Before I summarize the chapter, I would like to take the opportunity here to publicize my own law, which has proven itself for many years within my family circle. The law deals with the situation where you are looking for something, for example your phone somewhere in the house, but you cannot find it. The law combines insights about attention, perception, and memory. My children called it “Roelofs’ Law”, which states: It’s where it should be, but you didn’t look hard enough.

After reading the manuscript of this book, Pim Levelt (personal communication, April 2, 2024) told me that a related law informed his family’s search for lost objects, called “Christiaan’s law”, named after one of Pim’s sons. It may be that Christiaan and I discovered the law independently, which often happens in science (e.g., Simon, 1981). Alternatively, we learned the law from someone else but forgot from whom. In his book *Forgetting: Myths, Perils and Compensations*, Draaisma (2015) explains the mechanism for this: Semantic memory helps you remember facts (like laws), but it does a poor job of retaining the circumstances in which you acquired these facts (e.g., discovered yourself or heard from someone else), which is the specialty of episodic memory.

Summary

In the 19th century, researchers discovered the mathematical form of associative forgetting (Ebbinghaus) and memory consolidation (G. Müller). With processing models in hand (Wernicke, Wundt), researchers also discovered the need for mental mechanisms beyond association, such as attentional control (Wundt). After the discovery of imageless thinking and mental set (Külpe), controversy arose over whether attentional control is achieved associatively (G. Müller) or procedurally (Selz). Since the 1950s, evidence has accumulated for multiple long-term memory systems (Milner), including declarative associative memory and procedural memory, and for multiple attentional systems (Posner), which achieve alertness, orientation, and control. Attentional control, mediated by the procedural system, is supported by the frontal lobes (Wundt, Posner and Raichle).

CHAPTER 3

Decline and return of consciousness theory

In the first couple of decades of the 20th century, after the creation of scientific psychology, questions arose on how to apply psychological theories to solve practical problems in situations such as psychological clinics (Witmer), courtrooms and industry (Münsterberg), and schools (Thorndike). This showed the success of scientific psychology. But some doubts also arose concerning one of the pillars of the new science. For Wundt and James, conscious mental processes were the subject of scientific psychology. This opinion had the upper hand in the early years of scientific psychology but came under fire later on. Freud argued for a theoretical view of the mind in which consciousness plays only a modest role. The behaviorists (Pavlov, Thorndike, Watson, Tolman, Hull, Skinner) banished consciousness from their psychological theories altogether. But in the mid-20th century, it became clear how restricting the behaviorist straitjacket was: There was a need for mentalistic theories of the mind, even to explain the basic behavior of animals other than humans. A new psychology of consciousness took shape in the form of cognitive psychology. In modern-day scientific psychology, consciousness is once again the subject of extensive research and theory formation. The distinction that Wundt and James made between attention and consciousness can still be found in the modern consciousness theory of the Frenchman Dehaene, who also gives it a modern twist.

Psychology in practice

Back in America after studying with Wundt in Germany, Lightner Witmer (1867-1956) began to apply psychological knowledge to patients. His diagnoses and treatments were so successful that they eventually led to the founding of the first psychological clinic in America, at the University of Pennsylvania in 1896. Witmer's team approach to *clinical psychology* typically used a psychologist in conjunction with a medical doctor and a social worker. Assessment of patients included the performance of tasks using instruments that Witmer took from Wundt's lab, like the chronoscope for measuring reaction times. To document his clinical cases, Witmer started the first journal in clinical psychology, called *The Psychological Clinic*. The journal appeared from March 1907 (see Witmer, 1907). After Witmer's work, clinical psychology has become an important branch of psychology. For the history of psychotherapy, I refer to Foschi and Innamorati (2022).

At Columbia University, Cattell's student Edward Thorndike (1874-1949) applied psychology to school-related topics to form *educational psychology*, such as in his books *The Principles of Teaching, Based on Psychology* (1906) and *The Psychology of Arithmetic* (1922). After studying with Wundt, Hugo Münsterberg (1863-1916) was asked by James to come to Harvard, where he laid the foundation for *forensic psychology*, which studies topics like the reliability of eyewitness testimony and false confessions (Münsterberg, 1908). He also founded another new field, *industrial psychology*, which deals with topics like the selection of personnel (Münsterberg, 1913).

Looking back on the latter, Schmidt and Hunter (1998) reported a meta-analysis of 85 years of research findings on personnel selection procedures. They concluded that the best predictor of job performance was a test of general mental ability plus a work sample test, an integrity test, or a structured interview. In the next chapter, I discuss Spearman's (1904) discovery of the theoretical basis for this, expressed in his two-factor theory of mental abilities (i.e., a general intelligence factor plus specific factors).

Despite the success of Witmer, Thorndike, and Münsterberg in applying scientific psychological knowledge, also some doubts arose concerning one of the pillars of the new science. For Wundt and James, psychology was the science of consciousness. While Wundt included the unconscious in his theorizing about the mind in the *Beiträge* (1862a), he was skeptical about knowing the unconscious, arguing that "the phenomena of consciousness are composite products of the unconscious mind, from the nature of which, once they have fully entered consciousness, it is only rarely possible to draw direct conclusions about their formation" (p. xvi). Later, from the *Grundzüge* onward, he stopped theorizing about the unconscious (for an extensive discussion, see Araujo, 2016). The view of psychology as the science of the conscious mind prevailed in the early years of scientific psychology but later came under fire due to the work of Freud and the behaviorists. While Freud emphasized the unconscious, the behaviorist completely rejected theories of the mind, both of consciousness as well as the unconscious. Modern cognitive psychology has shown how both conscious and unconscious processes can be understood through empirical research and modeling, which I discuss in this chapter and the next.

Freudian practices

In Vienna, Sigmund Freud (1856-1939) argued for a theoretical view of the mind in which consciousness plays only a modest role. He proposed a tripartite model of the mind, consisting of partly conscious agents called *ego* (*Ich*) and *superego* (*Über-Ich*) and an agent called *id* (*Es*) that operates wholly unconsciously (e.g., Freud, 1910, 1923). The superego embodies the moral principle, the ego the reality principle, and the id the pleasure principle. The ego and superego try to keep the id in check. Mental disorders may arise because of frustration of the id. To discover what the frustrations are, Freud proposed two methods, namely free association and dream analysis.

Although Freud's emphasis on the unconscious was considered important, the specifics of his theory of the unconscious were received with skepticism by psychologists. One of scientific psychology's criticisms of Freud's theory was that it could not be falsified (e.g., Benjamin, 2024; Boring, 1950), which violates a basic requirement for a good theory (e.g., Popper, 1959). Recently, Tallis (2024) discussed the scientific status of Freud's views more favorably.

The discovery of conditioning laws

The behaviorists banished consciousness from their psychological theories altogether. They redefined psychology as the science of behavior. In 1913, John Watson (1878-1958) published an article entitled *Psychology as the Behaviorist Sees It*, in which he declared the aims of behaviorism. According to Watson, psychology had failed as a science. The measurement of response times was fine, but introspection was considered to be an unreliable method. Psychology needed to restrict itself to more objective methods, like the speed and accuracy of learning in puzzle boxes and mazes by animals, explained later. Classical and operant conditioning were at the heart of behaviorism. It was assumed that these learning principles applied to humans as well as other animals, called the *continuity* hypothesis.

The type of learning called *classical conditioning* was discovered by the Russian Ivan Pavlov (1849-1936) in the 1890s. Pavlov's *Conditioned Reflexes* (1927) provided a full account of his discovery. Normally, dogs start to salivate when they perceive food. Pavlov observed that when the food is presented together with another surrounding stimulus (in his seminal study, the sound of a metronome), after a few repetitions, his dogs started to salivate in response to the stimulus, even in the absence of food. Pavlov concluded that the surrounding stimulus becomes associated with the food and evokes salivation on its own.

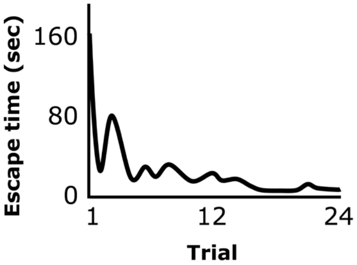


Figure 3.1. Illustration of an escape curve from Thorndike (1911). Sec = seconds.

Another form of learning, *operant conditioning*, was first extensively described by Thorndike in his book *Animal Intelligence* (1911). Historian Benjamin (2007) wrote that Thorndike "began his animal research career testing baby chicks, first in his room until his landlady objected and then in the basement of William James's home. He continued his animal work at Columbia" (p. 137). There, he examined the behavior of hungry cats trying to escape from cages called *puzzle boxes* to obtain food. A cat could escape from the box by a simple response such as "pulling at a loop of cord, pressing a lever, or stepping on a platform ... The animal was put in the enclosure, food was left outside in sight, and his actions observed" (p. 26). Initially, it would take cats a long time to escape, but with repeated trials, they escaped more quickly. This was because successful responses occurred more frequently, and unsuccessful responses occurred less frequently. Thorndike called this the *Law of Effect*, which holds that behavior followed by satisfying consequences is repeated, whereas behavior followed by unpleasant consequences is not. By plotting escape time against trial number, Thorndike provided objective evidence for his law. The curves showed that time to escape decreased over trials, as shown in Figure 3.1. If each successive trial produces a saving in procedural memory, as Ebbinghaus noted for learning and relearning in declarative memory (Chapter 2), a downward curve is to be expected, as observed. Thorndike maintained that his law holds for humans, too: “We learn by the gradual selection of the appropriate act or judgment, by its association with the circumstances or situation requiring it, in just the way that the animals do” (p. 284).

Escape time decreased because of the Law of Effect. In Thorndike’s own words:

> The Law of Effect is that: Of several responses made to the same situation, those which are accompanied or closely followed by satisfaction to the animal will, other things being equal, be more firmly connected with the situation, so that, when it recurs, they will be more likely to recur; those which are accompanied or closely followed by discomfort to the animal will, other things being equal, have their connections with that situation weakened, so that, when it recurs, they will be less likely to occur. The greater the satisfaction or discomfort, the greater the strengthening or weakening of the bond. (p. 244)

In addition, escape time decreased because of the *Law of Exercise*. In Thorndike’s own words:

> The Law of Exercise is that: Any response to a situation will, other things being equal, be more strongly connected with the situation in proportion to the number of times it has been connected with that situation and to the average vigor and duration of the connections. (p. 244)

It is clear that the Law of Effect and Law of Exercise apply not only to escape time but, in general, to other domains as well. For example, in experiments with human participants performing reaction time tasks, a curve similar to that in Figure 3.1 is obtained for reaction time on repeated trials, with the Law of Exercise in operation. Theorists disagree on whether the decrease in reaction time over trials is best characterized by a power function (known as the “Power law of practice”), which implies that learning decreases over trials, or by an exponential function, which implies that learning occurs at a constant rate, as Heathcote et al. (2000) argued.

In 1920, Watson conducted his “Little Albert” experiment demonstrating classical conditioning of emotions in humans (Watson & Rayner, 1920). The participant was a one-year-old boy. When exposed to a white rat, a rabbit, a dog, and other stimuli, Albert showed no fear of any of these stimuli. However, when these stimuli were repeatedly paired with a loud sound evoking fear, he later exhibited a fear response to the stimuli. Thus, classical conditioning occurs in humans and other animals, supporting the continuity hypothesis.

However, over the years, behaviorists discovered that the relationship between stimuli and responses was more complex than they initially thought. Clark Hull (1884-1952) tried to deal with the complexity through mathematical formulas from which behavioral predictions could be derived. Deriving predictions from theoretical hypotheses is called the *hypothetico-deductive method*, which is at the heart of scientific theorizing. In discussing the psychophysical work of Weber and Fechner (Chapter 2), Hull (1943) proposed replacing their stimulus strength threshold, “conceived as a process of the physical stimulus entering the door of consciousness” (p. 323), with a “response threshold” which, when exceeded by activity induced by a stimulus, “will evoke observable reaction” (p. 324). The theoretical notion of a reaction threshold was used in mathematical derivations. However, despite increased mathematical sophistication, several empirical findings by behaviorists suggested that the behaviorist approach was too restrictive and that theorizing required reference to mental constructs.

Edward Tolman (1886-1959) studied how rats learned to find food in mazes, and based on the results of his experiments and those of others, he claimed that rats create *cognitive maps* to navigate a maze. In reviewing the evidence, Tolman (1948) described the experiments as follows:

> In the typical experiment a hungry rat is put at the entrance of the maze … and wanders about through the various true path segments and blind alleys until he finally comes to the food box and eats. This is repeated (again in the typical experiment) one trial every 24 hours and the animal tends to make fewer and fewer errors (that is, blind-alley entrances) and to take less and less time between start and goal-box until finally he is entering no blinds at all and running in a very few seconds from start to goal. The results are usually presented in the form of average curves of blind-entrances, or of seconds from start to finish, for groups of rats. (p. 189)

Tolman’s evidence for cognitive maps included the observation that when rats become familiar with a maze for several days without receiving a food reward (that is, by freely exploring the maze), they later learned the correct route to the food more quickly and with fewer errors, indicating that latent learning had occurred during the familiarization. Other evidence reported by Tolman and colleagues concerned the difference between response and place learning (Tolman et al., 1946). In one condition (place learning), the food was always located in a specific place in the maze, while in another condition (response learning), rats had to follow a certain path through the maze (i.e., always turning right). Place learners needed fewer trials than response learners to reach the food, and they learned faster. According to

Tolman, the place learners constructed a cognitive map of the maze, which allowed them to quickly navigate to the food.

Cognitive maps are beyond the scope of a behaviorist theory and demonstrate the limitation of behaviorism. The findings of Tolman and others led to the demise of behaviorism in the 1950s, although Burrhus Skinner (1904-1990) continued to defend behaviorism until his death almost half a century later.

The principles of classical and operant conditioning appeared to be valid but also somewhat limited. Still, they apply to humans. For example, operant conditioning underlies *addiction*, which is a disorder characterized by a compulsion to engage in behavior that is inherently rewarding despite adverse consequences. Examples include addiction to smoking, gambling, food, and drugs.

After the decline of behaviorism, brain research made important discoveries on the neural underpinnings of conditioning. Earlier, during a decade of research in the 1920s reported in his *Brain Mechanisms and Intelligence* in 1929, Lashley had searched for the traces of learning (the "engram") in the brain by making experimental lesions to the brains of rats (a technique pioneered by Flourens in the early 1800s, see Chapter 1). In particular, he had examined how lesions affected maze learning by the rats and noted that the amount of damage, but not its location, was correlated with the degree of impairment. He summarized his ideas in a presidential address to the American Psychological Association convention in 1929 (Lashley, 1930). What later turned out to be important is that Lashley's experimental lesions were limited to the cortex. Beginning in the 1980s, experimental brain research showed that specific *subcortical* areas, like the hippocampus and the basal ganglia, play a key role in memory, in line with the human patient evidence discussed in Chapter 2.

Since the 1980s, brain research in rats has revealed that Tolman's cognitive maps are stored in part of the hippocampus (declarative memory) and that response learning involves the basal ganglia (procedural memory). Packard and McGaugh (1996) observed that functional inactivation with a local anesthetic of the hippocampus or the caudate nucleus of the basal ganglia has differential effects on place and response learning. If the hippocampus with the cognitive maps is experimentally inactivated, place learning is no longer possible for a rat. Conversely, if the caudate nucleus is experimentally inactivated, response learning is no longer possible. The part of the hippocampus that contains the cognitive maps is close to where the consolidation of new declarative memories happens (e.g., Zheng et al., 2024). Not surprisingly, atrophy of the hippocampus because of Alzheimer's disease not only hampers consolidation but also spatially disorients the patients. They get lost because their cognitive maps are disrupted.

Brain research also showed that classical conditioning of emotions, as observed in Watson's study of Little Albert, is critically mediated by the amygdala (see Eichenbaum, 2012, for a review). Emotional memories are associations between emotional responses and stimuli or events. As with declarative and procedural memories, the consolidation of emotional memories occurs during sleep.

In the 1990s, it was discovered that the Law of Effect is implemented by the basal ganglia (e.g., Packard & Knowlton, 2002). The neurotransmitter *dopamine* appears to provide the learning signal. That is, the basal ganglia represent the response options for a stimulus in procedural memory. If the selected response leads to a satisfying consequence, the dopamine level is increased, which strengthens the connection between the stimulus and response. However, if, instead, the response leads to an unsatisfactory outcome, the dopamine level is reduced, which weakens the connection between the stimulus and response. Thus, dopamine carries the teaching information for learning the appropriate response to a stimulus.

Modern instantiations of Thorndike's laws

The connections between situations and responses hypothesized by Thorndike (1911) bear some similarity to the IF-THEN rules in modern psychology. A major difference, however, is that the IF and THEN parts refer to mental representations and processes, while behaviorists prohibited any reference to mental states and linked external situations directly to overt responses. As Allport (1980), cited by Fodor (1983), stated:

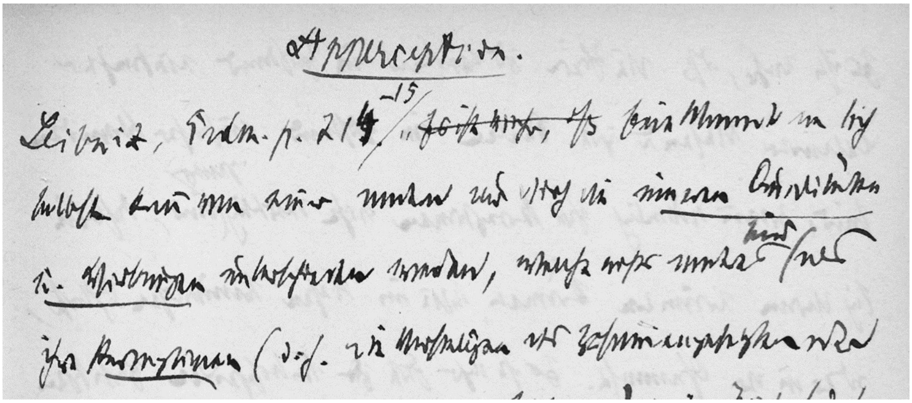
> In the old psychology … linkages between a calling cue and a particular category of action were called 'habits'. The key idea … was that actions ('responses') are addressed or evoked by particular calling conditions ('stimuli'). If we undo the restriction that these a-b pairs must be directly observable events, and instead interpret the a's and b's as specific 'states of mind', providing in addition some relatively simple mechanisms for their interaction, then this simple associationistic conception can have surprising power. Its simplest and most direct application in information processing terms can be seen in so-called 'Production Systems'. (p. 30)

Work in theoretical neuroscience on the basal ganglia has shown how IF-THEN production rules can be realized by networks of spiking neurons (e.g., Eliasmith, 2013). New rules are learned via the basal ganglia with dopamine as a teaching signal, following the Law of Effect. According to this view, input areas of the basal ganglia, such as the caudate nucleus and the putamen, represent the IF (i.e., condition) part of the rules, which is tested against information in the neocortex (e.g., in Broca's area). Output areas such as the globus pallidus release the corresponding action via the thalamus into the cortex (e.g., in Broca's area). Over time, after repeated successful application of the rule, the IF-THEN link is established directly in the cortex via Hebbian learning following the Law of Exercise, without necessary mediation by the basal ganglia (Hélie et al., 2015).

Consciousness regained

Although (brain) research continued to make important discoveries on classical and operant conditioning, from the 1960s onward, a new psychology of consciousness took shape in the form of cognitive psychology. In modern-day scientific psychology, consciousness is once again the subject of extensive research and theory formation. Modern theorizing also attributes an important role to unconscious processing in human cognition (e.g., Lachman et al., 1979; Posner, 1978; Sanders, 1998). This modern view is reminiscent of the view of Helmholtz, who assumed unconscious inferences in perception, including listening to music, as he pointed out in his *Optik* (1867b) and *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (*The Study of the Sensations of Tone as a Physiological Foundation for Music Theory*), published in 1863. The distinction that Wundt and James made between attention and consciousness can still be found in the modern consciousness theory of the Frenchman Stanislas Dehaene (1965-), who also gave it a new twist. Today, Dehaene holds Ribot's chair of experimental psychology, the first in France at the time, at the Collège de France in Paris (Nicolas et al., 2016). I first discuss Wundt's view and then Dehaene's.

From the first edition of the *Grundzüge* in 1874 (Figure 3.2. shows a fragment of handwritten preparatory notes), Wundt illustrated his ideas about consciousness and attention with reference to the human eye. Just as the visual field can be divided into peripheral and foveated parts, consciousness consists of a broad field of awareness, which he called the *Blickfeld*, and a central attended part, called the *Blickpunkt*, where apperception operates. The content of the Blickpunkt can be reported in detail. In modern terminology, the Blickfeld would correspond to *phenomenal consciousness* and the Blickpunkt to *access consciousness*, as the philosopher Ned Block (1942-) called the distinction in 1995. He stated: "Phenomenal consciousness is experience ... access-consciousness, by contrast, is availability for use in reasoning and rationally guiding speech and action" (p. 227). According to Block (2014), we experience more than we can report. Furthermore, access consciousness is thought to require attention, while phenomenal consciousness does not. This is in line with some modern proposals (e.g., Lamme, 2003; Tononi et al., 2016) but not with others (e.g., Dehaene, 2014; Mashour et al., 2020; Naccache, 2018).



Apperception.

Figure 3.2. Handwritten notes by Wundt, dated 1870/1873, on Leibniz, apperception, perception, and consciousness in preparation for the first edition of the *Grundzüge* (1874), where he introduced his version of the concept of apperception.

The recurrent processing theory of Lamme (2003) and the integrated information theory of Tononi (e.g., Tononi et al., 2016) are mainly about phenomenal consciousness. These theories assume that phenomenal consciousness arises as a result of recurrent processing (Lamme) or integration of information (Tononi) in the brain, independent of attention. In contrast, the global neuronal workspace theory of Dehaene and colleagues (e.g., Dehaene, 2014; Dehaene et al., 2006; Mashour et al., 2020; Naccache, 2018) focuses on access consciousness, explaining both phenomenal and access consciousness in terms of the global availability of information (for reasoning, speech, action) that requires attention. In their view, information in both the center and surrounding can be reported, albeit in varying degrees of detail (e.g., if one looks at a row of letters, one might report that the foveated letter is a "B", but the peripheral letters are only "letters" or "something"). I refer to Storm et al. (2024) for an extensive discussion of the various alternative theories.

Similar ideas to Wundt's about attention and consciousness in relation to the human eye were expressed by Helmholtz in his *Optik* (1867b), who wrote:

> The eye is an optical tool with a very large field of vision, but the images are only clear in a small, very narrow area of this field of vision. … However, the mobility of the eye makes it possible to look closely at each individual point in the field of vision one after the other. Since we can only turn our attention to one object at a time, the one clearly seen point is sufficient to keep it completely occupied, however … the large field of vision, despite its indistinctness, is suitable for revealing the main features of the entire surroundings with a quick glance and to immediately notice new phenomena appearing on the sides of the field of vision. (p. 66)

Figure 2.6 in the previous chapter illustrates these properties. The figure shows a color-word Stroop stimulus and an arrow surrounded by *x*'s on different sides of a computer screen. When you fixate the Stroop stimulus on the left side of the screen, you notice that there is something on the right side. However, reporting the identity of what it is (i.e., pressing a left or right button to indicate whether the arrow points left or right) requires a shift in the focus of attention (i.e., a shift of the gaze).

Recently, M. Cohen et al. (2016) argued that the visual environment is represented by *ensembles and summary statistics* (see also Whitney et al., 2014), neuronally supported by brain areas distinct from the areas underlying object processing, such as the parahippocampal gyrus for scenes versus the fusiform gyrus for objects. The ensembles and summary statistics capture the essence of the environment ("the main features of the entire surroundings" of Helmholtz) and give the impression that more is perceived (phenomenal consciousness, the subjective experience of a rich visual word) than focused on (access consciousness). Evidence suggests that deriving ensembles and summary statistics in perception is not costless but requires some attention. On this view, both phenomenal consciousness and access consciousness are attention-dependent (see also Naccache, 2018, and Pitts et al., 2018).

The discovery of mental scope

In one of the experimental tests of his view on consciousness and attention, Wundt (1893) used a *fall tachistoscope* to display arrays of letters, illustrated in Figure 3.3. In very briefly showing a 4 × 4 matrix of letters, participants indicated to have seen more letters than they could verbally report, which was typically around five letters. According to Wundt, this suggests that the Blickfeld is larger than the Blickpunkt. That is, they differ in *scope* (*Umfang*). Wundt (1903) described the operation of his tachistoscope as follows:

> It consists of a vertical wooden board in front of which a black screen falls between rails as soon as it is pulled by the spring F visible in side view B. In the upper part of the screen there is a square opening … When the screen is in the raised position, the visual impressions (the letters) are covered by the screen in such a way that the small white circle on it, which serves as a fixation point, is in the middle of what is subsequently exposed through the opening when the screen falls down. The front view A therefore represents the opening at the moment when the object is exposed by the falling screen for a very short time, only to disappear again behind the upper part of the screen the next moment. (p. 335)

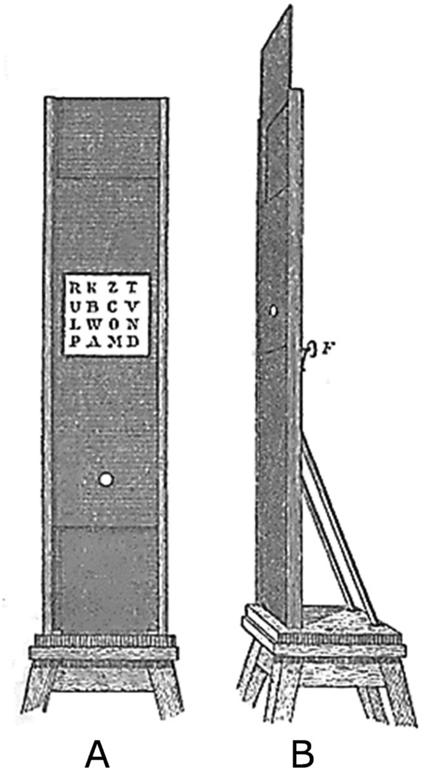


Figure 3.3. The fall tachistoscope of Wundt (1903).

With reference to Wundt's work and also using a tachistoscope, Sperling (1960) improved on the experimental procedure by post-cueing the row of letters to be verbally reported. His tachistoscope worked with light bulbs controlled by microswitches, producing flashes of light lasting 50 milliseconds. The results provided evidence that participants had indeed perceived most of the letters in the other rows. For example, for a display with three rows of four letters, a high, medium, or low tone (lasting half a second) was played, indicating the row to be reported. The tone onset was 150, 300, or 500 milliseconds after letter display offset. Participants were able to report most of the letters in the cued row, indicating that they must have processed most of the letters of the entire display. This is because when the tone is played, the letters have already disappeared.

Also using a tachistoscope, but with one-second displays, Eriksen and Eriksen (1974) experimentally studied selective attention when reporting one of the letters in a row (e.g., an H surrounded by two S's on each side). The participants pressed a small lever switch to the left or right to indicate H or S. This is a situation to which Wundt had applied his processing model of apperception since the 1880 edition of the *Grundzüge*. Incongruent flanker letters (e.g., SSHSS) prolonged reaction time compared to congruent flankers (e.g., HHHHH). To explain performance on the Eriksen flanker task, Eriksen and Yeh (1985) proposed a zoom lens model that was, unaware to them, very similar to Wundt's proposal about apperception in 1874 and the subsequent three editions of the *Grundzüge*.

Wundt (1874) assumed that the attentional width may be adjusted voluntarily to optimize processing (*Anpassung der Aufmerksamkeit*, p. 722), with a reciprocal relationship between width and precision, expressed as

$$e \times h = k$$

Here, *e* denotes the width (*Extension*), *h* indicates the precision (*Helligkeit*), and *k* refers to a constant (*Konstante*). The distributions of attention may differ in terms of whether the capacity is narrowly focused or more widely distributed. Using the Eriksen flanker task, Gratton et al. (1992) provided evidence for adjustment of the attentional distribution based on the previous trial type, with wider processing and, thus, larger flanker effects after congruent than after incongruent trials. This adjustment is not only observed in the Eriksen flanker task but also in the color-word Stroop task, with both manual and vocal responding (Lamers & Roelofs, 2011), and in picture-word interference (Shitova et al., 2017), in behavioral as well as neuroimaging measures. The adjustment engages the anterior cingulate cortex (e.g., Aarts et al., 2008). Wundtian variation in attentional width is illustrated in Figure 3.4, assuming that the distribution of attention across the visual field is bell shaped.

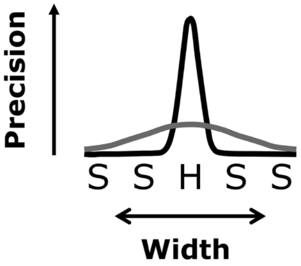


Figure 3.4. Illustration of a Wundtian reciprocal relation between width and precision of attention to an incongruent flanker stimulus. The black curve denotes a narrow focus of attention, and the gray curve indicates a wider distribution.

The ability to adjust the width of the attended region invites a revised interpretation of the relation between Wundt's Blickfeld and Blickpunkt sketched above, namely that they refer to different aspects of the distribution of attention. (This alternative interpretation arose from a discussion I had with Herman Kolk about Wundt's findings with the tachistoscope, in January 2022). The Blickfeld would correspond to the whole distribution of attentional capacity over the entire visual field, while Blickpunkt would be the center. Typically, there is an increased detail resolution in the center (receiving most capacity) and a decrease in the surrounding area (receiving less capacity). In Wundt's experiment with the tachistoscope, broadly distributed attention during the initial presentation of the display of letters gives the impression of seeing the entire display, albeit with little detail, while actually reporting letters requires focused attention, with capacity necessarily allocated to a few letters.

The limited capacity of focal attention is also evident from phenomena such as change and inattentional blindness (e.g., Mack & Rock, 1998; Simons & Levin, 1997). Changes and unexpected events in the visual field outside the focus of attention often remain unnoticed, even when they are large. For example, Simons and Chabris (1999) found that about half the participants failed to notice a person in a gorilla costume walking through the visual field during a visual task they were assigned, which consisted of counting the number of ball passes made by one of two teams.

Yet it seems unlikely that the only difference between center and surrounding is the amount of attentional capacity. As previously mentioned, M. Cohen et al. (2016) argued that the center and the environment are represented differently by object representations and representations of ensembles and summary statistics supported by different brain regions, respectively. Moreover, according to Wundt, apperception is required for synthesizing the perceptual features of stimuli, reminiscent of the feature integration theory of attention of Anne Treisman (1935-2018), developed in the 1980s (e.g., Treisman, 1986; Treisman & Gelade, 1980). When searching for items with a single feature in a display, such as squares or circles in red among green ones, the visual search can be performed in parallel, with the red items simply appearing. Whitney et al. (2014) argued that ensemble coding supports such pop-out. However, when searching for combinations of features, such as red squares among red and green squares and circles, visual search must be performed serially from item to item. Detecting combinations of features, here red and square, requires focused attention, like Wundt's apperception.

A global workspace

My revised interpretation of attention deployment in Wundt's experiment with the tachistoscope is consistent with Dehaene's (2014) view of consciousness (for a recent review, see Mashour et al., 2020). According to this theory, there is no consciousness without attention. Based on a proposal by Bernard Baars (1946-) in 1988, Dehaene's theory of consciousness assumes a *global workspace* (a central system) that is connected to specialized systems, including perceptual systems (input modules) and motor systems (output modules), long-term memory, as well as an attention system (another central system). The global workspace is a *working memory*, a term coined by George Miller (1920-2012) and colleagues in the book *Plans and the Structure of Behavior* (1960). Alan Baddeley (1934-) proposed a related but more limited concept of working memory (Baddeley & Hitch, 1974). Information in the global workspace can be shared between perceptual and motor systems, be used for thinking and other mental processes, or be put in long-term memory, reminiscent of Aristotle's common sense (Chapter 1). Only information in the global workspace is conscious. Dehaene links the global workspace to the prefrontal and parietal cortex:

> The proposal is simple: consciousness is brain-wide information sharing. The human brain has developed efficient long-distance networks, particularly in the prefrontal cortex, to select relevant information and disseminate it throughout the brain. Consciousness is an evolved device that allows us to attend to a piece of information and keep it active within this broadcasting system. Once the information is conscious, it can be flexibly routed to other areas according to our current goals. Thus we can name it, evaluate it, memorize it, or use it to plan the future. Computer simulations of neural networks show that the global neuronal workspace hypothesis generates precisely the signatures that we see in experimental brain recordings. (2014, p. 161)

In order for a stimulus, such as a face or a written word, to enter the workspace, it must have sufficient *strength* and receive *attention*, as illustrated in Figure 3.5 (following Dehaene et al., 2006). The left part of the figure illustrates the four possibilities when the stimulus is weak or strong, and attention is focused elsewhere (absent) or on the stimulus (present). A stimulus is weak when its strength is below Fechner's liminal point (as illustrated in Figure 1.12) and strong when its strength is above it, as shown in the right part of Figure 3.5.

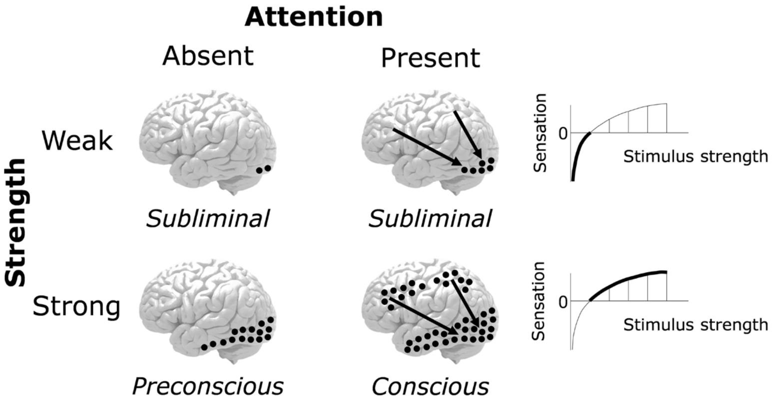


Figure 3.5. The dependence of subliminal, preconscious, and conscious states on the relationship between visual stimulus strength (weak, strong) and whether attention is focused elsewhere (absent) or on the stimulus (present), according to Dehaene et al. (2006). How this corresponds to Fechner's (1860) curves is illustrated on the right.

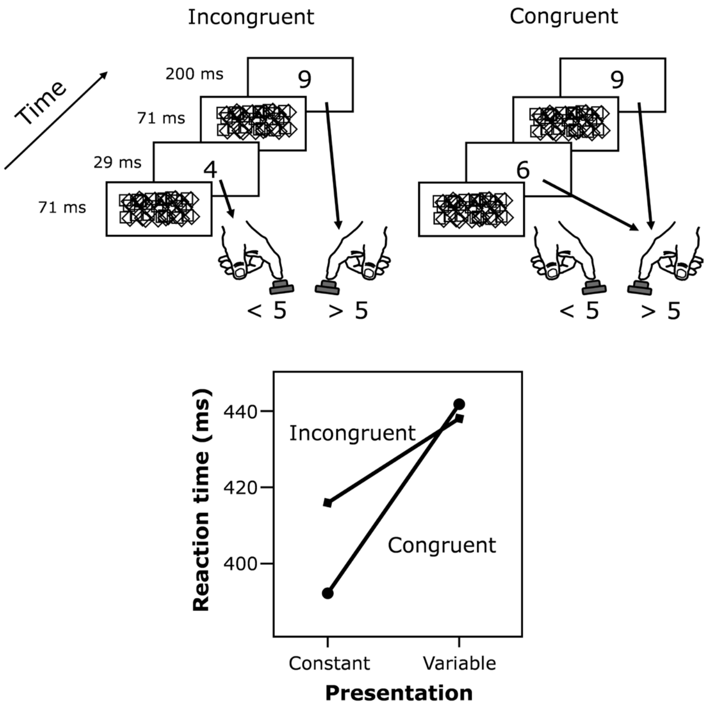


Figure 3.6. Incongruent trials (top left), congruent trials (top right), and the reaction times for these trials with constant or variable presentations (bottom). ms = milliseconds. Observations of Naccache et al. (2002).

A visually masked face or word that is briefly flashed on a computer screen for 29 milliseconds would not be strong enough to surpass the threshold of consciousness, regardless of whether attention is directed to the screen or not. The stimulus remains *subliminal*, as under Fechner's account (Chapter 1). However, there will be more extensive processing in the input modules for face or word perception when attention is directed to the place where the (unseen) face or word is briefly flashed than when attention is paid to other places on the screen. Thus, according to Dehaene's theory, attention may facilitate unconscious processing. When the stimulus is strong, it may become conscious, but only when attention is assigned to it. For example, when the face or word is presented for 200 milliseconds and attention is directed to it, the stimulus will cross the consciousness threshold and enter the global workspace. However, when the stimulus is strong, but attention is paid to other places on the screen, the stimulus will remain unconscious. Still, as soon as it receives attention, the stimulus will become conscious. Hence, according to Dehaene, a strong stimulus that does not receive attention will be *preconscious*

(Dehaene, 2014; Dehaene et al., 2006). If we assume a different distribution of attention across the visual field (e.g., Figure 3.4), a person may be aware of a face or word in the periphery without being able to identify the face or word.

Evidence for these four possibilities (subliminal without attention, subliminal with attention, preconscious, or conscious) comes from behavioral and neuroimaging experiments reviewed by Dehaene (2014). For example, in an fMRI experiment by Dehaene et al. (2001), written words were flashed on a screen for 29 milliseconds and either preceded and followed by visual masks (i.e., patterns of superimposed diamonds and squares) presented for 71 milliseconds or without masks. The words were only visible when there were no masks. Participants were asked to name the words silently in their heads. The results showed that activation was low and limited to the visual cortex for the masked words, but activation was high not only in the visual areas but also in the frontal and parietal cortex for the visible words (i.e., the brain lit up like a Christmas tree). Dehaene described a similar result for the auditory modality (based on additional analyses of an experiment by Sadaghiani et al., 2009). The stimulus strength of a target sound was set such that it was detectable in half of the trials in a noisy fMRI scanner (carefully calibrated for each participant separately). Participants were asked to press a button when they heard the sound. The results showed that activation was low and limited to the auditory cortex when the sound went unnoticed, but activation was high not only in the auditory cortex but also in the frontal and parietal cortex when the sound reached consciousness.

Other experiments by Naccache et al. (2002) in the laboratory of Dehaene indicated that attention may facilitate unconscious processing. In one behavioral experiment (Figure 3.6), the stimuli were the digits 1, 4, 6, and 9. On each trial, one of the digits was presented for 200 milliseconds on a computer screen (e.g., 9). Participants had to indicate whether the digit was numerically larger or smaller than 5 by pressing a left button (smaller) or a right button (larger). Just before the target digit was shown, another digit was briefly flashed for 29 milliseconds and masked, thus remaining subliminal. This prime digit could be congruent with the target (i.e., requiring the same response, e.g., the digit 6) or incongruent (requiring a different response, e.g., the digit 4). Attention was manipulated by presenting the visual target digits always at 810 milliseconds after the previous trial (the constant condition) or also randomly at 1094 or 1449 milliseconds (the variable condition).

With constant intervals, participants could set their attention window to around 800 milliseconds for the next trial, which would imply attention to the target digit but also the subliminal prime. However, with variable intervals, such optimal setting of the attention window was not possible, and the target and prime digits received much less attention. As James (1890) stated in his *Principles*, "*There is no such thing* *as voluntary attention sustained for more than a few seconds at a time*. What is called sustained voluntary attention is a repetition of successive efforts" (p. 420). Reaction times to the targets were longer with the variable than the constant presentations (Figure 3.6, bottom). Most importantly, a difference in reaction time between the congruent and incongruent trials was only obtained for the constant presentations. This demonstrates that attention facilitated subliminal processing.

Whereas, according to Dehaene's theory, attention may facilitate unconscious processing, this is not possible according to Wundt's theory. The differences between the views on consciousness of Wundt and Dehaene are illustrated in Figure 3.7. For Wundt, attention highlights part of consciousness. For Dehaene, attention is necessary for consciousness (no consciousness without attention, unlike Wundt), but attention can also facilitate unconscious processing (again, unlike Wundt). A stimulus is only conscious if it is strong and attention is focused on it.

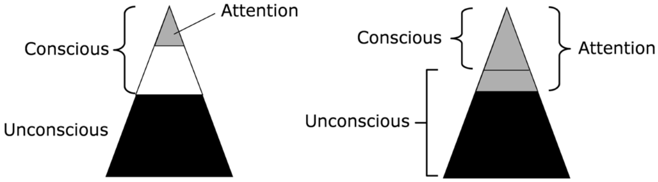


Figure 3.7. The views on consciousness of Wundt (left) and Dehaene (right).

Brain damage to the parietal cortex can impair the ability to focus attention on a particular spatial location, leading to *spatial neglect* (e.g., Bartolomeo et al., 2012). In severe cases, patients eat only the right half of their plate or draw only the right half when copying an image. The left visual field is processed by the right hemisphere, and with right parietal damage, the patient may no longer be able to attend the left visual field, causing information in the left visual field to no longer reach consciousness. In Dehaene's conceptualization, the information no longer reaches the global workspace.

The philosopher Daniel Dennett (1942-2024), author of the book *Consciousness Explained* (1991), stated that an important criterion for a theory of consciousness is that it may not represent a "Cartesian theater". This is a place in the mind or brain where a *homunculus* (a small person in the head) perceives all incoming sensory information and uses it as a basis for decision making and commanding actions. A homunculus is a miniature copy of its host. Because it is a copy, any question about how a particular mental function is achieved is simply shifted from the host to the homunculus. Therefore, a theory that postulates a Cartesian theater does not explain consciousness.

Dennett (1981) argued that a computer model provides protection against homunculi. This is because such a program breaks down a mental function, such as perception or consciousness, into subroutines, and these subroutines further into subroutines until a level is reached where the subroutines can be executed directly by a computer. A flowchart or diagram

> is typically the organizational chart of a committee of homunculi (investigators, librarians, accountants, executives); each box specifies a homunculus by prescribing a function *without saying how it is to be accomplished* (one says, in effect: put a little man in there to do the job). … If we then look closer at the individual boxes we see that the function of each is accomplished by subdividing it via another flow chart into still smaller, more stupid homunculi. … Eventually this nesting of boxes within boxes lands you with homunculi so stupid (all they have to do is remember whether to say yes or no when asked) that they can be, as one says, "replaced by a machine". (pp. 123-124)

When my son Yoram was in elementary school, he learned that the retina maps the outside world upside down onto visual cortex, and then he wondered why we do not see the world upside down. This is the Cartesian theatre view, implying that a homunculus watches the images in visual cortex and sees them upside down. However, for the software of the brain (i.e., the mind), it does not matter how the retina maps the visual world; it just processes the images and links it to information from other senses (correcting the upside-downness). Computer software may perform tasks without human intervention, like recognizing fingerprints or doing complex calculations. And we may have a look at the software to see how the task is accomplished by the program. Thus, trying to understand the software of the brain (the mind) by formalizing theories as computer models and running simulations banishes homunculi and thus prevents a Cartesian theatre in a theory.

Dehaene and his colleagues have implemented their global workspace theory of consciousness as a computer model *programmed as a neural network with spiking neurons*. By running computer simulations, they have demonstrated that the model accounts for many empirical observations on consciousness, including the influence of stimulus strength and attention as well as findings on brain activation. Dehaene has described his theoretical and empirical work on consciousness in the book *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts* in 2014.

The crucial point here is that a computer model consists of subroutines, each of which is simpler than the entire program itself. While Baars's (1988) verbal description of the global workspace could be criticized by saying that it is unclear which processes act on the contents of the workspace, this is made explicit in computational terms in Dehaene's theory. Thus, it can be said that workspace theory does without homunculi. Yet there are heated debates in the literature about whether workspace theory can really explain *all* the features of consciousness. For example, can it explain phenomenal consciousness? And what kind of attention (as discussed in the previous chapter) is needed? Naccache (2018) argued that global workspace theory explains phenomenal consciousness, and Pitts et al. (2018) discussed the issue of the kind of attention. Hatamimajoumerd et al. (2022) provided evidence that a report instruction enhances frontal activation, and Panagiotaropoulos (2024) reviewed evidence for a crucial role of the prefrontal cortex in phenomenal consciousness.

Consciousness and production systems

Regarding the computational properties of a program that realizes consciousness, or the global workspace, Dehaene (2014) stated:

> It closely resembles what computer scientists call a "production system," a type of program introduced in the 1960s to implement artificial intelligence tasks. A production system comprises a database, also called "working memory," and a vast array of if-then production rules (e.g., if there is an A in working memory, then change it to the sequence BC). At each step, the system examines whether a rule matches the current state of its working memory. If multiple rules match, then they compete under the aegis of a stochastic prioritizing system. Finally, the winning rule "ignites" and is allowed to change the contents of working memory before the entire process resumes. Thus this sequence of steps amounts to serial cycles of unconscious competition, conscious ignition, and broadcasting. Remarkably, production systems, although very simple, have the capacity to implement any effective procedure – any thinkable computation. (p. 105)

Production systems have been developed not only in the field of artificial intelligence but also as models of the human mind since the 1970s, when Newell and Simon proposed production system models of human problem solving (Newell, 1973; Newell & Simon, 1972). In the previous chapter, I discussed production system accounts of controlled memory retrieval and solving the Tower of Hanoi puzzle (Simon, 1975). Production system theories have been developed for a wide range of higher-level cognitive processes by John Anderson and colleagues (Anderson, 1983;

Anderson et al., 2004) and Newell (1990), for executive control by David Meyer and David Kieras (1997), and for human intelligence, as assessed by the Raven test, by Patricia Carpenter and colleagues (1990). A Raven test problem consists of a matrix of eight geometric figures and one missing figure, the task of which is to determine the regularities in the rows and columns and select the missing figure from choice options listed below the matrix (Chapter 4). As indicated earlier, Chris Eliasmith (2013) provided a theoretical account of how production systems can be realized by networks of spiking neurons, with a central role for the basal ganglia. Prior to Baars's (1988) and Dehaene's (2014) proposals of a global workspace for consciousness, Zenon Pylyshyn gave the following characterization of production systems in 1981:

> A production system consists of two main parts: a communication area, called the *workspace*, and a set of condition-action pairs, called *productions*. If the condition side of a production is satisfied by the current contents of the workspace, then that production is said to be evoked, and the action on its action side is carried out. … All messages are broadcast, since the contents of the workspace are visible to all productions. … The system is responsive to a limited number of symbols at a time, which may be thought of as being in its focal attention. … These symbols then identify goals. A typical production system contains many goal-setting and goal-consummating productions. … Thus, in order to attend to more aspects, it is necessary to trade off space for time. A natural approach is to assign a single symbol to designate a whole group of symbols, which can then be reconstructed from it whenever necessary. (pp. 80-82)

This latter process is called "chunking", which is further discussed in the next chapter. There, we also see that effective goal management (through goal-setting and goal-consummating productions) is one of the most important ingredients of general intelligence, variation of which is an important cause of individual differences in problem-solving ability.

Figure 3.8 summarizes the production system's view of consciousness. Information from the senses, such as sight, or from declarative memory, is conscious when it is in the global workspace or working memory. Access to the workspace requires attending the information, which is accomplished by production rules in procedural memory. Information in the workspace or in declarative memory can trigger production rules, thereby retrieving declarative information, changing the contents of the workspace, or creating movement. The allocation of attention can be goal-directed (top-down) or triggered by a salient stimulus (e.g., a strong, unexpected stimulus), as proposed by Wundt (1896). Many of the interactions between procedural and declarative memory, between perception (e.g., vision) and declarative memory, and between procedural memory and movement (i.e., a manual response) occur outside the workspace, that is, automatically. For example, when viewing the on-screen position of a subliminal stimulus (e.g., a digit flashed for 29 milliseconds, preceded and followed by masks), a corresponding response (e.g., a press of the left or right button) may be slightly activated (indicated by the direct link between the input and output systems in Figure 3.8) without consciousness. This can result in shorter reaction times, as observed by Naccache et al. (2002). When the subliminal stimulus is presented outside the focus of spatial attention, no priming is obtained (Lachter et al., 2004; Lien et al., 2010).

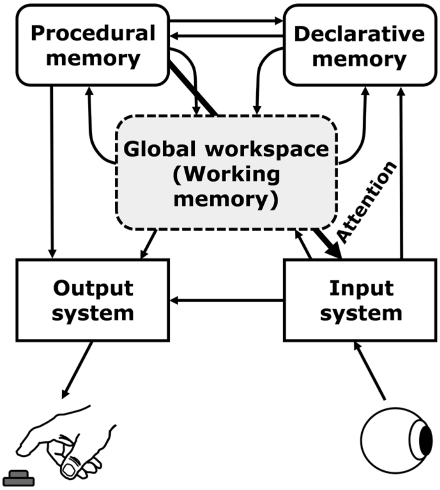


Figure 3.8. Illustration of a production system's view of consciousness

Summary

In the early 20th century, skepticism arose about the possibility of scientifically studying the conscious mind. Instead, behaviorism in America advocated studying behavior alone, inspired by the discovery of classical and operant conditioning (Pavlov, Thorndike). However, discoveries such as navigation using cognitive maps (Tolman) indicated that conditioning principles are insufficient to explain even simple behavior. Later in the 20th century, researchers again began studying mental processes, including consciousness. The 19th-century observations on mental scope suggested that attention emphasizes part of consciousness (Wundt). However, guided by the view that consciousness is supported by a central workspace that enables global information exchange (Dehaene), researchers found evidence that attention is necessary for consciousness and that attention can even facilitate unconscious processing.

CHAPTER 4

From intelligence test to theory

Psychological tests like those for intelligence have played an important role in scientific psychology ever since its earliest years (Galton). A major problem with these early tests was that they were not based on scientific insight into the underlying mental abilities. For example, it was not clear just what intelligence was, as measured by the intelligence tests. The lack of basic theory formation led to failed tests like those of Wundt's student J. Cattell or to psychologically empty constructs like the "general intelligence factor g" of Wundt's student Spearman. Later tests by Spearman's students Wechsler, Raven, and R. Cattell were successful in measuring intelligence, but intelligence theory still failed to materialize. True insight into intelligence demands research into the nature of intellectual capabilities and individual differences within them. Early scientific psychological research was performed in areas such as gender differences (Thompson, Hollingworth). Insight into the nature of intellectual abilities took shape beginning in the mid-20th century thanks to the work of cognitive psychologists (Brown, G. Miller, Broadbent, Bruner) and AI pioneers Newell and Simon, culminating in "intelligent" computers (Artificial Intelligence). Modern cognitive theories of intelligent behavior like those of Duncan provide an explanation for Spearman's g, with a remarkable similarity to what Wundt had proposed.

Individual differences examined

Scientists estimated that our genetic common ancestors (our genetic Adam and Eve) lived in Africa about 100,000 to 150,000 years ago (Poznik et al., 2013). In 2001, the journals *Science* and *Nature* published the first analysis (covering more than 90%) of the human genome, which is the genetic blueprint for a human being. It is now estimated that the human genome contains about 20,000 protein-coding genes (Amaral et al., 2023). These genes influence many of our mental abilities, including our intelligence, and an important question is to what extent individual differences in intelligence are genetically determined.

The issue of *genes versus environment*, also referred to as predisposition versus upbringing, was central to the work of the Englishman Francis Galton (1822-1911) in London, England. He coined it as the issue of "nature versus nurture". Galton pioneered the use of twins to study the roles of genes and environment. He was basically interested in measuring humans in every way possible. This included measuring our ability to make sensory discriminations, which he assumed was linked to general intellectual power. Galton (1883) wrote: "The only information that reaches us concerning outward events appears to pass through the avenue of our senses; and the more perceptive the senses are of difference, the larger is the field upon which our judgment and intelligence can act" (p. 27). If a person has good sensory abilities, the intellectual processes that work with them can also become good. Using weight discrimination (Weber), Galton claimed to have obtained evidence of this: "The trials I have as yet made on the sensitivity of different persons confirms the reasonable expectation that it would, on the whole, be highest among the intellectually ablest" (p. 29). To quantify the relationship between variables (e.g., sensory discrimination and intelligence), Galton developed the *correlation coefficient*, which he applied in many of his studies, including the analysis of questionnaires, which he also pioneered. Galton observed that individual differences are normally distributed, and he invented a device known as the bean machine for demonstrating properties of the *normal distribution*. The bean machine consisted of a vertical board with rows of pins. Beans were dropped from above and then bounced left or right when they hit the pins. The beans were collected in bins at the bottom, with the distribution of the beans across the bins approximating a normal distribution. To quantify normal variation, Galton conceived of the *standard deviation*.

Galton's (1873, 1874) handwritten personal notes show that he read both Wundt's *Grundzüge* from 1874 and Donders' classic article from 1868, although he did not have high expectations of the subtraction technique: "nothing very much results from it all" (p. 19). History has proven him wrong, as we have seen in the previous chapters.

Other researchers criticized Wundt's proposal that apperception is an important component underlying intelligence, linked to the frontal lobes. In a letter to Wundt dated April 22, 1887, J. Cattell (one of his former students, see Chapter 2) mentioned the criticism of Alexander Bain published that same month. Cattell wrote: "Have you noticed what Prof. Bain says of you in the last number of 'Mind'? He should not criticize you when he cannot read German". Bain (1887) disapproved of Wundt's claim that the laws of association are insufficient to explain intellectual processes. Bain wrote:

> In Wundt's conception these laws are afflicted with the incurable disqualification of *passivity*, which restricts their unassisted workings to the lower forms of sensation and memory. Instead of pushing them to the explanation of the higher faculties of reasoning and imagination, as the English associationists profess to do, he considers it necessary to take an entirely new departure, to lay down a principle of Intellectual Activity, with laws of its own and a foundation of its own; locating it in a purely spiritual region of the mind, which has nothing in common with the physical constitution of the senses and the brain. This principle of activity he names Apperception, and thus expounds. (p. 175)

Rather than trying to understand through experiments the nature of the mental processes that support intelligence, as Wundt wanted to do, many researchers followed Galton in their efforts to measure individual differences in intellectual abilities. Researchers "in the late nineteenth century were obsessed with the search for that Holy Grail of psychological testing, an index of *general* intelligence independent of any specific abilities" (Lovie & Lovie, 1996, p. 80). Carson (2018) discussed the social and cultural context of this sacred fire for measuring individual differences in intelligence.

Much inspired by Galton's pioneering work on individual differences, J. Cattell created *mental tests* (a term he coined) for measuring elementary psychological abilities, like reaction time to sounds, time for naming colors, judgment of 10 seconds time, and bisection of 50 cm. Cattell's (1890) article about his tests in the journal *Mind* ended with remarks by Galton. In his dissertation work supervised by Cattell, Clark Wissler gave the tests to students at Columbia University in New York. Wissler (1901) found that mental laboratory tests (e.g., reaction time, bisecting a line, memory) showed little intercorrelation, that physical tests (e.g., hand strength, fatigue) showed a general tendency to intercorrelate, but only to a very small extent with the mental tests, and that the grades of the students intercorrelated to a considerable extent, but not with the tests performed in the laboratory. Based on these disappointing results, Cattell decided to stop making psychological tests himself. Instead, he spent much of his time editing his journals. However, in later years, Cattell established a company, *The Psychological Corporation*, that published intelligence tests, including the WAIS, to be discussed later. Cattell's daughter Psyche was active in creating tests to measure the intelligence of infants and young children (Cattell, 1960), which were published by her father's company.

Kraepelin (1896) advocated the use of psychological tests in psychiatry, such as those developed by his student Axel Oehrn as part of his dissertation (1896). These tests consisted of counting syllables, addition, writing to oral dictation, reading, and remembering lists of numbers and syllables (adapted from Ebbinghaus, 1885). Ten healthy participants were tested by Oehrn, including Kraepelin and himself. Oehrn discussed the means and variances of test performance in terms of the mental processing stages thought to be involved, the effects of practice and fatigue, and individual differences in test performance. He concluded:

> The concept of psychological performance, which we tried to make accessible to experimental investigation, has itself dissolved in the course of this test into a whole series of individual components, which only when they interact together represent the characteristics that we usually refer to as human performance. … the methods used here provide the tools that enable us to gain ever deeper insight into the diverse interplay of functions and abilities that make up the wealth of individual forms of human intellectual talent. (p. 151)

Referring to the mental tests proposed by Cattell, Kraepelin, and Oehrn, the Frenchmen Binet and Henri (1895) put forward their own proposal for mental tests, which they argued should include tests of "memory, nature of mental images, imagination, attention, capacity to understand, suggestibility, aesthetic feeling, moral feeling, muscular strength and will power, skillfulness and glance" (p. 435). The tests still needed to be developed and applied, which Binet later did when developing tests for school children. In making his first tests, Binet tried them on his two daughters, the results of which are described in *L'Étude Expérimentale de l'Intelligence* (*The Experimental Study of Intelligence*), published in 1903.

While Oehrn (1896) tested adults, Ebbinghaus (1897) tested schoolchildren. In 1894, he moved from Berlin to Breslau, where the municipality asked him to develop methods to study the problem of school fatigue. Assuming that "the actual activity of intelligence is combining activity" (p. 16), he created a new combination test

(*Kombinationsmethode*, p. 18), requiring the completion of written texts by writing the correct words on places where they had been left out. In a footnote clarifying his idea of combining activity, Ebbinghaus noted that "[t]he term apperception, used by many psychologists, could also be used here" (p. 16). In addition to the combination test, Ebbinghaus used a test of addition and multiplication (*Rechenmethode*) and a memory test (*Gedächtnismethode*), which consisted of "giving the children short series of monosyllabic number words in different arrangements and with a specific speed, and then immediately after listening to each row they write down what they remembered from it" (p. 12), nowadays called *immediate serial recall*. To assess the effect of fatigue, the children were tested at four different times during a day. Ebbinghaus compared the test performance with the children's class division and found agreement for the combination and arithmetic tests but not for the memory test (he could not calculate correlations, a technique developed later). Performance declined throughout the day, except on the memory test. These results confirmed concerns about fatigue and suggested that immediate serial recall does not really tap into the ability underlying intellectual performance. The combination test of Ebbinghaus would later be incorporated into Binet's (1905) test battery and would also be used by Krueger and Spearman (1907), who also reanalyzed Oehrn's (1896) data, discussed later. In an obituary for Ebbinghaus, Woodworth (1909) wrote that the combination test "has been widely used, and has probably greater claims to be regarded as a test of intelligence than any other single test that has been introduced" (p. 256).

Alfred Binet (1957-1911), working in Paris, was also successful in creating tests to measure intelligence. French education changed greatly during the end of the 19th century because of a law that made it mandatory for children ages six to fourteen to attend school. Binet was asked by the French government to design a test that could separate the normal child from the child with learning difficulties (who would require extra education) and to measure the differences. Binet and his colleague Théodore Simon (1873-1961) created a test to achieve this (e.g., Binet, 1905; Binet & Simon, 1916). The test was successful in identifying children with learning difficulties, but there was no theory of intelligence to guide the choice of test materials. In 1908, Goddard made an English-language version of Binet's test, and in 1912, Stern proposed the concept of IQ (the IQ is a score obtained by dividing a child's score on the intelligence test by the child's chronological age). In 1916, Terman published a new version of Binet's test for the American market, the Stanford-Binet test.

Another student of Wundt, the Englishman Charles Spearman, was also much more successful than Cattell (1890) in measuring intelligence. Spearman's move into scientific psychology came late, following a military career, which he called his "wasted years" (Lovie & Lovie, 1996). While working in Leipzig on his dissertation, Spearman published a groundbreaking study about intelligence in 1904, which was conducted before he came to Germany.

The discovery of *g*

In his 1904 study, Spearman reported on his analyses of the abilities of schoolchildren in towns near London in England, including school performances on classical languages (Greek and Latin), French, English, mathematics, and music, as well as tests of sensory discrimination for light, pitch, and weight (inspired by Galton and the psychophysical studies of Weber and Fechner). For each school subject and each test, the children were ranked based on their performance and the correlations between the rankings were calculated. Spearman called his studies "experiments" (as did Duncan, 2010), although they were concerned with correlations rather than manipulations of independent variables to see the effect on dependent variables, as an experiment was defined after Woodworth's (1938) *Experimental Psychology* (Winston, 1990). Some of the "experiments" were done in Spearman's own house. Calling the sensory discrimination tasks "interviews", he wrote:

> [One] school was particularly favorable for my purpose, as it was within 100 yards of my own house; all the children and their families resided in the immediate neighborhood, so that I could easily obtain any information concerning them; the rector and schoolmaster most obligingly gave their valuable co-operation, for which I hereby tender hearty thanks. Each child was separately interviewed in my house, on a different day for each different sense. (p. 246)

One of the purposes of the study was to investigate whether there is a correlation between sensory discrimination and general intelligence, as Galton claimed. Spearman tested this hypothesis in samples of schoolchildren and observed "a correspondence between what may provisionally be called 'General Discrimination' and 'General Intelligence' which works out with great approximation to one or absoluteness" (Spearman, 1904, p. 284). One hundred years later, Ian Deary and colleagues (2004) replicated this finding with a similar sample of schoolchildren and modern structural equation modeling of the data, observing that general intelligence and general discrimination had a correlation of 0.92. They published this replication in the same journal as Spearman's original 1904 study, *The American Journal of Psychology*, founded by Hall.

Another landmark observation by Spearman was that all correlations were positive. Table 4.1 shows his correlation matrix for the rankings of the children on school subjects and a sensory test, with correlations between 0.40 and 0.83.

Table 4.1. Spearman's (1904) table of correlations between the rankings of 36 children on school subjects and a pitch discrimination test, modified to show only correlations off the diagonal in the lower half.

	Classics	French	English	Mathem.	Discrim.
French	0.83				
English	0.78	0.67			
Mathem.	0.70	0.67	0.64		
Discrim.	0.66	0.65	0.54	0.45	
Music	0.63	0.57	0.51	0.51	0.40

To explain the "positive manifold", Spearman postulated the existence of a *general intelligence factor*, later denoted by the letter *g*, that underlies the performance on all school subjects and sensory tests. To the extent that the school subjects and tests require *g*, a high *g* will lead to good performance on all subjects and tests, and a low *g* will lead to poor performance. Furthermore, Spearman assumed that each school subject and test involves a specific ability, denoted by the letter *s*. The results and account were published by Spearman in the now classic 1904 article entitled *"General Intelligence," Objectively Determined and Measured*.

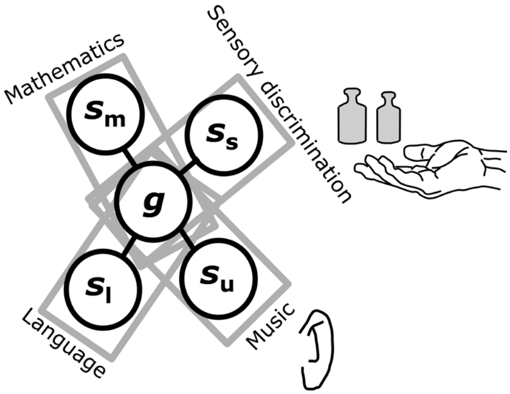


Figure 4.1. Illustration of Spearman's two-factor theory of intelligence. After the first figure in the Appendix of Spearman (1927).

Over the next thirty years, Spearman further developed his theory of intelligence, especially in a number of books. These include *The Nature of 'Intelligence' and the Principles of Cognition* (1923), *The Abilities of Man: Their Nature and Measurement* (1927), and *Psychology Down the Ages* (1937). The theory became known as the *two-factor theory of intelligence*, illustrated in Figure 4.1.

The theory states that any individual measurement of any ability (V), like language, mathematics, sensory discrimination, and music, can be divided into two independent components:

$$V = g + s_v$$

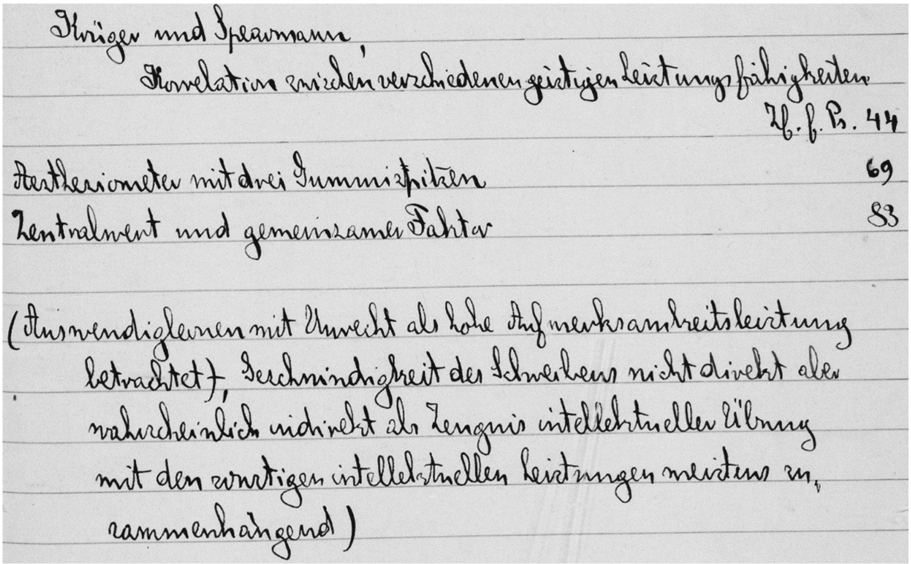
One component, the general factor g, varies from person to person, but is constant for each individual. The second component, the specific factor s, varies not only from individual to individual, but even from ability to ability for each individual, indicated by the subscript v (e.g., s_m denotes an ability specific to mathematics). In terms of depth and scope, this equation is psychology's equivalent of Einstein's famous mass-energy equation.

As a test of his equation, which assumes that all correlations among the measures of abilities V are due to the common factor g, Spearman (1904) examined whether the correlations in a table are hierarchical. That is, if the correlations are arranged in order of magnitude, with the highest correlation in the top left corner of the table, the correlations should decrease in the same proportion throughout the table, both in the vertical and horizontal directions. And this is what Spearman observed, as can be seen in Table 4.1. A more precise test would have been to calculate what are mathematically called the *tetrad differences* (i.e., for every four tests, the difference between the product of any two correlations and the product of the other two correlations), which are predicted to be zero. However, computing these would have been too much of an effort at the time, due to the lack of digital computers. Horn and McArdle (2007) reported that running such a test on a modern computer yielded an estimate of the probability of fit to the g model of 0.99 (i.e., an almost perfect fit).

The nature of *g*

In considering the psychological nature of g, Spearman rejected the idea that it reflects the capacity for attention, as Wundt (1880b, 1902) had suggested in his assumption that apperception is a crucial factor in intelligence. In a study that Spearman conducted together with Felix Krueger in Wundt's laboratory in Leipzig

(Krueger & Spearman, 1907), participants were tested on tone discrimination, touch discrimination, addition, immediate serial recall (i.e., lists of digits), and Ebbinghaus' combination test (i.e., filling in missing words in a text). Although predominantly positive correlations between test scores were obtained, they were low for immediate serial recall (referred to as *Auswendiglernen* in the article). The correlations formed a hierarchy indicating the presence of a general factor *g*. Krueger and Spearman also reanalyzed Oehrn's (1896) data set, with similar results. Based on these findings, they rejected an interpretation of the general factor in terms of attentional control ability. This ability should have played a role not only in the discrimination, addition, and completion tests, but also in immediate serial recall, which apparently was not the case. Ebbinghaus (1897) had also found that immediate serial recall differed from his combination and arithmetic tests in terms of correspondence to children's class classification and the effect of fatigue.



Krüger und Spearmann,
Korrelation zwischen verschiedenen geistigen Leistungsfähigkeiten
Z. f. Ps. 44

Aesthesiometer mit drei Gummispitzen 69
Zentralwert und gemeinsamer Faktor 83

(Auswendiglernen mit Unrecht als hohe Aufmerksamkeitsleistung
betrachtet), Geschwindigkeit des Schreibens nicht direkt aber
wahrscheinlich indirekt als Zeugnis intellektueller Übung
mit den sonstigen intellektuellen Leistungen meistens zu-
sammenhängend)

Figure 4.2. Wundt's handwritten notes, dated 1908, on Krueger and Spearman's (1907) article on the general factor, which Wundt associated with attention.

Responding to Krueger and Spearman (1907), Wundt (1911) made explicit his position that the general factor reflects an individual's general attentional capacity. Figure 4.2 shows Wundt's handwritten notes on Krueger and Spearman's article, in which he noted that immediate serial recall was incorrectly viewed as a task requiring high attentional performance ("Auswendiglernen mit Unrecht als hohe Aufmerksamkeitsleistung betrachtet"). In the *Grundzüge* of 1911, he stated:

> Spearman concludes from his results that the central factor, which determines all individual correlations, cannot be attributed to any psychological force, especially not to the tension of attention. … I find it hard to believe that these reasons are sufficient to reject the interpretation that attentional performance is the central factor. (p. 598)

Wundt was right about the low attentional demands of immediate serial recall. Modern research has shown that performance on such a task does not correlate with measures of attention and intelligence, while immediate serial recall combined with a secondary distractor task (e.g., sentence verification) correlates strongly (e.g., Conway et al., 2002; Engle et al., 1999; Kane & Engle, 2002; Oberauer et al., 2018). The crucial difference is that the task combination, but not the simple task, requires attentional control (e.g., Mashburn et al., 2024, for recent discussion). Immediate serial recall involves only short-term memory capacity, while when combined with a secondary distractor task, it draws on working memory capacity. The nature of the relationship between discrimination performance and intelligence, as shown in Krueger and Spearman's data, is discussed later.

Wundt had linked apperception to a specific part of the brain, namely the prefrontal cortex. To the extent that apperception contributes to intelligence, the prefrontal cortex should also be linked to intelligence. This assumption would become important for modern neuroimaging studies testing between different views on the nature of *g*, discussed later.

Spearman came up with another proposal further specifying the nature of *g* and its relationship to the brain. In a 1914 article in *Psychological Review*, he argued that "*all the intellective activity of any person depends in some degree on one and the same general fund of mental energy*" (1914, p. 103). But "the success of any intellectual performance is said to depend on the general energy *in some degree* only. This indicates that there is a *second* factor in the person's success, namely, his *specific capacity for that particular kind of performance*" (pp. 104-105). He then continued stating:

> The double relation may be found clearer by many readers when expressed physiologically. And, of course, the accord with physiology is itself an important evidence. According to the commonly accepted theory of cerebral localization of function, every mental performance involves an activity of some particular group of cortical neurons. To this the present theory adds, that the particular group of neurons needs more or less reinforcement by the energy of the whole cortex (or some even more extensive area). Thus, the two factors in success are quite distinct; firstly, there is the

> state of the particular group of neurons, their development and organization; and secondly, there is the whole cortex. The former may be called the 'specific' factor, as it is specific to that particular performance. The latter constitutes the 'general' factor, since it is required for all performances. (p. 105)

In his 1927 book *The Abilities of Man*, Spearman used a diagram that illustrated his ideas about the neural basis of the general and specific factors. The diagram is shown in Figure 4.3. He explained: "The whole area represents the cerebral cortex, whilst the shaded patch is some special group of neurons (for convenience of the figure, taken as collected in one neighbourhood). The arrow heads indicate the lines of force coming from the whole cortex" (p. 134).

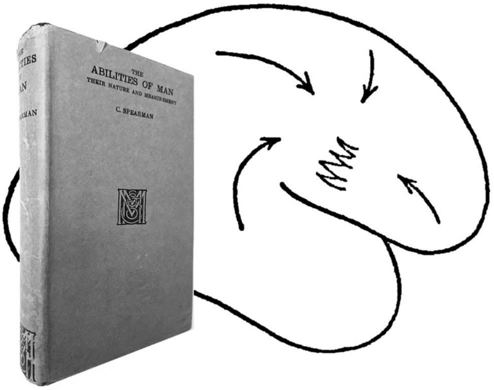


Figure 4.3. Spearman's (1927) *The Abilities of Man*, a first edition in dust jacket, together with a diagram showing the neural basis of his general and specific factors.

Spearman believed that his view of *g* as the energy of the entire cortex was consistent with Lashley's (1929) ideas about equipotentiality and mass action. In *Psychology Down the Ages*, Spearman (1937) stated: "Here … comes the most luminous conception of all; that of Lashley. According to this, the G would measure some "mass action" of the cortex of the brain" (p. 237). He wrote:

> G, we found, could be explained as measuring some "general energy" – probably derived from a large portion of the nervous system. … But "energy" as commonly conceived needs to be supplemented by "engines" in which to operate. And such engines, it has been suggested, are supplied by the nervous system, in so far as

> its functions are *localized*. And in point of fact, just such localized functions would appear to constitute the abilities measured by the S's. (pp. 260-261)

Previously, we saw that Lashley had investigated the effect of experimental lesions in the brains of rats on their maze learning and sensory discrimination, finding no cortical localization of learning (holism) and observing localization of visual discrimination in the occipital cortex. Spearman's view of the mind is similar to Fodor's, with localized specialized systems (Spearman's S's and Fodor's modules) and a general nonlocalized ability (G and the central systems). It is no surprise that the epigraph of Fodor's book was a quote from Spearman (1927) about faculty psychology ("... The doctrine loses every battle – so to speak – but always wins the war..."). Like Fodor with his modularity theory, Spearman held that his two-factor theory reconciled the historical views of localization and holism.

In an article entitled *Mental Tests of Dementia* (Hart & Spearman, 1914), the two-factor theory was tested on observations about dementia in a study that Spearman conducted with physician Bernard Hart. At the time, "dementia" referred to a variety of mental disorders, including what was called dementia praecox, general paralysis, manic depression, paranoia, and other psychiatric and neurological disorders. Contrary to what was commonly believed at the time (and what is clear today, e.g., Seeley et al., 2009; Segal et al., 2023), Hart and Spearman assumed that the entire cortex was diffusely affected in the disorders. They tested 68 patients, all inmates of Long Grove Asylum. Despite the heterogeneity of the mental disorders, Hart and Spearman found evidence for a general intellectual decline across all disorders, which was believed to support their view of *g*. Modern studies have confirmed the general cognitive decline associated with *g* in dementia, now understood in a more limited sense, including Alzheimer's dementia, frontotemporal dementia, dementia with Lewy bodies, and vascular dementia (e.g., Gavett et al., 2015). However, this finding does not necessarily imply that the entire cortex is involved in *g*, but would also be obtained if *g* is supported by a circumscribed cortical area (i.e., the prefrontal cortex) and this area is affected in the different forms of dementia, in addition to the areas specifically affected in each form (for example the hippocampus in Alzheimer's dementia, see Chapter 2). In the behavioral variant of frontotemporal dementia, in which the frontal lobes in particular degenerate rather than the entire cortex diffusely, a progressive loss of general intelligence *g* is found (Roca et al., 2013). In a study of 1,294 cases diagnosed with one of six psychiatric disorders (attention-deficit/hyperactivity disorder, autism spectrum disorder, bipolar disorder, depression, obsessive-compulsive disorder, and schizophrenia) and 1,465 matched controls, Segal et al. (2023) found that part of the brain's attention system in the frontal lobes was consistently affected, while other systems were selectively involved in different disorders.

Others, such as Godfrey Thomson (1881-1955), argued that *g* does not reflect any single psychological ability, such as attentional control (Wundt) or a mental energy fund (Spearman). According to Thomson (1916), test scores are positively correlated due to the overlap in the mental elements sampled by the tests. Using numerical examples, Thomson made it clear that by sampling mental elements, a hierarchy of correlations (as shown in Table 4.1) could be obtained without assuming a general factor *g*. Thomson (1920) further specified what was being sampled, assuming that the elements "correspond to a neurone, or to a synapse, or to a nervous arc" (p. 326).

Garnett (1920) demonstrated mathematically that sampling could produce an account of the data essentially equivalent to a two-factor account, but he pointed out that Spearman's account was preferable because it was simpler. He wrote that "while waiting for further experimental evidence, it [the two-factor account] is surely preferable, because so much more simple, to speak and to think of Professor Spearman's general factor together with specific factors than of the larger number of elements of which the general factor and the specific factors may be supposed to be made up" (p. 256). The latter is what Thomson assumed. Garnett proposed that "the single general factor is a measure of the subject's Will or power to concentrate attention", which he later discussed further (Garnett, 1921) with reference to James, but not to Wundt, who actually proposed an attentional account of the general factor (Wundt, 1911).

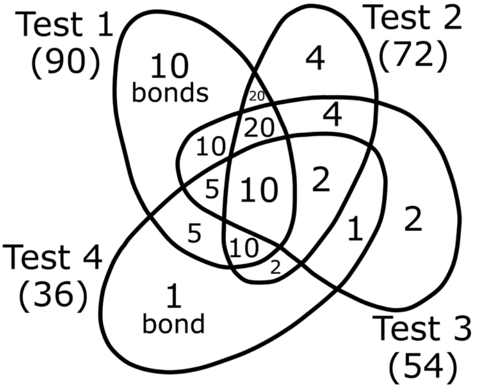


Figure 4.4. Illustration of Thomson's sampling theory. Adapted from Figure 35 of the fifth and final 1951 edition of his *The Factorial Analysis of Human Ability.*

Figure 4.4 shows a numerical example that Thomson (1951) used to illustrate his sampling account, assuming that "each test calls upon *a sample of the bonds* which the mind can form, and that some of these bonds are common to two tests and cause their correlation" (p. 309). He wrote:

> In the present instance we have arranged this artificial example so that the tests can be looked upon as samples of a very simple mind, which can form in all 108 bonds (or some multiple of 108). The first test uses five-sixths of these (or 90), the second test four-sixths (or 72), the third three-sixths (54), and the fourth two-sixths (or 36). (p. 309)

> What the "bonds" of the mind are, we do not know. But they are fairly certainly associated with the neurones or nerve cells of our brains … Thinking is accompanied by the excitation of these neurones in patterns. The simplest patterns are instinctive, more complex ones acquired. … It is not difficult to imagine that the items of the Stanford-Binet test call into some sort of activity nearly all the neurones of the brain, though they need not thereby be calling upon all the patterns which those neurones can form. (pp. 313-314)

Spearman and Thomson were engaged in a debate over the nature of *g* for almost thirty years, both in their publications (e.g., Spearman, 1916, 1937; Thomson, 1916, 1920, 1951) and at scientific meetings (for transcripts of conversations, see Deary et al., 2008). The controversy was still unresolved when they discussed their views at a symposium of the British Psychological Society held in Reading in April 1939. Burt (1939), who was also present, summarized the state of the art:

> There is no mathematical incompatibility between the two-factor theory and the sampling theory … Applied to the facts that both are concerned to interpret – the simple hierarchical tendency – the two procedures give virtually the same result. … The real question, therefore, is – which theory best fits what we know of the working of the mind or central nervous system? And this … is an issue that can be answered only by non-mathematical evidence. As Spearman himself has observed: "the burden of further proof is in large measure transferred to physiology." (p. 86)

Overviews of intelligence research in the 20th century after the Spearman-Thomson debate can be found in Jensen (1998) and R. Sternberg (2000). Some of the research used physiological methods, such as EEG, in examining intelligence, with largely inconclusive results. In the 21st century, a version of Thomson's sampling theory has been put forward by Bartholomew et al. (2009). Kovacs and Conway (2016) argued that *g* results from sampling multiple domain-general attentional control processes and multiple domain-specific processes in an overlapping manner. Later, I discuss more recent neuroimaging evidence that has been used to adjudicate between the positions of Spearman and Thomson (Duncan et al., 2000), arguing that the evidence actually supports Wundt's position.

Psychological tests for *g*

Spearman's students created tests to accurately measure an individual's general intelligence. In the 1930s, David Wechsler (1896-1981) designed an intelligence test (Wechsler, 1944) that would become the Wechsler Adult Intelligence Scale, or WAIS, in the 1950s. Modern versions of the WAIS are still among the most widely used intelligence tests today. In the 1930s, John Raven (1902-1970) developed the Progressive Matrices test (Raven, 1940), which Spearman considered the best test of *g*.

The Advanced Progressive Matrices version of the Raven test comprises 60 visual problems, arranged in order of increasing difficulty (Raven et al., 1998; see Hamel and Schmittmann, 2006, for a 20-minute version). Each problem consists of a 3 × 3 matrix of eight geometric figures and one missing figure, with the task of determining the regularities in the rows and columns and selecting the missing figure from eight choices given below the matrix.

Figure 4.5 illustrates a Raven test problem. To protect the security of the Raven test, the illustrated problem is not one of the actual problems in the test but only analogous to it (adapted from Carpenter et al., 1990). In the example, the figures vary in geometric shape (circle, square, and triangle), bar texture (black, striped, white), and bar orientation (vertical, horizontal, slanted). The shapes and textures vary evenly across the rows and columns, while the orientation is constant. The bottom row of the matrix shows a triangle and circle, with striped and white bars and a slanted orientation. The missing figure must, therefore, be a square with a slanted black bar.

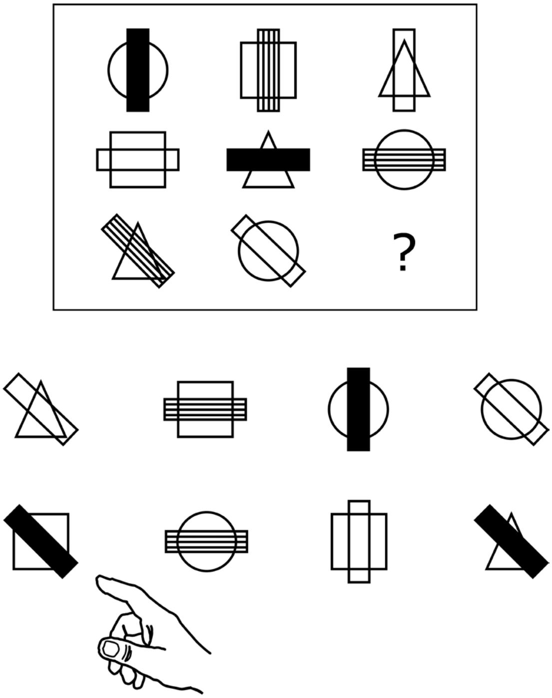


Figure 4.5. Illustration of a problem from the Raven test. The variation between the three geometric shapes (circle, square, and triangle) and the three bar textures (black, striped, and white) is each determined by a distribution-of-three-values rule, and the orientation of the bar (vertical, horizontal, slanted) is determined by a constant-in-a-row rule. The hand points to the correct answer.

In the 1940s, Englishman Raymond Cattell (1905-1998) created the Culture Fair Intelligence Test (Cattell, 1949), which aimed to measure *g* without cultural influences. In the 1960s, he proposed that *g* can be divided into two subtypes of intelligence: fluid and crystallized (Cattell, 1963).

The subtype of *fluid intelligence* is the procedural ability to solve new problems with no assumption of prior knowledge, while *crystallized intelligence* is a person's acquired declarative knowledge, such as vocabulary and world knowledge. Whereas fluid intelligence declines with age, crystallized intelligence improves with age, as experiences tend to expand one's knowledge. Crystallized intelligence is the product of educational and cultural experience in interaction with fluid intelligence. Fluid and crystallized intelligence are thus correlated with each other. The Raven Progressive Matrices test measures fluid intelligence, and the WAIS measures both fluid and crystallized intelligence (in older versions referred to as "performance" and "verbal" IQ).

IQ scores obtained with the WAIS follow a normal distribution with the mean set at 100 and a standard deviation of 15. Standardization needs to be updated regularly because test scores have increased almost linearly during the past century; this is called the *Flynn effect* (Flynn, 1984). The increase in IQ score is due to changes in non-*g* sources of IQ (e.g., education) and not in *g* itself (e.g., Ritchie & Tucker-Drob, 2018).

The *g* factor is robustly observed not only in Western populations, but also in non-Western, non-industrialized countries. Warne and Burningham (2019) found Spearman's *g* in 94 of 97 datasets examined (97%) with a total of 52,340 participants from 31 non-Western countries.

In his highly influential book *Human Cognitive Abilities: A Survey of Factor-Analytic Studies*, Carroll (1993) provided evidence that in addition to fluid and crystallized intelligence, there exist other broad abilities located between the specific abilities *s* and the general ability *g* in a hierarchy of factors. The other abilities are general memory and learning (e.g., free recall), broad visual perception (e.g., spatial relations), broad auditory perception (e.g., sound discrimination), broad retrieval ability (e.g., verbal fluency), broad cognitive speediness (e.g., rate of test-taking), and processing speed (e.g., choice reaction time).

Early studies of other factors

One of the topics in early intelligence research concerned gender differences. Thorndike and others before him believed in the *variability hypothesis*. This hypothesis states that men display greater variability than women, and as a consequence, men are more likely than women to have either very high or very low intelligence. In *The Principles of Teaching, Based on Psychology*, Thorndike (1906) stated:

> Although the male and female *types* are closely alike in intellectual capacities, there is an important difference in the deviations from the type in the two cases namely, that the males deviate more. The highest males in any quality are more gifted than any of the women, and the lowest males inferior to all women. Thus, though girls in general rank as high or higher than boys in high school and college, they less often lead the class; thus there are far more eminent intellects among men than among women and also twice as many idiots. (pp. 96-97)

Helen Thompson's (1874-1947) extensive and detailed work examined the variability hypothesis. In her dissertation *The Mental Traits of Sex: An Experimental Investigation of the Normal Mind in Men and Women* (1903), supervised by Angell in Chicago, Thompson had groups of 25 male and 25 female students perform tests of sensory, motor, and intellectual functions. Tests of motor ability included measurement of reaction times, speed of finger movements and rate of fatigue, coordination, and motor automatisms. Sensory tests covered skin and muscle senses, taste and smell, hearing, and vision, all of which included discrimination tasks (e.g., weight and pitch discrimination). The examination of intellectual abilities included tests of memory, association, ingenuity, and general information. The materials of the memory tests consisted of series of nonsense syllables, with each series containing ten syllables. During the association tests, the number of associations with words was counted. The ingenuity tests included visual, mathematical, and mechanical puzzles. Tests of general information asked for knowledge of general facts, such as "Name two English writers who wrote before Shakespeare". Moreover, there were questions on English literature, history, physics, mathematics, biology, and chemistry. Finally, participants had to answer questionnaires asking for background information, including questions about individual and social aspects of their personality and questions about intellectual interests, working methods, and beliefs.

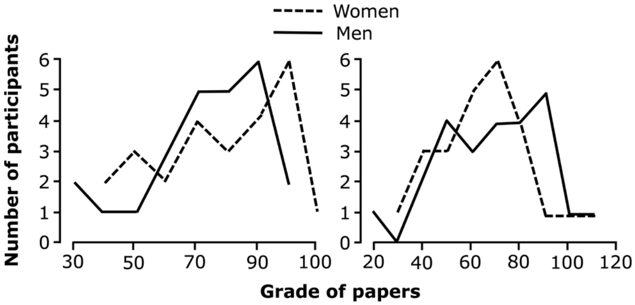


Figure 4.6. Thompson's (1903) distribution of summation grades in the literary subjects (left) and in the scientific subjects (right) for women and men. Adapted from her Figure 79 and Figure 80.

Thompson (1903) reported the outcomes in 80 graphs showing frequency distributions of the scores for men and women (two graphs are illustrated in Figure 4.6). Although differences in mean performance or distribution between men and women were found on several of the tests, in general, there were more similarities than differences. She wrote:

> The results of the series of tests on general information may be summed up as follows: In average grade on the entire series of questions there is no difference between the men and the women. There is, however, a difference in grouping. The

> men are more numerous at both good and bad extremes than the women, and the women more numerous than the men in the middle ranges. The women stand better than the men in the literary subjects, and not so well in the scientific. (p. 128)

Figure 4.6 displays Thompson's graphs showing the summation grades for the literary subjects (left panel) and for the science subjects (right panel). The graphs show an opposite distribution: more women than men at the high extreme for literary subjects and more men than women for scientific subjects. Using the results of the questionnaires, Thompson was able to link the distribution differences to differences in interests and education. She stated:

> In the results of the tests on general information, as in those on ingenuity, special training is unquestionably a factor. … Many of the women were preparing to be teachers, and had, therefore, from practical considerations devoted themselves primarily to those subjects in which the openings for women are most numerous, viz., literary subjects. Many of the men, on the other hand, intended to be physicians, and hence were laying the stress of their work on scientific studies. (p. 129)

Thompson's study attracted attention. The *New York Times* (September 19, 1900) summarized her research with the headline "Women Not Inferior to Men".

Leta Hollingworth (1886-1939) empirically tested the variability hypothesis by examining some thousand case records of very low intelligence at the Clearing House for Mental Defectives in New York. The outcomes of her study were briefly mentioned in a critical discussion of the literature in Hollingworth (1914) and more extensively in Hollingworth (1922). Although there were more men than women in the database, seemingly supporting the variability hypothesis, the ratio of men to women decreased with age. Hollingworth assumed that men faced greater societal expectations than women. Consequently, deficiencies were often detected at an earlier age in men than in women, explaining the overrepresentation of men in the database. Although the outcomes refuted Thorndike's belief, he later supervised Hollingworth's dissertation and offered her a university position. Hollingworth summarized her conclusions as follows:

> The boy who cannot compete mentally is found out, becomes at an early age an object of concern to relatives, is brought to the Clearing-House, and directed toward an institution. The girl who cannot compete mentally is not so often recognized as definitely defective, since it is not unnatural for her to drop into the isolation of the home, where she can "take care of" small children, peel potatoes, scrub, etc.

> If physically passable, as is often the case, she may marry, thus fastening herself to economic support; or she may become a prostitute, to which economic pursuit feeble mentality is no barrier. (pp. 515-516)

The work of Thompson (1903) and Hollingworth (1914, 1922) pointed out the importance of environmental factors, which became a topic of research in itself, separate from the study of intelligence. Rather than concentrating on personal characteristics, like gender differences, Kurt Lewin (1890-1947) put emphasis on both the person and the environment, which for him was the momentary social situation (Lewin, 1936). Because of this, Lewin is often taken to be the founder of *social psychology*. He was among the first to study *group dynamics*, a term that he coined. After emigrating to the US from Germany (where he worked at Wolfgang Köhler's institute in Berlin) in the 1930s to escape the Nazis, he became director of the Center for Group Dynamics at MIT. Lewin's central idea is expressed by the equation

$$B = f\,(P\,,\,E)$$

where behavior (B) is a function (*f*) of personal characteristics (P) and environmental factors (E). In a "force field analysis", Lewin attempted to examine the forces that influence a (social) situation, consisting of helping or hindering forces toward a goal. The emphasis on group dynamics and field forces reveals an influence of Gestalt psychology (Lewin's background in Germany), which is discussed next. Lewin maintained that psychological research should be used to make societies better (e.g., fighting social prejudice, like Thompson and Hollingworth did), which was labeled *social action research*.

Special situational forces in human development come from the family, extensively studied by Charlotte Bühler (1893-1974) in Vienna in the 1930s (e.g., Bühler, 1937). Together with Hildegard Hetzer, Bühler also created developmental tests for children in the preschool years (Bühler & Hetzer, 1932). For each year, there was a different test, which examined intellectual activity, object manipulation, social responses, learning, body control, and sensory perception. From the scores, a developmental profile could be created, indicating where the toddler did okay or development was behind. In addition to developmental psychology, Bühler was also interested in personality and clinical psychology and served for a number of years on the editorial board of the journal *Character and Personality*, edited by Spearman.

Charlotte's husband Karl worked closely with Külpe and later did important work on the psychology of language (Bühler, 1934). The philosopher Karl Popper was one of his students. Bühler also arranged and edited the posthumous publication of Külpe's *Vorlesungen über Psychologie* (*Lectures on Psychology*) in 1922 (Külpe had died in 1915).

The return of Wundt and James

Whereas behaviorism dominated psychology during the first half of the 20th century in America (say from 1913, when Watson published his famous article, to 1957, when Chomsky published a devastating review of Skinner's book *Verbal Behavior*), it had much less impact in Europe. This is already clear from the work of Lewin and the Bühlers. Moreover, while the behaviorists studied conditioning in cats (Thorndike), rats (Watson, Hull, Tolman), and pigeons (Skinner) in America, psychologists in Europe studied problem-solving behavior in other species, including chimpanzees and humans, guided by another theory, namely Gestalt theory. The aim of Gestalt psychology was not to measure intelligence, as J. Cattell, Binet, and others sought to do, but to understand how it works. The key assumption of *Gestalt psychology* was that "the whole is something else than the sum of its parts", as Kurt Koffka (1886-1941) put it in his *Principles of Gestalt Psychology* (1935, p. 176). Major areas of research by Gestalt psychologists concerned perception (e.g., Wertheimer, 1912) and problem solving in great apes (Köhler, 1921) and in humans (Wertheimer, 1945).

In 1913, Wolfgang Köhler (1887-1967) left Germany for Tenerife (Spain) to study how caged chimpanzees solve problems. He observed that when bananas were hanging out of reach on the ceiling of a large cage, chimps stacked wooden crates to create a ladder to retrieve the food. Also, when bananas were placed on the ground outside of the cage, they used combined sticks to lengthen the reach of their arms. According to Köhler, the chimps arrived at these solutions by seeing how the parts (wooden crates) should be combined as a whole (ladder) to reach a goal (bananas). Thus, the chimps had solved the problems through *insight* rather than trial-and-error, as behaviorists like Thorndike assumed for other animals. The chimpanzees differed in intelligence, with a chimp named Sultan being the smartest. When Köhler moved to Berlin in 1920 to become director of the Psychological Institute, the chimpanzees, including Sultan, came with him to live out their lives in the Berlin Zoo (Fahrenberg, 2019). Köhler documented his research findings in the 1921 book *Intelligenzprüfungen an Menschenaffen* (*Intelligence Tests on Great Apes*), later translated into English as *The Mentality of Apes* (1925).

Max Wertheimer (1880-1943) studied problem solving in humans. He called this "productive thinking", which is solving a problem with insight, as opposed to "reproductive thinking", which is solving a problem by retrieving previous knowledge. This distinction corresponds to that between fluid and crystallized intelligence. One of Werthheimer's participants was Albert Einstein, a good friend of his. Wertheimer reported on his findings in the book *Productive Thinking* (1945), which appeared in print after his death.

Elsewhere in Europe, other aspects of the mind were studied. Working in Cambridge, England, Frederic Bartlett (1886-1969) published his now classic book entitled *Remembering: A Study in Experimental and Social Psychology* (1932). In one of his experiments, Bartlett asked his English participants to read and remember a Canadian Indian story entitled *War of the Ghosts*, the plot of which developed in a way that was foreign to European culture. Bartlett observed that his participants changed the story as they tried to remember it; that is, they transformed the story into more familiar forms. This suggests that remembering is a *reconstructive* process where information is changed to fit into existing cultural schemata. Notice the many differences between the memory studies of Bartlett and Ebbinghaus (Chapter 2). Whereas Ebbinghaus studied memory using nonsense syllables devoid of meaning, Bartlett asked for the recall of meaningful stories. For Ebbinghaus, recall was the retrieval of associations in memory, and for Bartlett, recall was the reconstruction of memory traces under the guidance of schemata. In both cases, episodic memory was studied.

In 1947, Jerome Bruner (1915-2016), together with his student Cecile Goodman, published a study arguing against behaviorism and psychophysics, advocating instead for social and personality factors in perception (Bruner & Goodman, 1947). The research was done in America, when behaviorism still dominated. They asked 10-year-old children to estimate the size of U.S. coins, and observed that the children overestimated the size, especially of higher denomination coins. The overestimation was greater for poor than for rich children. Apparently, poor children value coins more highly and therefore see them as bigger. Bruner and Goodman wrote: "Weber's Law would predict in all cases a straight line plot parallel to the axis representing actual size" (p. 43), contrary to their observations, and concluded with the following words:

> If we are to reach an understanding of the way in which perception works in everyday life, we social psychologists and students of personality will have to join with the experimental psychologists and reexplore much of this ancient field of perception whose laws for too long have been taken for granted. (p. 43)

Bruner's new program for studying perception, later called the "New Look", was criticized by Fodor in *The Modularity of Mind*. As explained in Chapter 1, Fodor argued that perception is largely mediated by modules whose operation is unaffected by knowledge in the central systems, including social and personality factors. Fodor did not discuss Bruner and Goodman's work in detail, but a closer look reveals their results to be more ambiguous than initially suggested. The overestimation was obtained for coins, but not for disks, indicating that the effect depended on the central identification of the coins. Furthermore, the overestimation was stronger when the size of the coins was estimated from memory than when the coins were actually shown, indicating that actual perception led to correction and reduced the bias. Importantly, no child saw two coins instead of one, no matter how poor. Perceptual systems largely provide information about the world as it is and prevent us from hallucinating, which was essentially Fodor's point. Bruner and Goodman's results, replicated by Van Ulzen et al. (2008), indicate that social and personality factors can influence the way we perceive the world, but the effect is limited and occurs in central systems rather than in perception itself.

In 1959, linguist Noam Chomsky (1928-) published a review of Skinner's book *Verbal Behavior* (1957), in which Chomsky argued that children acquire their first language without being explicitly taught. According to him, Skinner's operant conditioning principles cannot explain why humans can speak and understand sentences that they have never heard before. As an alternative, Chomsky proposed that humans possess an *innate language-acquisition device*, explaining why a first language is acquired so rapidly. Chomsky's review, together with the findings of Tolman and other behaviorists, caused the decline of behaviorism in America. This led to renewed interest in the mind, and the study of topics that also had been investigated by Wundt and James.

At Harvard, where James had worked, psychologist Roger Brown (1925-1997) undertook some of the first experimental studies on children's language acquisition (Brown, 1973), including two children whom he dubbed "Adam" and "Eve". Other important work by Brown includes his 1965 article (co-authored by David McNeil) on the *tip of the tongue* phenomenon. This is the experience of failing to retrieve a word from memory (often involving a person's name) combined with partial recall (e.g., correct recall of the number of syllables, place of stress, and the initial sounds) and the feeling of knowing the word. This shows that even remembering words is a reconstructive process. In the *Principles*, James (1890) had described this experience as "a gap that is intensely active" (p. 251). Brown also studied *flashbulb memories* (Brown & Kulik, 1977). These concern memories of what people were doing at the time they heard about major traumatic events such as that two planes flew into the Twin Towers in New York on September 11, 2001. People often have a highly detailed memory of the moment and specific circumstances when they heard the news. I remember being in my office at the Max Planck Institute in Nijmegen and, after hearing the news, I walked into the hallway and saw colleagues leaving their offices in shock. One account of this is that the amygdala, activated by the emotion, facilitates consolidation of the memory by the hippocampus, which is connected to the amygdala.

Wundt had observed that attention (the Blickpunkt) has limited capacity. That is, only a few items can be attended to simultaneously and kept in short-term memory. This observation was further supported by the work of George Miller in the 1950s, who found that the capacity is about seven plus or minus two (Miller, 1956). Importantly, the capacity can be increased by recoding the elements. For example, briefly maintaining the nine elements T, H, E, O, E, S, R, E, U exceeds capacity for most people; by recoding them into the word TREEHOUSE, the nine elements remain within capacity for almost all people. This process is called *chunking*, already observed by Wundt (1893, 1896).

Psychologists also revived the selectivity aspect of attention of Wundt and James. In the early 1950s, researchers started to investigate the question of how we can recognize what one person is saying when others are speaking at the same time (e.g., Broadbent, 1952), or what Cherry (1953) called the "cocktail party problem" (p. 976). In one of his tests, Cherry presented one continuous spoken message into headphones on the participants' left ear and another message on the right ear, creating the situation described by J. Müller (1840): "If two people say different things to us in both ears, we can pay attention to the words of one while ignoring those of the other" (p. 96). Cherry instructed the participants to repeat aloud one of the messages while trying to ignore the other and not make any mistakes. It was found that participants noticed the voice (male or female) of the rejected ear, but detailed aspects such as language (English or German), individual words, or semantic content went unnoticed.

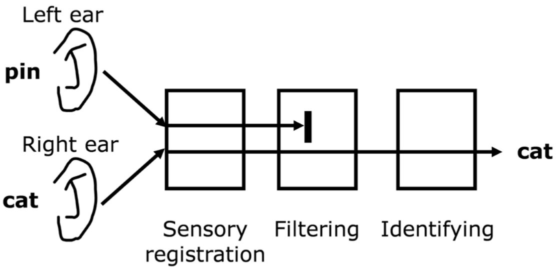


Figure 4.7. Broadbent's filter theory of attention, based on the version of Treisman (1960).

To account for the selectivity of attention, Bartlett's student Donald Broadbent (1926-1993) proposed a filter model (Broadbent, 1958), which he formalized using a flow chart (illustrated in Figure 4.7). A flow chart specifies the sequence of mental processing stages. Broadbent applied his model to selective listening experiments.

Suppose, for example, that the spoken word *pin* is presented through someone's left ear and the word *cat* through the right ear, and that the task is to report the right-ear word. According to Broadbent, after sensory registration of the words, a filter blocks further processing of the left-ear word so that the person is able to identify and report the right-ear word, *cat*.

When selectively listening to one of two continuous spoken messages (as in Cherry, 1953), Moray (1959) found that participants sometimes noticed their name embedded in an ignored message, suggesting that highly relevant stimuli can suddenly capture attention. This finding was replicated and extended by Wood and Cowan (1995), who found that approximately 35% of participants reported hearing their own name in an irrelevant message. Conway et al. (2001) found that participants who detect their name in the irrelevant message have relatively low working memory capacity (i.e., updating ability, see Chapter 2), indicating that they have difficulty maintaining the goal of blocking or inhibiting distracting information.

Researchers also revived the introspection method of Külpe by having participants introspectively report on how they were performing tasks. For example, Simon and his colleagues asked participants to think aloud while they tried to solve problems (e.g., Simon & Hayes, 1976). And together with Newell, Simon proposed an account of problem solving by humans in terms of procedural knowledge (Newell et al., 1958; Newell & Simon, 1972), thereby reviving the ideas of Selz. To prove that procedural rules could really do the thinking, such as solving the Tower of Hanoi puzzle (Simon, 1975), computer programs were created. The series of steps taken by the programs corresponded to the mental steps of the human participants and the difficulties they experienced, as revealed by their thinking aloud (e.g., Kotovsky et al., 1985). Others showed that serial rule application accounts well for how participants solve the problems of the Raven Progressive Matrices test (Carpenter et al., 1990). All this work supports the idea that intelligence can be seen as the ability to solve problems through the application of production rules. It should be noted that the modern researchers were generally unaware of their historical predecessors. As previously indicated, when Simon began his study of human thought, he was familiar with the work of De Groot but not with Selz and Külpe, about whom he only learned later.

Through their work on computer programs for intelligence, Newell and Simon became the founders of a new field of science called *Artificial Intelligence*. Artificial intelligence (AI) aims to construct computer programs that exhibit intelligent behavior, which includes not only solving the Tower of Hanoi puzzle or playing chess but also abilities like language comprehension and vision. In 1997, the chess program of IBM, called Deep Blue, defeated the world champion Gary Kasparov through a combination of fluid intelligence (brute force thinking) and crystallized intelligence (an extensive record of previous games in memory). Importantly, the work of Simon and colleagues also promoted a computer metaphor of the human mind, according to which the brain is an organ that processes information. The task for psychology became to account for information processing (Lachman et al., 1979).

The *g* factor from a modern perspective

Earlier, I indicated that Wundt (1896) distinguished between simple and complex apperceptive functions. He assumed that the simple functions of relating and comparing, as well as apperceptive inhibition, play a central role in the performance of relatively simple tasks, such as performing Stroop-like tasks. The complex functions of synthesizing and analyzing were thought to be involved in more intellectual tasks, in addition to the simple functions. According to Wundt (1897), the ability here concerns "the *perception of similarities and differences and other inferred logical relations between the contents of experience*" (p. 263). In 1990, Carpenter and colleagues showed that the ability to analyze stimuli for similarities and differences and to induce abstract relationships is central to the Raven test (illustrated in Figure 4.5). As explained earlier, each problem in the Raven test consists of a 3 × 3 visual matrix, with the bottom right cell missing. Each of the other cells contains one to five visual elements, such as geometric figures, structured bars, and bar orientations. The task is to look through the rows and columns to determine the regularities and then select the missing cell from the eight alternatives given below the matrix. In Wundt's terms, this involves perceptual relating and comparing, and inhibiting irrelevant information to determine regularities through apperceptive analysis and synthesis. Attention plays an essential role in this. In line with Wundt and directly following Selz, Anderson, Newell, Simon, and Carpenter, John Duncan (1953-) claimed that solving Raven-like problems involves working serially from one subgoal to another, each with focused attention until the overall goal is achieved (as illustrated in Figure 2.4 for the Tower of Hanoi puzzle). Duncan summarized his theory and empirical work on intelligence in the book *How Intelligence Happens* in 2010.

While Wundt (1911) maintained that *g* reflects someone's attentional capacity, supported by the frontal lobes, Spearman (1914, 1927) argued that *g* reflects a person's mental energy, connected to the entire cortex. Thomson (1916, 1951) argued that *g* does not reflect a single psychological ability but an overlap between tests in samples of mental elements, which were also expected to be distributed across the cortex. Recall that Thomson stated that "the items of the Stanford-Binet test call into some sort of activity nearly all the neurones of the brain" (1951, p. 314). Next, I review modern studies, including a meta-analysis and targeted neuroimaging studies, as well as examinations of twins and patients. These studies challenge the views of Thomson and Spearman and support Wundt's position.

In a meta-analysis of brain imaging studies in the literature with manipulations of response conflict, novelty, working memory load, and perceptual difficulty, Duncan and his colleague Adrian Owen observed that all activated common regions in frontal cortex (Duncan & Owen, 2000). The shared regions were later expanded to include the parietal cortex, and they were linked to attention and general intelligence (e.g., Duncan, 2006, 2010, 2013; Duncan & Manly, 2012; Duncan et al., 2020). This provides evidence for a link between attention, intelligence, and the frontal lobes, as Wundt proposed. Furthermore, the finding that only a limited part of the brain is connected to intelligence challenges Thomson's sampling theory and Spearman's energy theory, both of which would predict that the entire brain should be involved. Figure 4.8 illustrates the frontoparietal network underlying general intelligence (I offered my brain for an MRI scan to project the network onto it). In the remainder, I focus on the work of Duncan and colleagues, but related work has provided converging evidence for a link between intelligence and attention (e.g., Conway et al., 2021; Kane & Engle, 2002; Mashburn et al., 2024; Rueda, 2018) and between intelligence and frontoparietal cortex (e.g., Jung & Haier, 2007; Feilong et al., 2021).

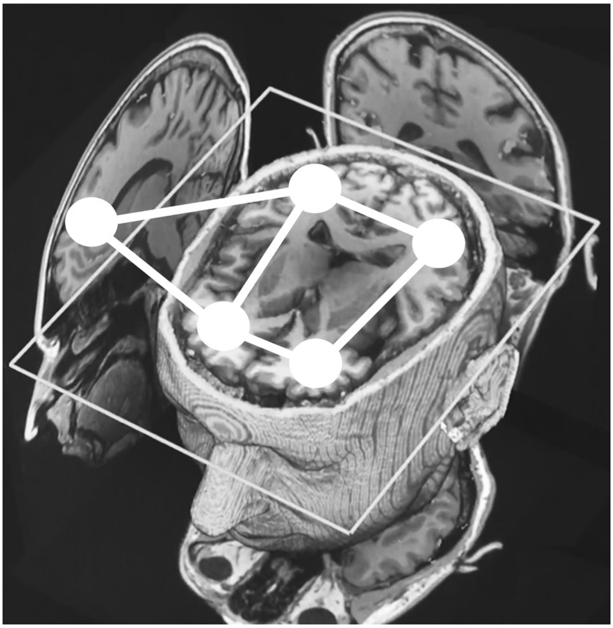


Figure 4.8. Network of frontoparietal areas underpinning general intelligence.

In a frequently cited article published in *Science* in 2000, Duncan and colleagues reported a PET imaging experiment that specifically tested for the neural locus of *g* (Duncan et al., 2000). Students from Cambridge University in England performed a Raven-like task in the PET scanner. On each trial, they had to indicate by pressing one of four buttons which of four spatial figures or letter sequences was the odd one in the series. Items were difficult (high *g*) or easy (low *g*). Subtracting the low *g* PET images from the high *g* ones revealed activation in frontal cortex in both the spatial and verbal conditions, indicating that *g* is specifically linked to the frontal lobe rather than the entire cortex. This supports Wundt's attentional control account rather than Spearman's mental energy and Thomson's sampling accounts. Curiously, Duncan and colleagues viewed their experiment as a test between Spearman's and Thomson's theories, while widespread brain activation would be expected under both theories, and they did not take into account Wundt's theory, which was actually supported. PET imaging is a somewhat insensitive method, and later fMRI studies, in Duncan's lab and elsewhere, revealed that *g* is connected to both frontal cortex and parietal cortex (Duncan, 2006, 2010, 2013).

Sonia Bishop, Duncan, and colleagues (2008) examined genetic influences on brain activation during performance of the same Raven-like task used by Duncan et al. in 2000. They looked at the influence of different alleles of the *COMT* gene, which codes for the COMT enzyme that breaks down dopamine in frontal and parietal cortex. The alleles are *val* and *met*, whereby a person receives one allele from the father (e.g., *val* or *met*) and another from the mother (e.g., *val* or *met*), so the possible genotypes are *val/val*, *val/met*, and *met/met*. The *val* allele codes for a version of the COMT enzyme that works harder than that of the *met* allele. As a consequence, dopamine will be available longer in frontal and parietal cortex with *met/met* than *val/met* and longer with *val/met* than *val/val*. The longer availability was expected to ease the performance of intelligence-requiring tasks. Bishop and colleagues observed that the difference in activation between high and low *g* items in the frontoparietal network (including dorsolateral prefrontal cortex and the anterior cingulate cortex) was larger for the people with the *val/val* genotype than with the *val/met* genotype, and the activation difference was smallest for people with the *met/met* genotype. This reveals influences of different genotypes on brain activation in the frontoparietal network for intelligence during the performance of a Raven-like task. The study combines several theoretical ideas from the history of research on intelligence, including genetic influences, localization of function, and performance of Raven-like tasks.

The findings of Duncan and colleagues sparked a debate. Robert Sternberg (1949-) argued that a link between intelligence and frontoparietal activation does not imply that the relation is a causal one. Sternberg (2005) stated: “Biological approaches seem to have a certain attraction for suggesting a causal mechanism for intelligence (Duncan et al., 2000). But they really are not attractive, because the existing data are all correlational” (p. 243). However, Duncan et al. studied brain activation by experimentally manipulating item difficulty (low *g* versus high *g*) and found that the frontal cortex was differentially activated. As indicated in the prologue to this book, experimental manipulation is the gold standard for testing causal involvement, as Woodworth (1938) explained in his *Experimental Psychology*. What Duncan et al.’s PET neuroimaging study could not demonstrate is whether the frontal cortex is *necessary* for intelligence, which can only be demonstrated in patient studies or by using brain stimulation methods.

One such patient study was conducted by Alexandra Woolgar, Duncan, and colleagues (2010). They noted that damage to the frontoparietal cortex reduces fluid intelligence, while damage to the temporal cortex does not. Similarly, Aron Barbey and colleagues (2012) observed that damage to brain areas that are common to attention and intelligence in frontoparietal cortex reduces both general intelligence and attentional control ability. These studies indicate that frontoparietal cortex is necessary for attentional control and intelligence.

In a large twin study (with 582 individuals from 293 same-sex twin pairs), Naomi Friedman and colleagues found that the genetic variance in *g* (i.e., WAIS-IQ) significantly correlated with the genetic variance for attentional control, although the correlation was not perfect (Friedman et al., 2008). This indicates that *g* and attentional control are closely related, but *g* is not just attentional control. Moreover, *g* is related to updating (working memory capacity), but not to inhibiting and shifting (Friedman et al., 2006), as distinguished in Chapter 2.

Further evidence for Wundt’s view comes from the observation that attentional control mediates the relationship between sensory discrimination and intelligence. Jason Tsukahara and colleagues (2020) reexamined this relationship, originally observed by Spearman (1904) and replicated by Deary and colleagues (2004). In one large-scale structural equation modeling study, they assessed whether individual differences in attentional control ability, measured by flanker, Stroop, and anti-saccade tasks assessing inhibition, can explain the relationship between sensory discrimination and intelligence. They observed that attentional control fully explained the relationship and concluded that attentional control is the “missing link between sensory discrimination and intelligence” (p. 3445). Jastrzębski and colleagues (2021) obtained a similar finding regarding working memory capacity, another component of attentional control.

Finally, Wundt's view clarifies the relationship between the size of the right tail of a reaction time distribution and measures of working memory capacity and fluid intelligence. Wundt (1908) had argued that external and internal disturbances of attention ("äußere und innere Störungen der Aufmerksamkeit", p. 581) may cause a frequency distribution to become more asymmetrical. For example, it is expected that lapses of attention will result in long reaction times, which should increase the right side of the distribution. Modern research by Florian Schmiedek and colleagues (2007) with a sample of 135 participants showed that the size of the right tail of the distribution of choice reactions correlates negatively with measures of working memory capacity and fluid intelligence (i.e., longer tails are associated with lower capacity and intelligence). The relationship was further illuminated in an fMRI experiment by Aarts and colleagues (2009), who had participants switch between responding to the arrow or word of congruent or incongruent arrow-word combinations (e.g., the written word *left* combined with a congruent left-pointing arrow or an incongruent right-pointing arrow), or to isolated arrows or words on neutral trials. Participants responded by pressing a left or right button. Reaction times were longer on incongruent than on congruent trials, reflecting response conflict. Reaction times were also longer on congruent than on neutral trials, reflecting task conflict. A congruent arrow-word combination activates both tasks, which compete to be performed. Analyses of the reaction time distributions revealed that response conflict was reflected in the body of the distribution and task conflict in the right tail. The neuroimaging data showed that both response and task conflict activated areas in the frontoparietal cortex, suggesting that the procedural system has to work harder in the face of conflict. However, the activation in the dorsolateral prefrontal cortex only reflected task conflict, demonstrating that the management of task goals lies in working memory. This explains the link between the size of the right distribution tail and measures of working memory capacity and fluid intelligence.

As stated previously (in Chapter 2), evidence suggests that inhibitory gating (one of Wundt's apperceptive functions) is implemented by alpha oscillations in the brain. Measures of resting-state alpha band activity correlate with measures of intelligence (e.g., Doppelmayr et al., 2002, 2005), including scores on the Raven test (Zakharov et al., 2020). Atchley et al. (2017) noted that error responses in Stroop task performance are preceded by a decrease in alpha band activity, suggesting that errors occur when the perception of the distractor word is insufficiently inhibited. In a study that I conducted, Raven scores measuring *g* correlated negatively with the magnitude of the Stroop effect in fast errors (Roelofs, 2021).

However, not everyone agrees that attentional control is central to intelligence, as Wundt maintained. More generally, researchers have still not reached a consensus on the issue of the nature of *g* and its neural basis. I already mentioned the new sampling theory of Bartholomew et al. (2009) reviving Thomson. While Kovacs and Conway (2016) argued that *g* reflects spatial overlap of brain networks, Barbey (2018) hypothesized that *g* reflects the ability to flexibly reorganize brain networks. It should be noted that Cole et al. (2012, 2015) provided evidence that the flexible reorganization underlying fluid intelligence is achieved by the prefrontal cortex, in line with Wundt's view.

Bartholomew et al. (2009) put forward a new version of Thomson's sampling theory with some changes in the mathematical assumptions. They argued that their account is consistent with evidence about the brain, particularly findings by Haier and colleagues. However, while Thomson involved the whole brain in *g*, Jung and Haier (2007) emphasized a link between intelligence and the frontoparietal cortex. Furthermore, studies examining a correlation between regional cortical volume and intelligence by Haier and colleagues found that the strongest correlations were for the frontal and parietal cortex. For example, Haier et al. (2004) observed that voxel clusters with a significant correlation between gray matter and intelligence were mainly in the frontal cortex (71.7%) and the parietal cortex (17.6%) rather than in the temporal cortex (9.6%) and the occipital cortex (0%). Recently, Feilung et al. (2021) used data from 876 participants in the Human Connectome Project and observed a link between *g* and fine-grained functional connectivity in the frontoparietal cortex rather than the whole brain. These findings provide evidence that intelligence is related to the frontoparietal cortex and not to the whole brain, as assumed by Thomson and Bartholomew et al.

In recent times, Spearman's energy thesis has literally returned in a new guise. Geary (2018) argued that the overall efficiency of mitochondrial functioning underlies *g*. Mitochondria produce the energy currency of cells, which applies to all neurons in the brain. However, this theory also fails to account for the evidence that *g* is supported by a particular part of the brain, namely the frontoparietal cortex, rather than by the entire cortex. In a recent study of 227 brain-damaged patients assessed with the Raven's Progressive Matrices, Lisa Cipolotti and colleagues (2023) obtained further evidence that right frontal regions rather than widespread brain areas or networks are critical for the mental functions underlying *g*, supporting Wundt's position.

Intelligence and production systems

An account of general intelligence in terms of serial mental work from one subgoal to another, as put forward by Duncan (2010), was previously proposed by Patricia Carpenter and colleagues (1990). They conducted a detailed investigation into the mental processes underlying performance on the Raven test. As participants attempted to solve each of the problem items on the Raven, errors were noted and eye gazes were recorded, indicating the visual scan of the rows and columns of the matrices. This provided evidence about when and how paired comparisons were made between the figures in the matrix. The participants were also instructed to talk out loud and explain how they tried to solve the problems. The eye gazes and verbal protocols revealed that participants attempted to solve a problem by breaking it down into successively smaller subproblems and then continuing to solve each subproblem. The induction of the rules governing the regularities in the matrices was incremental. The rules were derived one by one, and the induction of each rule consisted of many small steps, as reflected in the pairwise comparison of elements in adjacent figures, evident from the gazes. Measures of goal management correlated between the Raven test and the Tower of Hanoi puzzle. Performance on the Raven test was simulated using two production system models, called FAIRRAVEN and BETTERRAVEN, representing average and top participants, respectively. Computer simulations showed that performance differences were due to different abilities to induce abstract rules and dynamically manage complex goal hierarchies in working memory.

The importance of working memory is also supported by evidence that general intelligence (reasoning ability) and working memory capacity (updating ability, a component of attentional control) are strongly correlated (e.g., Colom et al., 2004; Friedman et al., 2006; Schubert et al., 2023; Süß et al., 2002). The correlation is not perfect, which means that working memory capacity is not identical to intelligence but does make an important contribution to it. While Kyllonen and Christal (1990) emphasized the importance of working memory for intelligence in an article entitled *Reasoning Ability is (Little More Than) Working-Memory Capacity*, Hagemann et al. (2023) emphasized that functions other than working memory (e.g., rule induction) are also involved in an article entitled *Fluid Intelligence is (Much) More Than Working-Memory Capacity*.

Summary

In the early 20th century, it was discovered that all correlations between school subject grades and sensory tests are positive, supporting a two-factor account of mental skills in terms of general intelligence *g* and specific abilities (Spearman). The general intelligence factor is related to the updating component of attentional control, which determines the capacity of working memory (Kyllonen, Friedman). Neuroimaging and patient studies linked *g* to the frontal (and parietal) lobes, consistent with some previous proposals (Wundt) but not others (Spearman, Thomson). Taken together, the 20th-century discoveries led to the view of intelligence as the procedural ability to work serially from one subgoal to another, each with focused attention, and updating working memory until the overall goal is achieved (Carpenter, Duncan, Newell, Simon).

CHAPTER 5

An integrated account

The expeditions into the realms of the mind of the past 200 years have had one overarching goal, namely to achieve an integrated account. As David Meyer and David Kieras (1999) stated: “Like the quest of Indiana Jones, the adventurous anthropologist in *Raiders of the Lost Ark* … our journey … has brought us in search of an alluring mystical treasure. The treasure we seek is a unified theory of cognition and action through which human performance can be understood and predicted in a variety of contexts, spanning elementary laboratory paradigms and complex real-world situations” (p. 17).

Wundt’s *Grundzüge* (1874, 1880b, 1902) and James’s *Principles* (1890) described important characteristics of the human mind, mainly based on behavioral evidence. A century later, Posner and Raichle (1994) updated and extended the descriptions in their *Images of Mind*, based on neuroimaging evidence, and summarized the findings in ten principles. Since then, the principles have been further supported by much evidence (e.g., Badre, 2020; Banich & Compton, 2023; Dehaene, 2023; Duncan, 2010; Eichenbaum, 2012; Gazzaniga et al., 2018; Kemmerer, 2022; Posner, 2012; Shallice & Cooper, 2011). Below, I first relate the principles to the discoveries about the mind of the past 200 years and then present an integrated account.

The principles

1. *Elementary operations are localized in discrete neural areas*. Posner and Raichle (1994) reviewed the neuroimaging evidence that the component operations of attention (a central function) and of auditory and visual word processing (input and output functions) are localized (e.g., Dehaene, 2009; Kemmerer, 2022). This principle reflects the outcome of the 19th-century controversy over localization versus holism, which was decided in favor of the former, starting with Broca's (1861) seminal evidence. The principle is at the heart of Wernicke's (1874) model. Wundt (1902) called it the *Principle of Relative Localization*: Only elementary processes are localized, and their exact location in the brain depends on their acquisition.
2. *Cognitive tasks are performed by networks of widely distributed neural systems*. This principle goes back to the work of Donders (1868a), who presented behavioral evidence that the performance of tasks involves an ordered sequence of component processes, such as sensation, discrimination, choice, and movement. Wernicke (1874) provided patient evidence that language tasks such as word production, repetition, and comprehension are performed by distributed networks in the brain, including temporal and frontal cortex. Modern neuroimaging evidence, reviewed by Posner and Raichle (1994), has revealed not only the networks but also the time course of the operation of the constituent processes.
3. *Computations in a network interact by means of "reentrant" processes*. Wundt (1874, 1880b, 1902) assumed that perceptions enter consciousness, after which attention works back on them by emphasizing some of the percepts. While Lamme (2003) argued that conscious perception involves localized, recurrent processing within the sensory cortex, Dehaene (2014) provided evidence that it involves recurrent activation from the global workspace, underpinned by frontoparietal cortex.
4. *Network operation is under hierarchical control*. This principle is at the heart of Wundt's (1874, 1880b, 1902) conceptualization of apperception, which can guide thinking and promote certain perceptions or responses through selective inhibition of others. The work of Anderson (1983), Carpenter et al. (1990), Duncan (2010), Newell and Simon (1972), and others has provided evidence that intelligence is the ability to manage goals and subgoals and the successive subordinate processing steps to achieve them.
5. *Once a computation is activated, the threshold for its reactivation is temporarily lowered*. This principle underlies phenomena such as priming (e.g., Dehaene, 2014).

6. *Less effort and attention are required to repeat a computation*. Wundt (1902) called it the *Principle of Practice and Adaptation*. Posner and Raichle (1994) reviewed the evidence that blood flow and electrical activity are reduced when a mental process is repeated. This principle reflects the consolidation of declarative and procedural knowledge, leading to skilled performance and habits (e.g., Eichenbaum, 2012).
7. *A computation activated from the bottom up by sensory input involves many of the same neural systems as the computation activated from the top down by attention systems*. This principle was postulated by Wundt (1874, 1880b, 1902) in his conceptualization of apperception. Posner and Raichle (1994) described the neuroimaging evidence that focusing attention on motion, color, or shape activated many of the same visual areas that were active when passively perceiving information of the same type.
8. *Practice in the performance of any task will decrease the number of neural networks necessary to perform it*. This principle underlies the observation that practice can eliminate the need for attention and smooth the paths between perception and action (Wundt, 1896, 1903). Posner and Raichle (1994) reviewed the evidence that when participants repeatedly generate verbs for the same nouns over many trials, activation in the anterior cingulate cortex disappears, and the generation task activates the same pathway used when repeating the nouns.
9. *The mind becomes capable of performing behaviors through the development of specific pathways connecting local computations*. This principle underlies the *Law of Contiguity* (Aristotle) and the *Law of Effect* (Thorndike, 1911). It also underlies the performance of novel tasks, in the laboratory or in the wild, that involve new, arbitrary pathways from stimulus to response, such as moving a lever to the left in response to a flash of red light (Donders, 1868a) or writing *46* in response to a green color patch (Calkins, 1896).
10. *The symptoms of mental disorders may result from damage to localized computations, to pathways connecting these computations, or to the attentional networks and neurochemical systems that modulate the computations*. This principle is observed, for example, in the different types of aphasia (Pick, 1908; Wernicke, 1874), the different forms of prosopagnosia, the syndrome of spatial neglect, and Parkinson’s disease due to a deficiency of dopamine (e.g., Kolb & Whishaw, 2021).

The point of view in my book is *neurocognitive* rather than *cognitive neuroscientific*. That is, the primary goal is to understand the mind rather than the brain. The modern umbrella term *cognitive neuroscience* encompasses both approaches, although it is often understood as a branch of neuroscience. The widely read introductory book by Michael Gazzaniga and colleagues (2002, 2018) is called *Cognitive Neuroscience: The Biology of the Mind*, which makes clear that their primary goal is to understand the brain. Similarly, Marie Banich and Rebecca Compton (2023) wanted to "explore how the neurological organization of the brain influences the way people think, feel, and act" (p. 3). This goal differs from that of Posner and Raichle in their *Images of Mind*, and from Tim Shallice and Richard Cooper's in the *The Organisation of Mind*, who aim to understand the mind using neuroscientific methods, especially neuroimaging. Some researchers, such as Max Coltheart, have expressed pessimism about this endeavor, stating that "no functional neuroimaging research to date has yielded data that can be used to distinguish between competing psychological theories" (2006, p. 323). But the discussions by Shallice and Cooper, among others, and in my book, prove this claim by Coltheart to be incorrect. For example, John Duncan and colleagues' (2000) PET imaging study provided evidence for explaining *g* in terms of a single mental ability rather than a sampling of several diverse mental abilities. Studies that appeared after Coltheart's article continued to use neuroimaging to test between cognitive theories. For example, the MEG study on picture-word interference by Piai and colleagues (2014), discussed in Chapter 2, provided evidence that the functional locus of picture-word interference lies in word planning and not in perceptual encoding or articulatory buffering.

The neurocognitive position was also advocated by Wundt in his *Grundzüge* of 1874, in which he put forward a multi-method and multi-perspective approach to the human mind, following a principle of consistency. That is, assuming that psychological and physiological measures provide evidence about the same system from different perspectives (i.e., mind and brain), evidence from multiple methods (e.g., reaction time, introspection, physiological measures) should be consistent. The rationale behind using multiple methods is to obtain convergent evidence. The idea is that if the evidence from multiple methods is consistent with each other, the conclusion can be strong even if each method has its weaknesses. The evidence from previous behavioral and patient studies to recent neuroimaging supports an integrated theory of key aspects of the human mind, I argue, which is illustrated below.

Putting it all together

In Chapter 1, I wrote that Gall's (1835) investigation into the faculties of mind received its initial impetus from his observations on memory for words and that Wernicke (1874) published a hugely influential theory of word production, repetition, and comprehension, and their breakdown in aphasia, after Broca's discovery about the localization of spoken language in 1861. Here, I illustrate an integrative account of key aspects of the mind using a production system model of word production, repetition, and comprehension. This computationally implemented model has been developed over the past thirty years at the Max Planck Institute for Psycholinguistics and the Donders Institute for Brain, Cognition and Behaviour of Radboud University in Nijmegen (e.g., Levelt et al., 1999; Roelofs, 1992, 2003, 2014b, 2023a, 2024). The model has several features derived from Levelt's (1989) general processing theory of speaking. Critical discussions of the model and alternative ones can be found in Kemmerer (2019, 2022) and Kröger (2023a, 2023b).

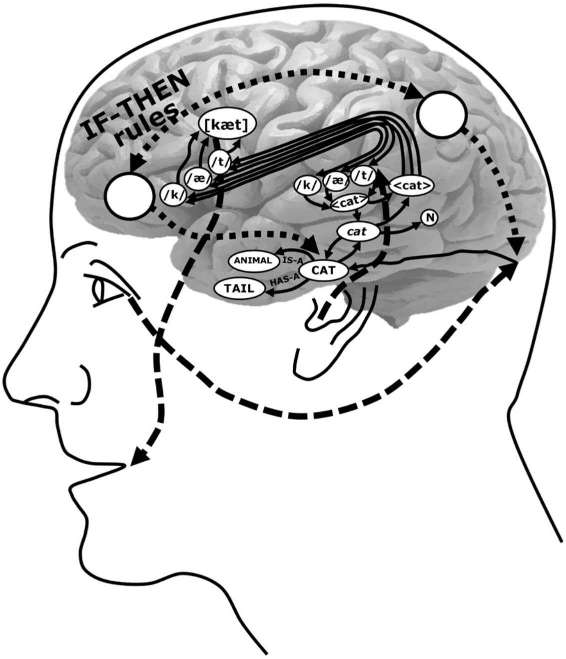


Figure 5.1. Side view of the human brain with the functional components for word production, repetition, and comprehension projected onto it. Sensory organs such as the ear and eye convey information about the outside world to the mind. There, perceptual processes activate information in declarative associative memory (ellipses) and trigger IF-THEN rules in procedural memory that achieve goals in working memory. The rules ensure that relevant information is amplified by the attention system (circles), and thus can become conscious, and select motor programs for movement, such as articulation. Problems requiring intelligence are solved by IF-THEN rules that work serially from one subgoal to another, each with focused attention, until the overall goal is achieved. The figure is inspired by Bastian's (1898) first diagram.

Figure 5.1 illustrates the model and shows the localizations of its functional components projected onto a side view of the human brain, as discussed in Chapter 1. The brain localizations adopted for the different aspects of words were initially based mainly on a meta-analysis of 108 neuroimaging studies on word production and comprehension by Indefrey and Levelt (2004). The localizations have found further support in neuroimaging studies over the past two decades (see Kemmerer, 2022, for a review).

The model is called WEAVER++, an acronym that stands for Word Encoding by Activation and Verification (e.g., Levelt e al., 1999; Roelofs, 1998), involving associative memory and procedural knowledge, respectively. The ++ (i.e., the increment operator in the programming language C) indicates that the model is an incremental extension of WEAVER, which was a model of word-form encoding (Roelofs, 1997) complementing a nameless model of lemma retrieval (Roelofs, 1992). Word encoding is done in WEAVER++ by combining elements into a coherent whole, which bears some similarity to the psychomotor skill of weaving that has been practiced since ancient times. There is also a connection between weaving and communication, which is evident from the English word *text*, derived from the Latin word for weaving, *texare*. Furthermore, Jacquard's invention of a programmable loom in the early 19th century led to the development of the modern computer on which the model runs (Essinger, 2007). Like Jacquard looms and classical computers, the model separates declarative content (threads, data) and procedural rules (punched cards, programs), unlike associative or connectionist models. The name of the model also refers to Ernst Weber (meaning weaver in German), according to Wundt, the father of experimental psychology. In his seminal article on the speed of thought, Wundt (1862b) compared the mind to a weaver, following Goethe. WEAVER++/ARC is the neurocognitive version of the model (Roelofs, 2014b, 2023a, 2024) that is illustrated in Figure 5.1. The letters A, R, and C in ARC stand for Arcuate Repetition and Conversation.

The model distinguishes between declarative and procedural aspects of word processing, as discussed in Chapter 2. An associative network that realizes declarative knowledge is represented in temporal and inferior frontal areas of the human brain, including Wernicke's area and Broca's area. A system of IF-THEN rules (reminiscent of Wundt's motivated mental acts) that realize procedural knowledge is represented in the basal ganglia, thalamus, and frontal cortex, including Broca's area. The associative network is accessed by spreading activation, while IF-THEN rules select from the activated nodes those nodes that meet the goals and task requirements specified in working memory (e.g., naming an object).

The associative network consists of concepts (e.g., CAT) thought to be represented bilaterally in the anterior temporal lobes; lemmas (e.g., *cat*) in the middle part of the left middle temporal gyrus; output lexical forms (e.g., <cat>) in the left posterior superior temporal gyrus and middle temporal gyrus (Wernicke's area); output phonemes (e.g., /k/, /æ/, and /t/) in the left posterior inferior frontal gyrus (i.e., Broca's area); and motor programs for syllable pronunciation (e.g., [kæt]) in the ventral precentral gyrus. Input phonemes (e.g., /k/, /æ/, and /t/) and input lexical forms (e.g., <cat>) are represented bilaterally in the middle to posterior superior temporal gyrus and superior temporal sulcus.

Concepts are part of a center of modality-general conceptual representations, which integrate modality-specific features represented in widespread brain areas for perception and movement. Lemmas specify the grammatical properties of words, represented in the left posterior temporal cortex, required for the production and comprehension of phrases and sentences. For example, the lemma of the word *cat* specifies that the word is a noun (N). Lemmas also allow the specification of morphosyntactic parameters, such as number (singular, plural) for nouns, so that the correct output lexical form can be retrieved (e.g., singular <cat>).

The output lexical forms are thought to be connected to output phonemes by the arcuate fasciculus, which is also thought to connect input phonemes to output phonemes, with the lexical and nonlexical phonological connections mediated by different parts of the arcuate fasciculus. Support for this view comes from a recent study that combined fMRI with diffusion-weighted imaging and probabilistic tractography by Nikki Janssen and colleagues, including myself (Janssen et al., 2023). The study found that the part of the arcuate fasciculus running from the left middle temporal gyrus to the inferior frontal gyrus supported lexical connections because this part was specifically engaged in verb generation (e.g., saying "eat" in response to the heard word "apple"), which requires the lexical connections. In contrast, the nonlexical phonological connections are supported by another part of the arcuate fasciculus running from the superior temporal gyrus to the inferior frontal gyrus, because this part was specifically engaged in pseudoword repetition, which requires the nonlexical connections.

The IF-THEN rules mediate top-down attentional influences in conceptually driven word production by selectively enhancing the activation of target concept nodes in the network depending on the goal specified in working memory. The rules also mediate the selective blocking of perception (Roelofs, 2003), similar to the perceptual inhibition achieved by Wundt's motivated acts of apperception (Wundt, 1902). As illustrated in Figure 5.1, one source of top-down control is the inferior frontal gyrus, which is part of frontoparietal and basal ganglia thalamocortical networks underlying domain-general attentional control processes and general intelligence, as discussed in Chapters 2 and 4.

Computer simulations conducted over the past thirty years have shown that the model explains a wealth of behavioral findings on the production and comprehension of words. For example, as mentioned in Chapter 1, computer simulations with the model indicated that the reaction time patterns of Donders (simple < go/no-go < choice) and his students (simple < go/no-go = choice) are obtained depending on the magnitude of the go/no-go cost, which differs between individuals (Roelofs, 2018a). Figure 5.2 shows the results for speech repetition in Donders' (1865, 1868a) original experiments.

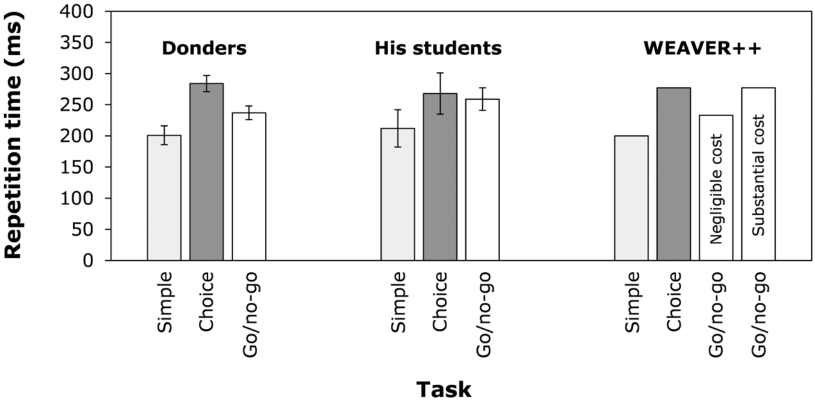


Figure 5.2. Reaction time patterns for the simple, choice, and go/no-go tasks of Donders and his students, and in WEAVER++ simulations by Roelofs (2018a) depending on the magnitude of the go/no-go cost (negligible vs. substantial). ms = milliseconds.

Also, the model accounts well for the classic findings on color-word Stroop task performance (i.e., key findings from half a century of research after Stroop, 1935; see MacLeod, 1991, for a review) as well as for findings on picture-word interference (Roelofs, 2003). The color-word Stroop and picture-word interference tasks were discussed in Chapter 2.

For example, simulations showed that the model accounts for the magnitude of the semantic effect from written distractor words in picture naming as a function of SOA, such as saying "cat" to a picture of a cat while trying to ignore the semantically related distractor word *dog* or the unrelated word *tree* superimposed on the picture. In the example stimulus in Figure 5.3, the words are capitalized, just as in the empirical study. The left panel of the figure shows the classic empirical findings of Glaser and Düngelhoff (1984) and WEAVER++ simulation results (Roelofs, 1992). The right panels show how the semantic effect at zero SOA varied empirically across the reaction time distribution, from decile to decile, in the studies of Roelofs and Piai (2017), shown in the top panel, and Scaltritti et al. (2015), shown in the bottom panel, and in WEAVER++ simulations (San José et al., 2021). The model captures the difference in distribution of the semantic effect between the two studies by assuming different frequencies of attentional lapses. While Wundt (1874) investigated interference via SOA manipulation and later tested his theory of attention by qualitatively examining reaction time distributions (Wundt, 1903), these modern empirical studies and the simulation results demonstrate the increase in precision obtained over the past 150 years. Simulations also showed that the model accounts for the MEG findings on the timing of picture-word interference (Piai et al., 2014), discussed in Chapter 2.

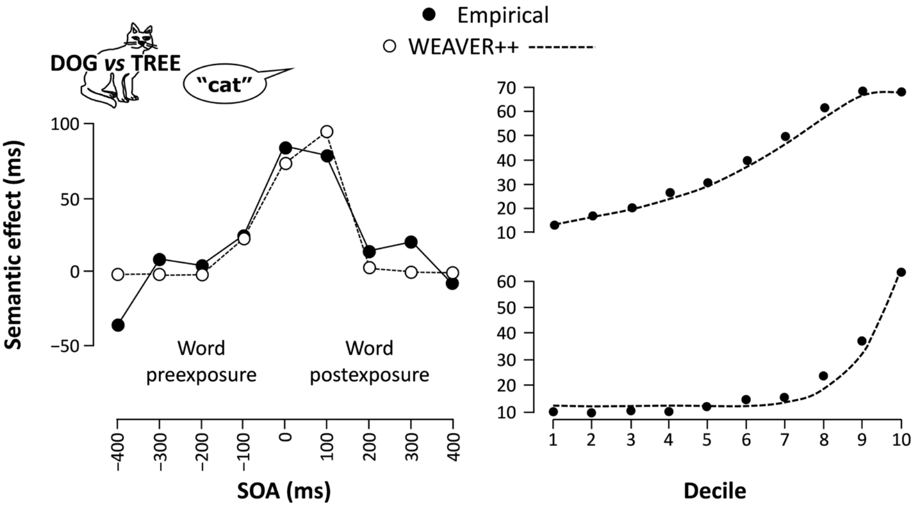


Figure 5.3. Left: The semantic effect of distractor words in picture naming as a function of stimulus onset asynchrony (SOA) observed empirically by Glaser and Düngelhoff (1984) and in WEAVER++ simulations (Roelofs, 1992). Right: The semantic effect across the reaction time distribution in the studies of Roelofs and Piai (2017) (top panel) and Scaltritti et al. (2015) (bottom panel) and in WEAVER++ simulations (San José et al., 2021). ms = milliseconds.

While cognitive processes typically occur on a scale of ten to several hundred milliseconds, some physiological responses, such as the hemodynamic BOLD response in fMRI, occur on a time scale of several seconds. Empirically, the Stroop effect of incongruent versus congruent words in color naming (e.g., the word *red* in green versus red color) is typically between 100 and 150 milliseconds, while the effect on the BOLD response occurs between 5 and 8 seconds after the color-word stimulus presentation (e.g., MacDonald et al., 2000). To directly relate mental processes to the BOLD response, a bridging assumption is required. Statistical packages for analyzing fMRI data consider the BOLD response as a gamma function. WEAVER++ simulations showed that the model can account for the Stroop effects on different time scales by assuming a gamma function for the BOLD response and identifying its parameters with functional parameters in the model (Roelofs & Hagoort, 2002; see also Roelofs et al., 2006). Figure 5.4 shows the empirically observed BOLD response in the anterior cingulate cortex and in the model. Each whole brain scan lasted 2.5 seconds in the fMRI study. The difference in color naming times between the incongruent and congruent conditions was empirically 116 milliseconds and 127 milliseconds in WEAVER++. The simulation showed that the model can capture the effects on different time scales.

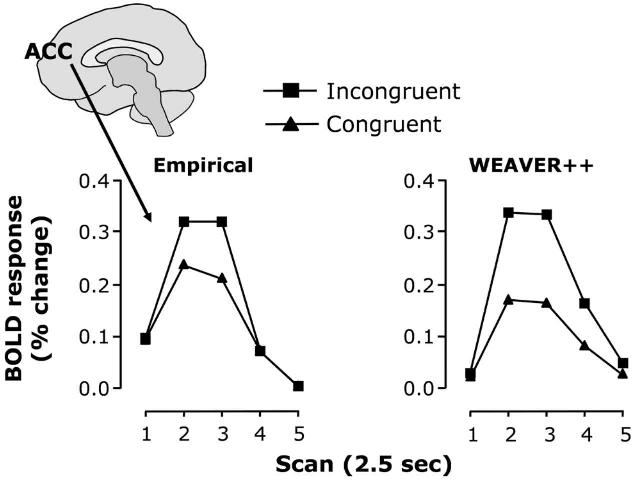


Figure 5.4. The BOLD responses in the anterior cingulate cortex (ACC) in Stroop task performance as empirically observed by MacDonald et al. (2000) and in WEAVER++ simulations (Roelofs & Hagoort, 2002). Sec = second.

In Chapter 1, I indicated that the term ‘autonomous’ refers to at least two properties which can apply independently of each other: computational independence and information encapsulation. That word planning components require some attention in WEAVER++ means that they do not run entirely on their own computing resources. Processing components are informationally encapsulated when they operate only with limited knowledge, linking specific inputs to specific outputs. For example, the phonological encoding component in WEAVER++ uses one or more morphemes (i.e., output lexical forms) and output phonemes to generate a phonological word representation, which requires morphophonological knowledge but no other information, such as semantics. Other researchers do not assume such encapsulation of information. For example, Alfonso Caramazza and colleagues assumed that the management of the articulatory buffer uses semantic information (e.g., Finkbeiner & Caramazza, 2006), and as a result, semantic interference occurs in the articulatory buffer. However, this assumption is not consistent with the evidence on the timing of the interference from Piai et al. (2014), also found in a meta-analysis of the MEG and EEG literature (see Roelofs, 2018b).

WEAVER++'s assumption that word planning components require some attention is supported by evidence from dual-task performance (Roelofs & Piai, 2011). The extent to which a task can be performed without interfering with other concurrent tasks indicates whether the tasks are performed by independent processing mechanisms and whether central attentional capacity is shared (Kahneman, 1973). In Chapter 1, I discussed Wundt's (1862b) pioneering research into the extent to which mental processes, such as visual and auditory perception and their coordination, can overlap in time, addressing a problem already raised by Aristotle. Since the 1950s, this issue has been extensively studied using dual-task paradigms (see Meyer & Kieras, 1997, for a review). Modern evidence indicates that in picture naming, processing of other visual information, requiring a manual response, is postponed until the phonological form of the picture name has been encoded (e.g., Roelofs, 2008b). The WEAVER++ model provides an account of how attentional capacity is allocated in the coordination of vocal responding, eye gaze shifting (i.e., overt orienting of attention), and manual responding.

In a critical experiment (Roelofs, 2008b), participants were presented with pictures displayed on the left side of a computer screen and left- or right-pointing arrows displayed on the right side of the screen, as illustrated in the left panel of Figure 5.5 (see also Chapter 2). The arrows > and < were flanked by two *x*'s on each side to prevent them from being identified through parafoveal vision. The picture and the arrow were presented simultaneously on the screen (zero SOA), or the arrow was presented 300 or 1000 milliseconds after picture onset. The participants' tasks were to name the picture (Task 1) and to indicate the direction in which the arrow was pointing by pressing a left or right button (Task 2). Eye movements were recorded to determine the onset of the shift of gaze between the picture and the arrow. Phonological encoding was manipulated by having the participants name the pictures in blocks of trials where the picture names shared the onset phoneme (e.g., the /k/ in "cat", "cup", "car"), the homogeneous condition, or in blocks of trials where the picture names did not share the onset phoneme (e.g., “cat”, “pin”, “sun”), the heterogeneous condition. If gaze shifts are initiated after phonological encoding, their latencies should show the phonological effect.

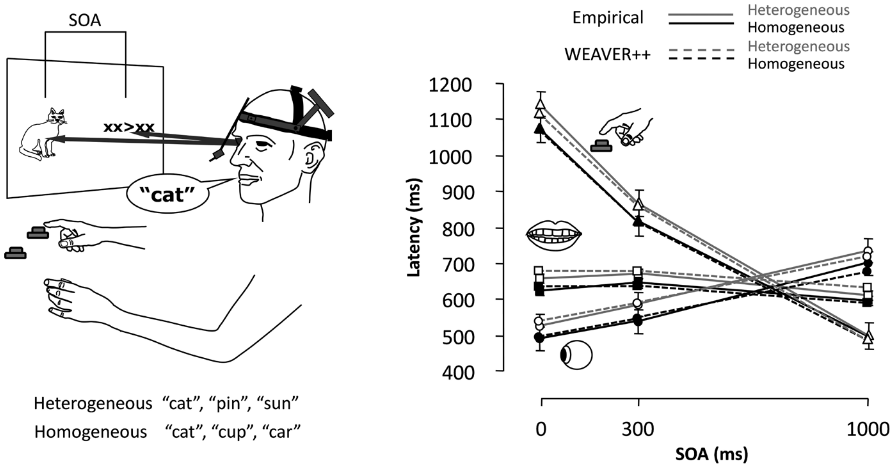


Figure 5.5. Overt orienting of attention in the coordination of vocal responding (Task 1), gaze shifting, and manual responding (Task 2) in a dual-task experiment of Roelofs (2008b): The left panel shows the experimental procedure and the right panel the empirical latency data and WEAVER++ simulation results. SOA = stimulus onset asynchrony for the two tasks.

The right panel of Figure 5.5 shows that phonological overlap in a block of trials reduced picture naming and gaze shifting latencies at all SOAs. Gaze shifts were dependent on phonological encoding even when they were postponed at the nonzero SOAs. Manual responses to the arrows were delayed and reflected the phonological effect at the short SOAs (i.e., 0 and 300 milliseconds) but not at the long SOA (i.e., 1000 milliseconds). The figure also shows the results of computer simulations with WEAVER++, which fit the empirical findings well. The critical assumption in the model is that the overt orienting of attention (and the reallocation of attentional capacity) depends on the completion of phonological encoding. This supports the assumption that word planning requires attentional capacity.

The model assumes that the allocation of attention in dual-task performance is actively scheduled (e.g., Kahneman, 1973) and that the interference between the two tasks is not due to a passive processing bottleneck (Pashler, 1984). Active scheduling is supported by evidence that the amount of interference between tasks depends on the updating ability of attentional control (Piai & Roelofs, 2013) and that the lateral middle frontal gyrus is involved (Szameitat et al., 2002), which is a key region of the frontoparietal control network.

Simulations have also shown that the WEAVER++/ARC model accounts for the results of lesion-deficit analyses linking damaged brain areas or damaged fiber connections to word production and comprehension impairments in poststroke aphasia syndromes (Roelofs, 2014b, 2024), such as Broca's aphasia and Wernicke's aphasia. Moreover, the model accounts for language impairment due to neurodegenerative diseases (Roelofs, 2023a).

Neurodegenerative diseases can specifically disrupt not only memory consolidation, as in Alzheimer's disease (Chapter 2), but also the content of declarative memory, such as knowing that a cat is an animal and has a tail. This is observed in frontotemporal degeneration, which typically gives rise to semantic and behavioral syndromes, first documented by Arnold Pick (1851-1924) in Prague (Pick, 1892, 1904). The semantic syndrome is characterized by a loss of conceptual knowledge and largely spared episodic memory, and the behavioral syndrome by personality changes and behavioral problems (i.e., disinhibition, apathy/inertia, loss of sympathy/empathy, hyperorality, repetitive/compulsive behavior, and executive deficits), although loss of conceptual knowledge also occurs. In *The Banana Lady and Other Stories of Curious Behaviour and Speech*, Kertesz (2007) provided detailed case descriptions. In both syndromes, the loss of knowledge is modality general, as it affects not only the ability to recognize and name objects through vision but also through touch and other modalities. In the semantic syndrome, also called *semantic dementia*, neurodegeneration affects the anterior temporal lobes bilaterally, while in the behavioral syndrome, the frontal lobes are affected and the anterior temporal lobes to a lesser extent. In both syndromes, naming objects is more impaired than understanding words, with greater overall impairment in the semantic than in the behavioral syndrome. In another syndrome, called nonfluent/agrammatic aphasia, in which neurodegeneration is located in Broca's area, conceptual knowledge is preserved, but production of words and sentences is impaired (e.g., Kertesz, 2007).

In September 1907, Pick traveled to Amsterdam for the first International Congress of Psychiatry, Neurology, Psychology and Nursing of the Insane. Among the more than 800 attendees were several key researchers, including the Spanish neuroscientist Santiago Ramón y Cajal, who had just received a Nobel Prize for his work on the structure of the nervous system, the Belgian experimental psychologist Albert Michotte, who was then a postdoc with Wundt, and the Dutchman Gerard Heymans, whose establishment of a psychological laboratory in 1892 had marked the beginning of experimental psychology in the Netherlands (Draaisma, 1992). The venue was the city's famous concert hall, the Concertgebouw. Upon the arrival of

Dutch Queen Wilhelmina and her husband Prince Hendrik, a choir sang the national anthem of the Netherlands, and "during the afternoon sang selections from Händel's oratorios, Joshua and The Messiah", according to a special correspondent in The Medical Record of New York on September 21, 1907. There were also a number of exhibitions, including one showing the noematachograph of Donders (Chapter 1), as a photograph in the City Archives of Amsterdam shows.

In a plenary address, Pick proposed an explanation as to why neurodegeneration is localized and leads to focal behavioral symptoms. The paper he read appeared as a chapter of a book about the work from his clinic in Prague (Pick, 1908) and was also included in the conference proceedings. According to Pick, neurodegenerative diseases target and spread through functional networks, which are localized. While stroke destroys brain areas regardless of function, neurodegeneration is function specific and, therefore, "signifies the *progression from circumscribed locality to circumscribed function*" (p. 26).

After Alzheimer (1911) wrongly rejected Pick's (1908) account based on inaccurate histopathological observations (Roelofs, 2023b), it was forgotten for almost a century. But Pick's account was clearly a sleeping beauty. Recently, unknowingly of Pick, the account has been independently re-proposed and empirically supported by evidence from network-sensitive neuroimaging (e.g., Seeley et al., 2009), making it now one of the best explanations available.

Implementing Pick's ideas, the WEAVER++/ARC model was applied to the picture naming and word comprehension performance observed by Julie Snowden and colleagues (2019) in a sample of 100 patients with frontotemporal degeneration, 30 diagnosed with semantic dementia and 70 with the behavioral syndrome. When naming, patients spoke the name of the object shown in each picture (e.g., a cat, say "cat"), and performance accuracy was assessed. Word comprehension accuracy was assessed using a word-to-picture matching test with the same items as the naming test. Patients had to match a printed word (e.g., *cat*) by pointing to one of four semantically related pictures (e.g., the cat, but not the dog or another animal). Computer simulations were conducted to see if WEAVER++/ARC could account for the performance accuracies of the individual patients, assuming a reduction in the activation capacity of the concept nodes in the network. The simulations showed that the model accounted for 98% of the variance of the individual naming and comprehension accuracies of the 100 patients. Furthermore, the capacity reduction in the model for each of the patients correlated with the amount of neurodegeneration in the anterior temporal lobes, but not in other areas, for each of the 100 patients (see Roelofs, 2023a).

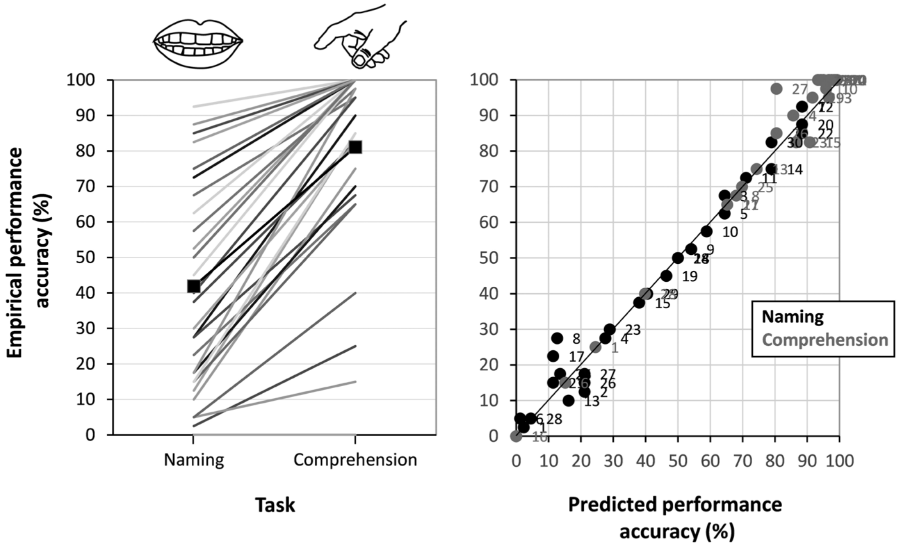


Figure 5.6. Performance accuracy in semantic dementia for naming and comprehension: The left panel shows the empirically observed performance of individual patients (*N* = 30) from Snowden et al. (2019) denoted by different lines and the group averages by squares and a black line. The right panel shows for each patient, denoted by dot and number, the performance accuracy predicted by WEAVER++/ARC plotted against the empirical performance accuracy.

To illustrate the results, the left panel of Figure 5.6 shows the naming and comprehension accuracies of the patients with semantic dementia. The performance of individual patients is indicated with different lines, and the group averages are indicated with squares and a black line. Naming is worse than word comprehension, which is not just a proportional difference. Predicting individual comprehension scores by naming scores, assuming a linear relationship, explained only 53% of the patients' variance. The right panel shows the model-predicted performance accuracy plotted against the empirically observed performance accuracy, indicated by dots and patient numbers. The agreement between model and real data is good, with the model explaining 98% of the variance in the data.

According to an alternative view, concepts consist of widespread modality-specific features without a central concept node, as advocated by Snowden et al. (2019) themselves and originally proposed by Wernicke (1874). For modality-general loss of conceptual knowledge to occur, several modality-specific representations or connections between them must be disrupted simultaneously. This alternative view of concepts does not explain the evidence that the conceptual disorder in semantic dementia occurs across all input modalities (i.e., not only vision, but also touch and other modalities). Furthermore, it does not explain why the impairment arises from degeneration of the anterior temporal lobes rather than from degeneration of widespread areas encoding modality-specific features or connections between them.

In Chapter 1, I discussed seven faculties of the mind that Spearman (1927) identified as historically proposed: Sensory perception, Intellect (Thought), Memory, Imagination, Attention, Language, and Movement. Here, I briefly indicate how these faculties relate to my account of the key aspects of the mind, as shown in Figure 5.1. Essentially, proponents of a horizontal faculty view see mental processes and behavior as resulting from an interaction between the faculties. Figure 5.1 can serve to illustrate how these interactions can come about. Vision and audition support *Sensory perception* that leads to activation of modality- and domain-general concepts in declarative *Memory*, which become conscious when amplified by *Attention*. The concepts can enter *Thought* and *Imagination* through the application of IF-THEN rules from procedural *Memory*, and the outcome can be used to initiate *Language* processes such as word planning, resulting in *Movement*, such as an articulatory response.

The articles that Donders never wrote

Donders' (1865) handwritten notebook contains raw data and notes about his reaction time experiments. In a letter to Helmholtz dated May 18, 1868, Donders wrote about this work with the noematachograph and an upcoming article: "I have also started to organize my large amount of material about the duration of psychological processes and have written an article that describes this. It will appear in the next issue of our journal" (1868d, p. 3). At the beginning of this classic 1868 article, Donders stated that he had not had time to write a full report, and the article ends by announcing further articles on the subject, which never appeared. The German version of the article *Die Schnelligkeit psychischer Processe* is subtitled *Erster Artikel* (*First Article*), suggesting that a second article would follow, and perhaps more. But in 1870, a very tragic event occurred: His daughter Marie died four days after giving birth to twins. In a letter to Helmholtz dated March 6, 1870, Donders wrote about the loss: "As a broken person, I will have to start again to fulfill the duty of life" (p. 2). According to his friend Bowman (1891), Donders was never able to overcome his grief over the death of his only child.

Donders' son-in-law, physiologist Theodor Engelmann (son of Wilhelm Engelmann, the Leipzig publisher of many of Wundt's books, including all editions of the *Grundzüge*), remarried Emma Vick, a professional pianist. She knew the composer Johannes Brahms, who came to Utrecht several times to stay with the Engelmann family and make music together at their home. Clara Schumann and Joseph Joachim were also there regularly. Brahms and Engelmann were good friends (for their correspondence, see Röntgen, 1918), and Brahms also knew Donders (who played the violin and recorded its sound with the phonautograph). Brahms dedicated his third string quartet to Engelmann and composed the *Akademische Fest-Ouvertüre* for an honorary doctorate he himself received from the University of Breslau, later the academic home of Wernicke, Ebbinghaus, and Alzheimer. Brahms was asked by Helmholtz (a friend of the German piano builder Theodor Steinweg, known as Steinway) to help evaluate his theory of the sensations of tone (Helmholtz, 1863), and he composed music for Exner's wedding. Wundt's friend Reinecke (in Figure 2.9) conducted the premiere of the final seven-movement version of Brahms' *Ein deutsches Requiem* at the Gewandhaus in Leipzig. In Utrecht, Engelmann succeeded Donders as director of the Physiological Laboratory when he died in 1889. Condolences came from Brahms.

Donders did not witness how reaction time measurement, his tasks, and the method of subtraction flourished under Wundt's hands in the last quarter of the 19th century. And he could not have imagined how his subtraction method would usher in the modern era of neuroimaging, the beginnings of which are described by Posner and Raichle (1994) and Raichle (1998).

Summary

In the second half of the 20th century, production system theories were found to provide integrated explanations of empirical discoveries about the mind (Newell and Simon, Anderson, Meyer and Kieras) and its neurobiological underpinning, as shown more recently (Eliasmith). Using my own production system model, I have illustrated that by integrating previous modeling insights (Wernicke, Wundt), a wealth of findings on word production, comprehension, and repetition can be explained, in both health and disease.

Epilogue

In the year of his death, 1920, Wundt published his memoirs *Erlebtes und Erkanntes*, the last revision of his *Grundriss*, and the tenth and final volume of his *Völkerpsychologie*. He had achieved what he had set out to achieve half a century earlier, starting with the publication of his *Grundzüge* in 1874: helping to establish a science of the mind. But after his death, Wundt and his work were quickly forgotten. Undeserved, as I have made clear in this book.

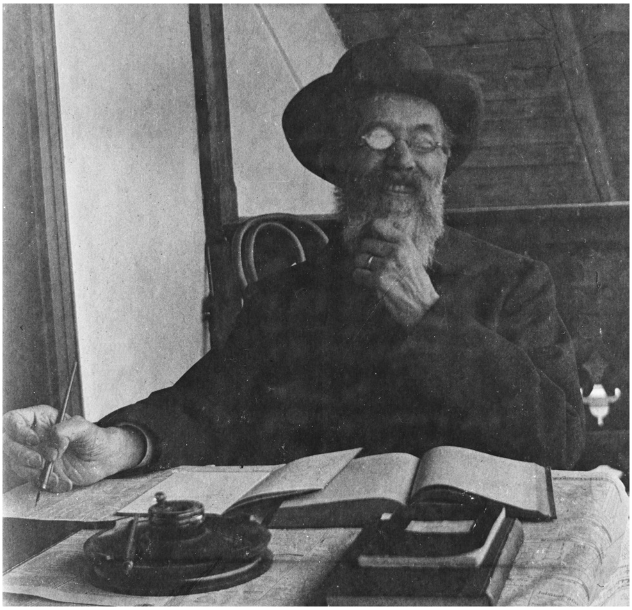


Figure E.1. Undated photo of a smiling Wundt, who was considered to be a very serious person.

Why did Wundt's work fall into oblivion? Brysbaert and Rastle (2009) came up with the following thoughts:

> Despite the fact that Wundt had a career of 65 years, was head of the best laboratory in the world, and was a prolific writer (he published more than 50,000 pages, in a time when texts were still written by hand), his scientific legacy is not very much more than of being 'the father of experimental psychology'. The main reason for this is that Wundt

> did not produce a useful theory like Newton or Darwin, or make an empirical discovery that had a wide-ranging, lasting impact (such as Lavoisier's discovery that oxygen was needed for the burning of a substance). Furthermore, although Wundt was considered to be a good teacher, his writings were far from clear and easy to read. (p. 89)

Two examples of unclear writing were then given by Brysbaert and Rastle, one from the 1896 edition of the *Grundriss*. However, low readability probably applies to any text that is more than a century old. It is not important whether Wundt's texts are clear to us, but to his contemporaries. And this seems to have been the case. In a review in the journal *Mind* of the first German (!) edition of the *Grundriss*, Stevenson (1896) stated:

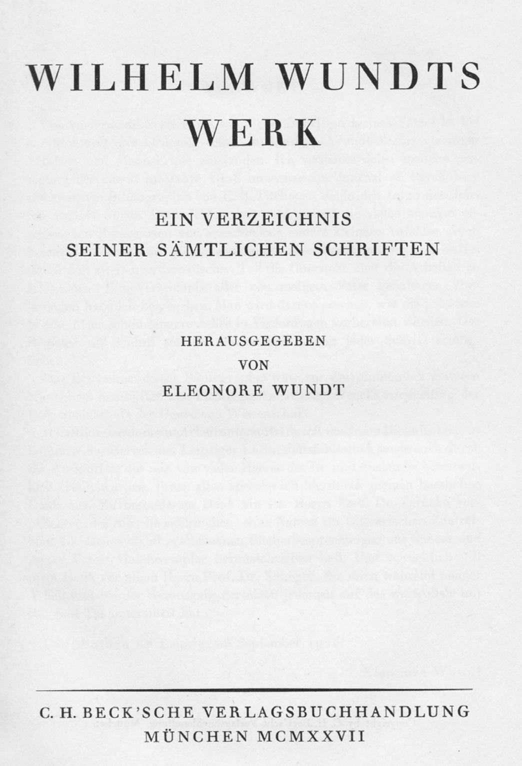
> The book is a brief, clear and consistent exposition of Wundt's psychological system; and more than this could hardly have been achieved within the compass of a single admirably printed volume. Much of the detail has appeared already in the *Grundzüge*; but the adoption of a purely psychological standpoint gives a special interest to the *Grundriss*. (p. 564)

Moreover, the Dutch translation of the *Grundriss* by Lem (Wundt, 1898) was intended for primary school teachers. This suggests that the writing could not have been very difficult.

Clearly, Wundt was no Newton or Darwin, but then again, that is true of most psychologists. And indeed, there is no Wundt's law as there is a Weber's law and a Fechner's law, but there was an apperception model with anatomical and physiological correlates. The fate of Wundt's work was initially shared by that of another German scientist, Wernicke, whose magnum opus *Der aphasische Symptomencomplex* was published in the same year as the first edition of Wundt's *Grundzüge*, namely 1874. However, in the 1960s and 1970s, Wernicke's model of aphasia was revived and vigorously defended by Geschwind (1965, 1972) and is now known to every aphasiologist. Wundt did not have a Geschwind.

Geschwind himself argued that the groundbreaking work of Wernicke and his German contemporaries had been largely forgotten because, after World War I, the language of science changed from German and French to English (Geschwind, 1964). Wernicke's 1874 book was translated into English in the 1970s (i.e., Eggert, 1977), but Wundt's 1874 book never was. Titchener only translated 338 of the 2035 pages of the fifth edition of the *Grundzüge* (Wundt, 1902), that is, only 17% of it. And the translated part was Wundt's description of the brain, not his account of the investigations of the mind.

It can also be argued that Wundt simply wrote too much. Boring (1950) estimated Wundt's written output at approximately 53,735 pages of text, cataloged by his daughter Eleonore in 1927 (see Figure E.2). Robinson (2001) republished her bibliography of Wundt's writings. While Wernicke's 1874 monograph had 72 pages, Wundt's had 870 pages, even tripling in size in the fifth edition. Covering a lot in one book can be a good quality, but it can also be a disadvantage, putting off potential readers interested in the subject. In his 115-page *Examen de la Phrénologie* (1842), Flourens wrote: "I wanted to be short. There is a big secret to being short: It is to be clear" (p. 8). Despite the French, Flourens' case against phrenology remains known to this day. Perhaps Wundt should have taken Flourens' advice more to heart. Although it is unclear whether Wundt ever read Flourens, his personal library contained several books by Ribot (i.e., 12 to be precise; see the list of the Max Planck Institute for the History of Sciences in Berlin), which were also characteristically short. For example, *Les Maladies de la Mémoire* (1881), which states what came to be called Ribot's law, runs to 169 pages.



WILHELM WUNDTS
WERK

EIN VERZEICHNIS
SEINER SÄMTLICHEN SCHRIFTEN

HERAUSGEGEBEN
VON
ELEONORE WUNDT

C. H. BECK'SCHE VERLAGSBUCHHANDLUNG
MÜNCHEN MCMXXVII

Figure E.2. Title page of an inventory of Wundt's written works and his lectures, compiled by his daughter Eleonore and published in 1927.

Ribot, the first professor of experimental psychology in France (Nicolas & Murray, 1999), promoted Wundt's work since the 1870s. For example, he described Wundt's neurocognitive model of apperception ("sa théorie de l'aperception sur une hypothèse anatomo-physiologique") in detail and also reviewed his chronometrical work. In the fifth revised edition of his monograph on German psychology, published in 1898 (the first edition appeared in 1879), *La Psychologie Allemande Contemporaine* (*Contemporary German Psychology*), Ribot characterized Wundt's importance:

> Fechner, despite the great brilliance of his work, confined himself to a single question; … Helmholtz, despite the high level of his analysis of elementary sensations, is only occasionally a psychologist; finally others, while following the same path as Wundt, are far from equaling him. In him alone we find a complete and systematic study of the problems of psychology. (p. 217)

Brysbaert and Rastle (2009) maintained that Wundt had not made an empirical discovery with a wide-ranging, lasting impact. However, in all editions of his *La Psychologie*, Ribot pointed to Wundt's (1874) observation that the scope of consciousness is wider than that of attention, Blickfeld (*le champ visuel*) versus Blickpunkt (*le point visuel*), today referred to as phenomenal and access consciousness. Wundt (1893) reported experimental evidence for the distinction using a tachistoscope, which was further corroborated by Sperling (1960). Wundt estimated the capacity of the scope of attention at four to six elements, depending on the modality. This is close to the findings of G. Miller (1956) and exactly consistent with those of Cowan (2001).

The type of approach to psychology that, according to Ribot, was characteristic of Wundt changed after World War I. It became behaviorism in America and Gestalt psychology in Europe. New generations in science often present themselves with the argument that the past was wrong and that their newer approach is the right one, as did the behaviorists and the Gestalt psychologists. And when Wundt's approach was revived in the 1950s in the new cognitive psychology of information processing, starting in America and England, it was done by researchers who did not read German. They therefore missed the pioneering work of Wundt and his contemporaries. In 1979, historian of psychology Thomas Leahey wrote:

> Modern researchers show no very deep awareness of earlier cognitive psychology. Broadbent mentions the "classical introspective psychologists," but his book contains no reference to Wundt. References to Wundt are also lacking in the books by Cherry and Kahneman, as well as the papers by Cherry, Treisman, and Deutsch and Deutsch.

> Neisser's 1977 work, *Cognition and Reality*, is a partial exception, for it alone discusses early views at any length, but surprisingly, in view of Neisser's similarity to Wundt (whom he does not discuss by name), it misrepresents Wundt's positions. Wundt has been misrepresented in American history of psychology since Boring's time. (p. 249)

The quotation from Shallice and Cooper (2011) in the prologue to my book suggests that historical awareness has not improved much since Leahey's observation. I hope that my book will help remedy this situation and bring 150 years of the history of psychology back into the minds of people.

In conclusion, in this monograph I have described crucial empirical and theoretical discoveries about the mind that have been made over the past 200 years, showing that the first major developments took place in the first half of the 19th century and not after the World War II, contrary to what Shallice and Cooper (2011) claimed. Moreover, I have shown that the physiological approach proposed by Wundt in his *Grundzüge* of 1874 was and remains fruitful. Physiological methods can be used to enlighten the mind, contrary to the claims of skeptical voices (e.g., Coltheart, 2006, 2013; Page, 2006; Uttal, 2001; Van Orden & Paap, 1997). Finally, I have demonstrated the feasibility of an integrative theoretical account, one that explains mental processes and their dependence on the brain not only qualitatively but also quantitatively. May such an approach continue to flourish in future scientific studies.

I end with optimism about future progress, as Wundt did shortly before his death. Blumenthal (2001) wrote:

> As the darkness closed in on Wundt's last days, and on the final days of what had been a great era in his nation's history, the optimism of Wundt's once gilded age shines in the last utterances of his memoirs (Wundt, 1920) and the last pages of his *Völkerpsychologie*. He proclaims a faith in the positive, creative, and moral powers of the human mind that he saw leading inevitably to a better future. (p. 142)

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Wundt, W. (1861/1862). *Manuskript und Entwürf zu ▯Die Geschwindigkeit des Gedankens▯* [Manuscript and draft of "The speed of thought"]. UBLNachlassWundt_mods_00005085. https://sammlungen-editor.uni-leipzig.de

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Wundt, W. (1879). *Der Spiritismus. Eine sogenannte wissenschaftliche Frage. Offener Brief an Herrn Prof. Dr. Hermann Ulrici in Halle* [Spiritualism. A so-called scientific question. Open letter to Prof. Dr. Hermann Ulrici in Halle]. Engelmann. https://wellcomecollection.org/works/kfdvfw5w

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Wundt, W. (1896). *Grundriss der Psychologie* [Outlines of psychology]. Engelmann. http://vlp.mpiwg-berlin.mpg.de/references?id=lit779

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Wundt, W. (1900-1920). *Völkerpsychologie: Eine Untersuchung der Entwicklungsgesetze von Sprache, Mythus, und Sitte* (Vols. 1-10) [Cultural psychology: An investigation into the developmental laws of language, myth, and custom]. Engelmann.

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Wundt, W. (1904). *Principles of physiological psychology* (E. B. Titchener, Trans.). Swan Sonnenschein. (Original work published 1902)

Wundt, W. (1908). *Grundzüge der physiologischen Psychologie* [Principles of physiological psychology] (6th ed., Vol. 1). Engelmann. http://vlp.mpiwg-berlin.mpg.de/references?id=lit1150

Wundt, W. (1910). *Grundzüge der physiologischen Psychologie* [Principles of physiological psychology] (6th ed., Vol. 2). Engelmann. http://vlp.mpiwg-berlin.mpg.de/references?id=lit1160

Wundt, W. (1911). *Grundzüge der physiologischen Psychologie* [Principles of physiological psychology] (6th ed., Vol. 3). Engelmann. http://vlp.mpiwg-berlin.mpg.de/references?id=lit47

Wundt, W. (1918). *Über die Aufgabe der Philosophie in der Gegenwart* [On the task of contemporary philosophy] [Audio]. https://www.jochen-fahrenberg.de/uploads/media/audio/Wundt_Redefragment_1874_(1918).mp3

Wundt, W. (1920a). *Erlebtes und Erkanntes* [Experienced and known]. Kröner.

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Zheng, X. Y., Hebart, M. N., Grill, F., Dolan, R. J., Doeller, C. F., Cools, R., & Garvert, M. M. (2024). Parallel cognitive maps for multiple knowledge structures in the hippocampal formation. *Cerebral Cortex*, *34*(2), bhad485. https://doi.org/10.1093/cercor/bhad485

Further watching, listening, and reading

Here, I provide references to books and articles that offer state-of-the-art and more in-depth discussions of empirical findings and theory development related to the topics of the chapters in this book. The *Classics in the History of Psychology* website gives access to several translated original texts by key figures in the history of the scientific study of the mind. Several of them were filmed in the 1920s and 1930s by Karl Dallenbach (1887-1971) and others. The researchers filmed include Boring, C. Bühler, K. Bühler, J. Cattell, Hull, Koffka, Köhler, Lewin, Pavlov, Pillsbury, Spearman, Stern, Thorndike, Titchener, and Woodworth. The film *Psychologists 1927-1933* was edited in 1970 by Rand Evans and can be viewed on the website of the Max Planck Institute for the History of Science in Berlin. The *Vox* magazine of Radboud University, Nijmegen, has made a short video clip of my replication with my daughter Sterre of Donders' classic "ki–ki" experiment, which can be seen on YouTube. Wundt's voice was recorded in 1918 and can be heard on Jochen Fahrenberg's website.

Evans, R. B. (1970). *Psychologists 1927–1933* [Video]. Max Planck Institute for the History of Science, Berlin. http://vlp.mpiwg-berlin.mpg.de/library/data/lit39550

Vox. (2018, April 6). Donders Instituut haalt wetenschappelijk topstuk naar Nijmegen [Donders Institute brings scientific masterpiece to Nijmegen] [Video]. YouTube. https://www.youtube.com/watch?v=F9gjQ9zdFg4&t=1s

Wundt, W. (1918). *Über die Aufgabe der Philosophie in der Gegenwart* [On the task of contemporary philosophy] [Audio]. https://www.jochen-fahrenberg.de/uploads/media/audio/Wundt_Redefragment_1874_(1918).mp3

There are many books on the history of psychology, of which I mention just a few. A classic text is *A History of Experimental Psychology* (1950) by Edwin Boring, who had personal contact with several key figures from the early history I discussed. Boring's portrayal of Wundt was heavily criticized and corrected by Arthur Blumenthal in 1975. The book *Thinking: From Association to Gestalt* (1964), edited by Jean Mandler and George Mandler, is out of print but available in libraries. It contains a selection of original texts (translated by the editors) from the history of theory and research into thought, from Aristotle to Selz and Wertheimer, with an emphasis on the Würzburg school. My copy of the book contains Chapter 5 "The New Psychology: Directed Thinking" (on the work of Watt) by mistake twice, as if the book wants to emphasize its importance. For a modern, broad coverage of theoretical issues in the history of psychology, I refer to the book *Historical and Conceptual Issues in Psychology* (2021) by Marc Brysbaert and Kathy Rastle. For a modern account of the history of psychology much further back in time than my book, I refer to *A History of Psychology: From Antiquity to Modernity* (2017) by Thomas Leahey. A shorter introduction is *A Brief History of Modern Psychology* (2024) by Ludy Benjamin. Fancher and Rutherford (2012) described the lives of several of the pioneers of psychology discussed in my book.

Benjamin, L. T. (2024). *A brief history of modern psychology* (4th ed.). Wiley.
Blumenthal, A. L. (1975). A reappraisal of Wilhelm Wundt. *American Psychologist*, *30*(11), 1081–1088. https://doi.org/10.1037/0003-066X.30.11.1081
Boring, E. G. (1950). *A history of experimental psychology* (2nd ed.). Appleton-Century.
Brysbaert, M., & Rastle, K. (2021). *Historical and conceptual issues in psychology* (3rd ed.). Pearson.
Fancher, R. E., & Rutherford, A. (2012). *Pioneers of psychology: A history* (4th ed.). Norton.
Leahey, T. (2017). *A history of psychology: From antiquity to modernity* (8th ed.). Routledge.
Mandler, J. M., & Mandler, G. (Eds.). (1964). *Thinking: From association to Gestalt*. Wiley.

Digitally scanned versions of many original books and periodicals are available at the Internet Archive in San Francisco (https://archive.org/), the Wellcome Collection in London (https://wellcomecollection.org/search/works), and the library of the Max Planck Institute for the History of Science in Berlin (https://vlp.mpiwg-berlin.mpg.de/library).

Chapter 1

A comprehensive review of modern cognitive neuroscience evidence on the mind, covering both neuroimaging and patient evidence, and a defense of the approach, can be found in *The Organisation of Mind* by Shallice and Cooper (2011). A discussion and defense of the modularity thesis was provided by Fodor (1983) in his *The Modularity of Mind*. An account of the number sense can be found in Dehaene (2011), and Dehaene (2023) literally illustrates, using a hundred spectacular color images, the power of neuroimaging to illuminate the mind. Levelt (2013) discussed the history of psycholinguistics, including the work of Wernicke and Wundt on language.

Dehaene, S. (2011). *The number sense: How the mind creates mathematics* (rev. ed.). Oxford University Press.

Dehaene, S. (2023). *Seeing the mind: Spectacular images from neuroscience, and what they reveal about our neuronal selves*. The MIT Press.

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. The MIT press,

Levelt, W. J. M. (2013). *A history of psycholinguistics: The pre-Chomskyan era*. Oxford University Press.

Shallice, T., & Cooper, R. (2011). *The organisation of mind*. Oxford University Press.

Of special interest on the *Classics* website are the seminal article of Broca (1861) on his discovery about language and Fechner's (1860) book on psychophysics.

Broca, P. (1861). Remarques sur le siège de la faculté du langage articulé, suivies d'une observation d'aphémie (perte de la parole) [Remarks on the seat of the faculty of articulated language, following an observation of aphemia (loss of speech)]. *Bulletin de la Société Anatomique*, *6*, 330-357. Broca's discussion of the localization of speech production in the left frontal lobe and the supporting evidence from his seminal patient Leborgne, nicknamed "Tan".

Fechner, G. T. (1860). *Elements of psychophysics*, Sections VII ("Measurement of sensation") and XVI ("The fundamental formula and the measurement formula"). Fechner's discussion of important psychophysical evidence, including Weber's, and the proposal of his law, later called "Fechner's Law".

Chapter 2

An extensive discussion of attentional control can be found in Badre (2020), while Posner (2012) discussed his theory of attention. Although now over a decade old, *The Cognitive Neuroscience of Memory* (2012) by Howard Eichenbaum remains a good introduction to the cognitive neuroscientific evidence regarding the brain systems for declarative, procedural, and emotional memory. Wixted (2004) discussed the mathematical form of the forgetting curve and its relationship to other memory phenomena. The best and most comprehensive modern introduction to the work of Wundt is Fahrenberg (2019). Levelt interviewed Wundt virtually in 1995. Wundt's digitized estate (Meyer et al., 2017) can be accessed on the website of the University of Leipzig, Germany, at https://sammlungen.uni-leipzig.de/wundt

Badre, D. (2020). *On task: How our brain gets things done*. Princeton.

Eichenbaum, H. (2012). *The cognitive neuroscience of memory: An introduction* (2nd ed.). Oxford University Press.

Fahrenberg, J. (2019). *Wilhelm Wundt (1832–1920): Introduction, quotations, reception, commentaries, attempts at reconstruction*. Pabst Science Publishers. https://jochen-fahrenberg.de/fileadmin/pdf2019/WUNDT__1832-1920_._Complete_Work__Fahrenberg_5.10.2019_.pdf

Levelt, W. J. M. (1995). Chapters of psychology: An interview with Wilhelm Wundt. In R. L. Solso, & D. W. Massaro (Eds.), *The science of mind: 2001 and beyond* (pp. 184–202). Oxford University Press. https://www.mpi.nl/publications/item145889/chapters-psychology-interview-wilhelm-wundt

Meyer, T., Mädebach, A., & Schröger, E. (2017). The digitization of the Wundt estate at Leipzig University. *History of Psychology*, *20*(3), 342–345. https://doi.org/10.1037/hop0000068

Posner, M. I. (2012). *Attention in a social world*. Oxford University Press.

Wixted, J. T. (2004). On common ground: Jost's (1897) law of forgetting and Ribot's (1881) law of retrograde amnesia. *Psychological Review*, *111*(4), 864–879. https://doi.org/10.1037/0033-295X.111.4.864

Of particular interest on the *Classics* website are the books of Ebbinghaus (1885/1913), James (1890), and Wundt (1897, 1904), and the classic article of Stroop (1935).

Ebbinghaus, H. (1913). *Memory: A contribution to experimental psychology* (H. A. Ruger & C. E. Bussenius, Trans.). Teachers College Press. (Original work published 1885) Ebbinghaus' report on his memory experiments and the proposal of the forgetting equation.

James, W. (1890). *The principles of psychology*. Holt. James's bestseller that provided an overview of late 19th century psychology.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662. Report on experiments using a color-word task that became the "gold standard" of attentional measures.

Wundt, W. (1897). *Outlines of psychology* (C. H. Judd, Trans.). Engelmann. (Original work published 1896) Authorized English translation of Wundt's classic 1896 *Grundriss* text. The best short introduction to his work.

Wundt, W. (1904). *Principles of physiological psychology* (E. B. Titchener, Trans.). Swan Sonnenschein. (Original work published 1902) Unauthorized English translation of Wundt's fifth revision of his classic 1874 *Grundzüge* text.

Chapter 3

Discussions on various aspects of consciousness are provided in chapters of *The Routledge Handbook of Consciousness* (2020), edited by Rocco Gennaro. A comprehensive review of modern cognitive neuroscientific evidence on consciousness and global workspace theory can be found in *Consciousness and the Brain* (2014) by Stanislas Dehaene. Lachter et al. (2004) reported modern experimental tests of Broadbent's filter theory.

Dehaene, S. (2014). *Consciousness and the brain: Deciphering how the brain codes our thoughts*. Viking.

Gennaro, R. J. (Ed.) (2020). *The Routledge handbook of consciousness*. Routledge.

Lachter, J., Forster, K. I., & Ruthruff, E. (2004). Forty-five years after Broadbent (1958): Still no identification without attention. *Psychological Review*, *111*(4), 880-913. https://doi.org/10.1037/0033-295X.111.4.880

Of particular interest on the *Classics* website are the book by Thorndike (1911) and the articles of Lashley (1930), Tolman (1948), Watson (1913), and Witmer (1907).

Lashley, K. S. (1930). Basic neural mechanisms in behavior. *Psychological Review*, *37*, 1-24. Overview of a decade of unsuccessful search for localized traces of maze learning in rat brains, leading to the proposal of the principles of mass action and equipotentiality.

Thorndike, E. L. (1911). *Animal intelligence: Experimental studies*. The Macmillan Company. The book in which the Law of Effect and the Law of Exercise were proposed.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*, 189-208. The classic article reviewing evidence for cognitive maps in rats.

Watson, J. B. (1913). Psychology as the behaviorist views it. *Psychological Review*, *20*, 158-177. The classic declaration of behaviorism.

Witmer, L. (1907). Clinical psychology. *Psychological Clinic*, *1*, 1-9. The beginning of clinical psychology.

Chapter 4

A current general introduction to intelligence is *The Science of Human Intelligence* (2023) by Richard Haier, Roberto Colom, and Earl Hunt. In *How Intelligence Happens* (2010), John Duncan explains his own theory of intelligence and the empirical support for it.

Duncan, J. (2010). *How intelligence happens*. Yale University Press.

Haier, R. J., Colom, R., & Hunt, E. (2023). *The science of human intelligence* (2nd ed.). Cambridge University Press.

Of particular interest on the *Classics* website are the articles by J. Cattell (1890), Hollingworth (1922), G. Miller (1956), and Spearman (1904).

Cattell, J. M. (1890). Mental tests and measurements. *Mind*, *15*, 373-381. One of the first attempts at what we would now call intelligence testing.

Hollingworth, L. S. (1922). Differential action upon the sexes of forces which tend to segregate the feebleminded. *The Journal of Abnormal Psychology and Social Psychology*, *17*(1), 35-57. Refutation of the variability hypothesis.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81-97. One of the earliest contributions to the revival of cognitive psychology after World War II.

Spearman, C. (1904). "General intelligence," objectively determined and measured. *American Journal of Psychology*, *15*, 201-293. One of the most influential articles in the history of psychometric intelligence theory.

Chapter 5

Integrated explanations of the mind, which are similar to and inspired my account, can be found in Anderson et al. (2004) and Meyer and Kieras (1999).

Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of the mind. *Psychological Review*, *111*(4), 1036–1060. https://doi.org/10.1037/0033-295X.111.4.1036

Meyer, D. E., & Kieras, D. E. (1999). Précis to a practical unified theory of cognition and action: Some lessons from EPIC computational models of human multiple-task performance. In D. Gopher & A. Koriat (Eds.), *Attention and Performance XVII. Cognitive regulation of performance: Interaction of theory and application* (pp. 17-88). The MIT Press.

Associationist-connectionist and symbolic-procedural approaches concern theorizing of the mind, not the brain. Ultimately, the psychological processes and representations assumed in these theories are implemented in the brain by networks of spiking neurons (e.g., Dumont et al., 2023). In his book *How to Build a Brain* (2013), Chris Eliasmith theoretically explained how structured symbolic representations and IF-THEN rules can be realized by such neural networks. A proof of concept of his ideas is the 2.5-million-neuron model of the brain called the Semantic Pointer Architecture Unified Network or SPAUN (Eliasmith et al., 2012), which successfully simulates performance characteristics in various tasks, including digit copy-drawing, serial working memory, and reinforcement learning at the level of neuroanatomy, neurophysiology, and behavior.

Dumont, N. S., Stöckel, A., Furlong, P. M., Bartlett, M., Eliasmith, C., & Stewart, T. C. (2023). Biologically-based computation: How neural details and dynamics are suited for implementing a variety of algorithms. *Brain Sciences*, *13*(2), 245. https://doi.org/10.3390/brainsci13020245

Eliasmith, C. (2013). *How to build a brain: A neural architecture for biological cognition*. Oxford University Press.

Eliasmith, C., Stewart, T. C., Choo, X., Bekolay, T., DeWolf, T., Tang, Y., & Rasmussen, D. (2012). A large-scale model of the functioning brain. *Science*, *338*(6111), 1202–1205. https://doi.org/10.1126/science.1225266

Sources of illustrations

Prologue

Figure P.1. Wundt's house in Großbothen. From Wontorra, M., Meischner-Metge, A., & Schröger, E. (Eds.) (2004). Wilhelm Wundt (1832-1920) und die Anfänge der experimentellen Psychologie [Wilhelm Wundt (1832-1920) and the rise of experimental psychology]. CD [ISBN 3-00-013477-8]. Image used with permission from Prof. dr. Schröger.

Figure P.2. The spine and title page of the first 1874 edition of Wundt's *Grundzüge*. Photo taken from the author's personal copy of the book.

Figure P.3. Lateral and medial views of the human brain, created by the author.

Chapter 1

Figure 1.1. The study of Wundt at Goethestraße 6 in Leipzig. Website of the library of the University of Leipzig. https://blog.ub.uni-leipzig.de/eine-schenkung-von-nachlassunterlagen-wilhelm-wundts-an-die-universitaetsbibliothek-leipzig. Image used with permission from the Universitätsbibliothek Leipzig.

Figure 1.2. Medieval view on the human mind. Dolce, 1562, from *Human Physiology* by John Elliotson, 1840. Wellcome Collection, London. Public Domain Mark 1.0 Universal. https://wellcomecollection.org/works/txzp8tfz/items?canvas=5

Figure 1.3. Phrenological brain map (from Fowler, 1896). Area 33 houses language and area 28 is the seat of the number sense. Wellcome Collection, London. Public Domain Mark 1.0 Universal. https://wellcomecollection.org/works/e7e75e9u

Figure 1.4. Illustration of the language model of Wernicke, created by the author. The brain is from Wernicke's (1880c) illustration of his model in the booklet *Ueber den wissenschaftlichen Standpunkt in der Psychiatrie*, taken from the author's personal copy of the booklet.

Figure 1.5. Exner's quantitative lesion-overlap "heat" map for language based on 31 persons with aphasia, from Exner (1881). Wellcome Collection, London. Public Domain Mark 1.0 Universal. https://wellcomecollection.org/works/gzd2wjyz

Figure 1.6. Spearman's (1937) diagram of mental faculties and their location in the brain, which aimed to represent the knowledge at the end of the 19th century. The diagram in Spearman's book *Psychology Down the Ages* (Vol. 1, p. 41) was shown on the right hemisphere

and falls under a copyright exception that allows use in non-commercial research. Wellcome Collection, London, https://wellcomecollection.org/works/chbasczb. The new, left hemisphere version of the diagram was created by the author.

Figure 1.7. Illustration of Donders' phonautograph and noematachograph (top) and the noematachogram (bottom), created by the author. Donders' device is in the Utrecht University Museum. The figure is reused from Roelofs (2018a) with permission from Elsevier.

Figure 1.8. Documentation of reaction times (left) and the associated annotated stimulus lists (right) in a handwritten laboratory notebook by Donders (1865). The notebook is in the archives of the Utrecht University Museum. Images used with permission from the Utrecht University Museum. High-resolution scans of the two notebook pages shown were provided to the author by curator Reina de Raat, with kind permission for use in this book.

Figure 1.9. Selfie of the author and his daughter Sterre after repeating Donders' classic experiment in 2018. With kind permission from Sterre Roelofs for use in this book.

Figure 1.10. Cover of the issue and title page of the German publication of Donders' classic 1868 article. Photo taken from the author's personal copy of the issue.

Figure 1.11. Wundt's 1861/1862 drawing of a pendulum from his handwritten notes as well as a stylized version that appeared in the 1874 first edition of the *Grundzüge*. The drawing (left) is from Wundt (1861/1862), Wundt Estate, UBLNachlassWundt_mods_00005085, Public Domain Mark 1.0 Universal. The stylized version (right) comes from the author's personal copy of the 1874 *Grundzüge*.

Figure 1.12. Illustration of Fechner's law, created by the author.

Figure 1.13. Illustration of a hybrid horizontal/central and vertical/input-output view of the structure of the mind, created by the author.

Table 1.1. Classic aphasia syndromes according to Wernicke (1874, 1886), made by the author.

Chapter 2

Figure 2.1. Experimental rooms in the Institute for Experimental Psychology of Wundt. From Wontorra, M., Meischner-Metge, A., & Schröger, E. (Eds.) (2004). Wilhelm Wundt (1832–1920) und die Anfänge der experimentellen Psychologie [Wilhelm Wundt (1832–1920) and the rise of experimental psychology]. CD [ISBN 3-00-013477-8]. Image used with permission from Prof. dr. Schröger.

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Figure 2.3. Wundt surrounded by his collaborators in 1912. From Wontorra, M., Meischner-Metge, A., & Schröger, E. (Eds.) (2004). Wilhelm Wundt (1832–1920) und die Anfänge der

experimentellen Psychologie [Wilhelm Wundt (1832–1920) and the rise of experimental psychology]. CD [ISBN 3-00-013477-8]. Image used with permission from Prof. dr. Schröger.

Figure 2.4. The reaction time distributions on the poster of Wundt, reconstructed using Wundt (1903), created by the author.

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Figure E.2. Title page of an inventory of Wundt's written works and his lectures, compiled by his daughter Eleonore and published in 1927. Photo taken from the author's personal copy of the booklet.

Ardi Roelofs studied experimental psychology at Radboud University in Nijmegen, the Netherlands, where he obtained his bachelor's, master's, and PhD degrees (all three with highest distinction). He then worked at the Massachusetts Institute of Technology in the USA, the Max Planck Institute for Psycholinguistics in Nijmegen, the University of Exeter in England, again the Max Planck Institute, and finally the Donders Institute for Brain, Cognition and Behaviour at Radboud University. He is a full professor there and was director of the research master's program in cognitive neuroscience. His research focuses on language and attention in health and disease.

This book presents a concise history of the scientific discovery of the mind. Although people have speculated about the nature and functioning of their minds for thousands of years, it was only about 200 years ago that they replaced the philosophical armchair with the laboratory and began to investigate the mind scientifically. Surprisingly, the work of one of the founders of scientific psychology, Wilhelm Wundt (1832–1920), has been largely forgotten, despite its relevance to current psychology. Taking a fresh look at history, this book discusses important empirical and theoretical discoveries made in the few decades before and in the 150 years after the publication of Wundt's groundbreaking monograph *Grundzüge der physiologischen Psychologie* in 1874. Crucial evidence from past behavioral and patient studies to recent neuroimaging is synthesized to support a thought-provoking account of key aspects of the human mind.

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ISBN 978-94-9329-679-4

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