

“Brilliant. . . Exhilarating.”

—RICHARD DAWKINS, from the Foreword

A THOUSAND BRAINS



**A NEW THEORY OF
INTELLIGENCE**

JEFF HAWKINS

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With a foreword by Richard Dawkins

BASIC BOOKS
New York

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Basic Books
Hachette Book Group
1290 Avenue of the Americas, New York, NY 10104
www.basicbooks.com

Printed in the United States of America

First Edition: March 2021

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Print book interior design by Trish Wilkinson

Library of Congress Cataloging-in-Publication Data

Names: Hawkins, Jeff, 1957– author.

Title: A thousand brains : a new theory of intelligence / Jeff Hawkins ; with a foreword by Richard Dawkins.

Description: First edition. | New York : Basic Books, 2021. | Includes bibliographical references and index.

Identifiers: LCCN 2020038829 | ISBN 9781541675810 (hardcover) | ISBN 9781541675803 (ebook)

Subjects: LCSH: Brain. | Intellect. | Artificial intelligence.

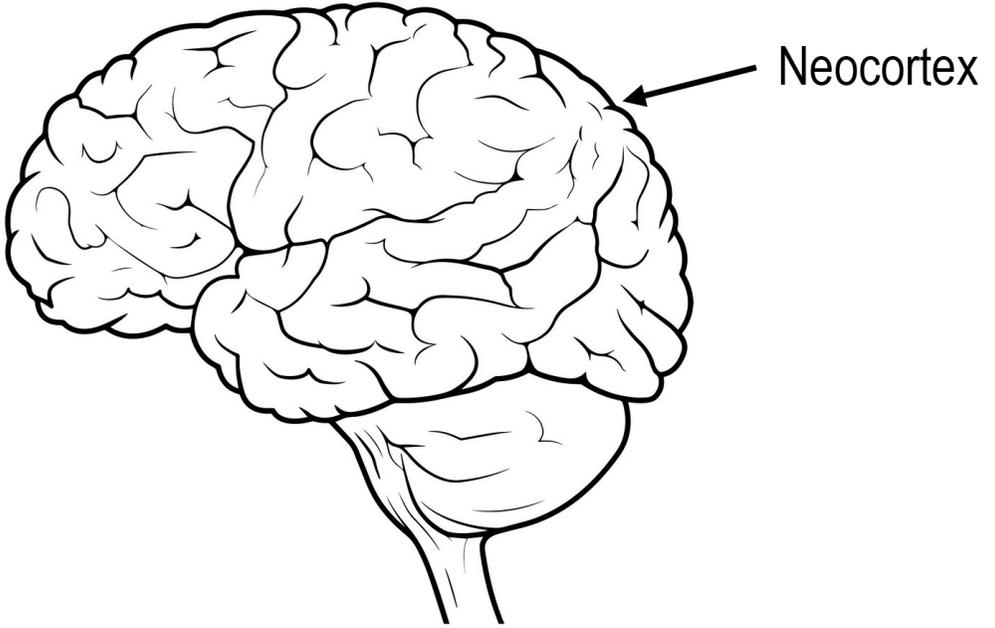
Classification: LCC QP376 .H2944 2021 | DDC 612.8/2—dc23

LC record available at <https://lccn.loc.gov/2020038829>

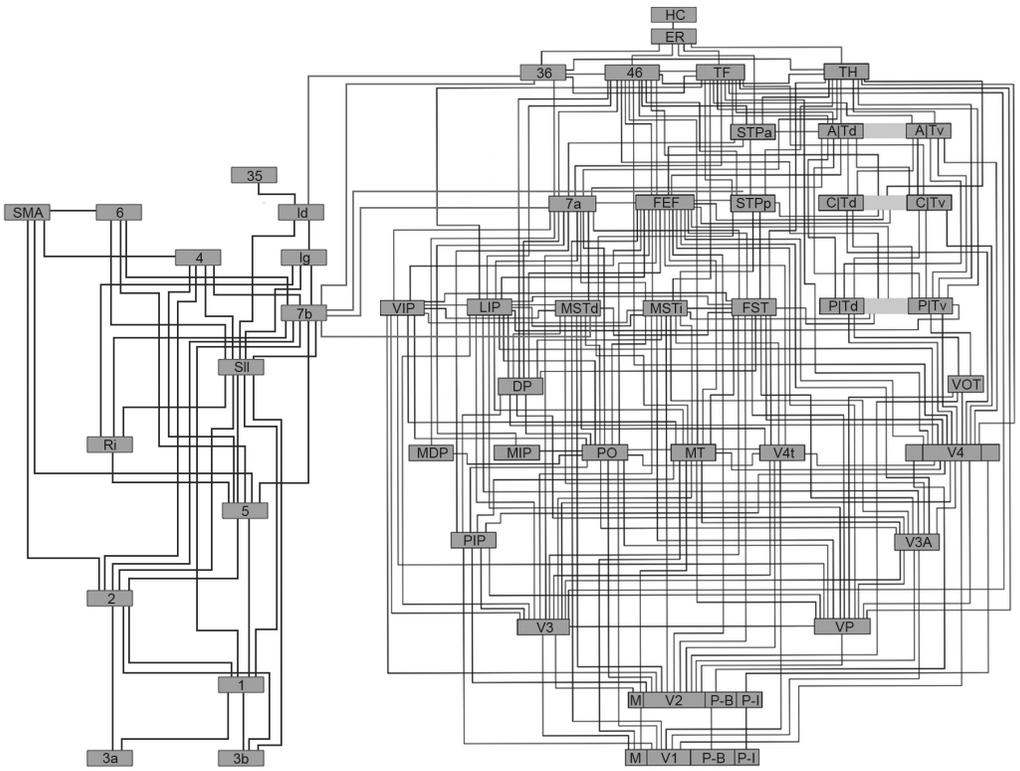
ISBNs: 978-1-5416-7581-0 (hardcover), 978-1-5416-7580-3 (ebook)

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10 9 8 7 6 5 4 3 2 1



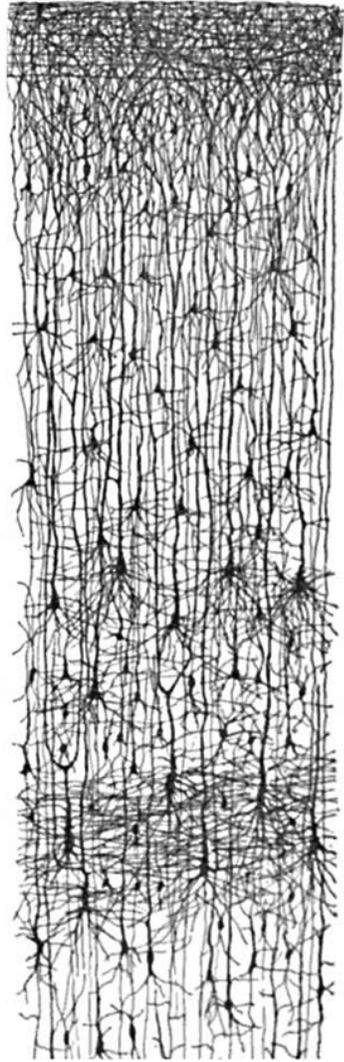
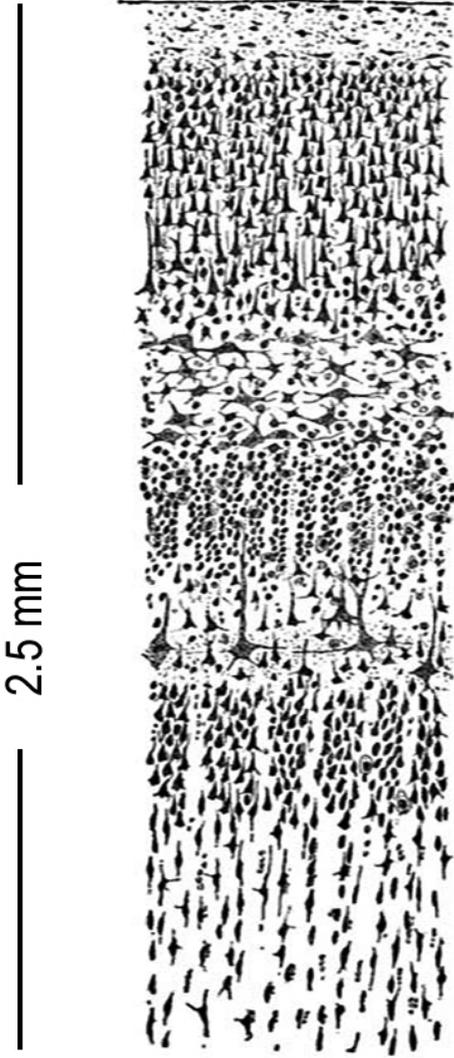
A human brain



Touch

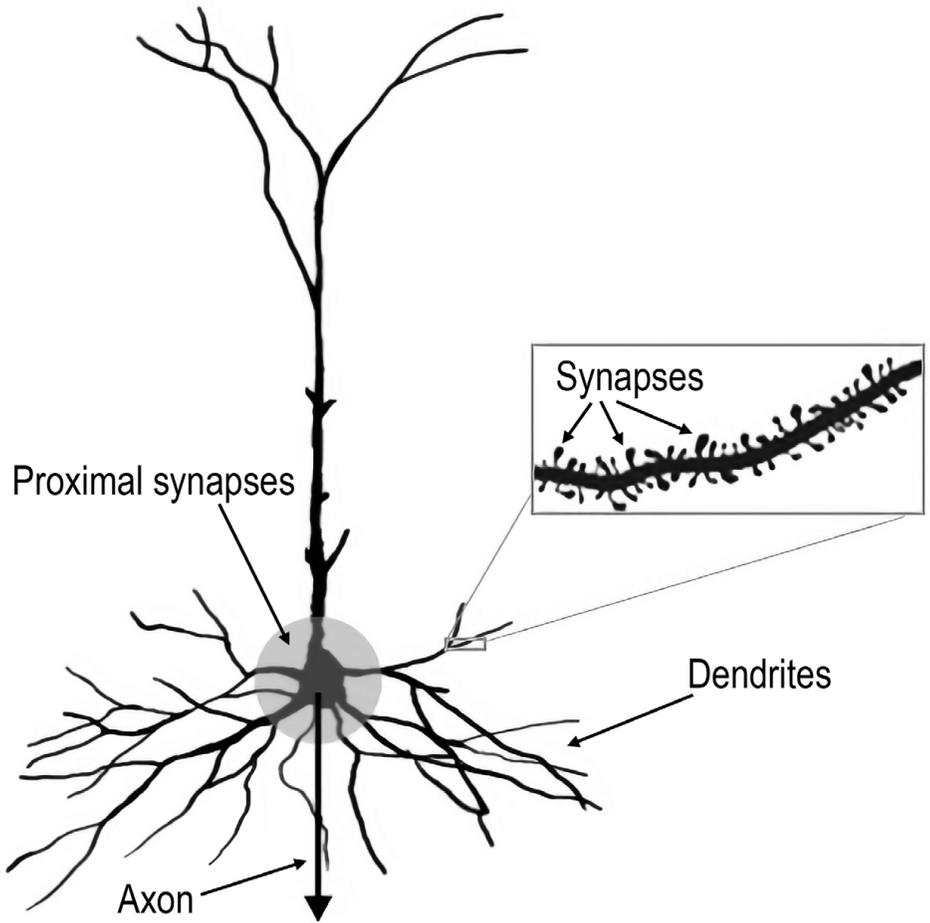
Vision

Connections in the neocortex

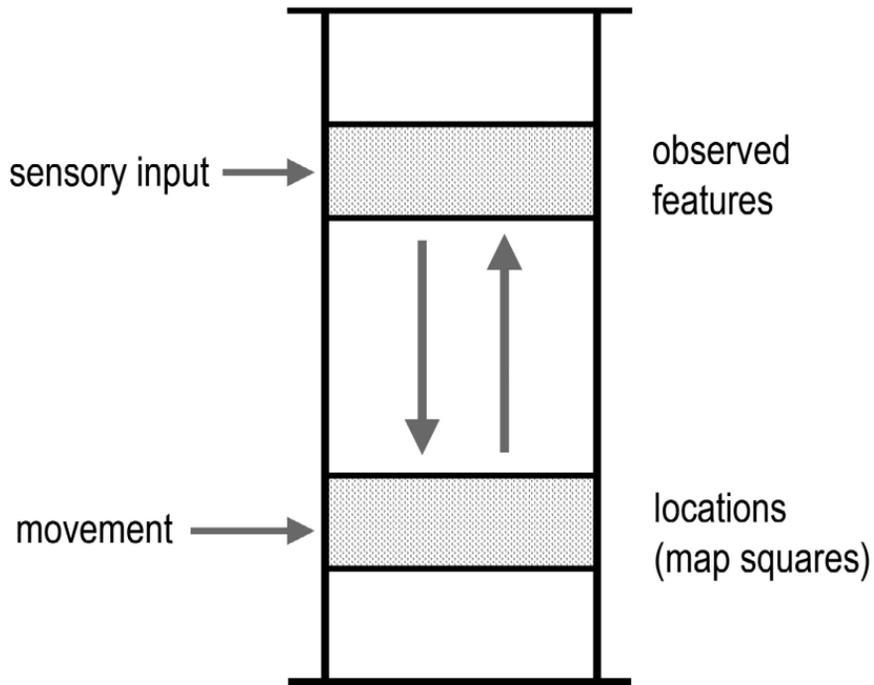


Cajal, 1899

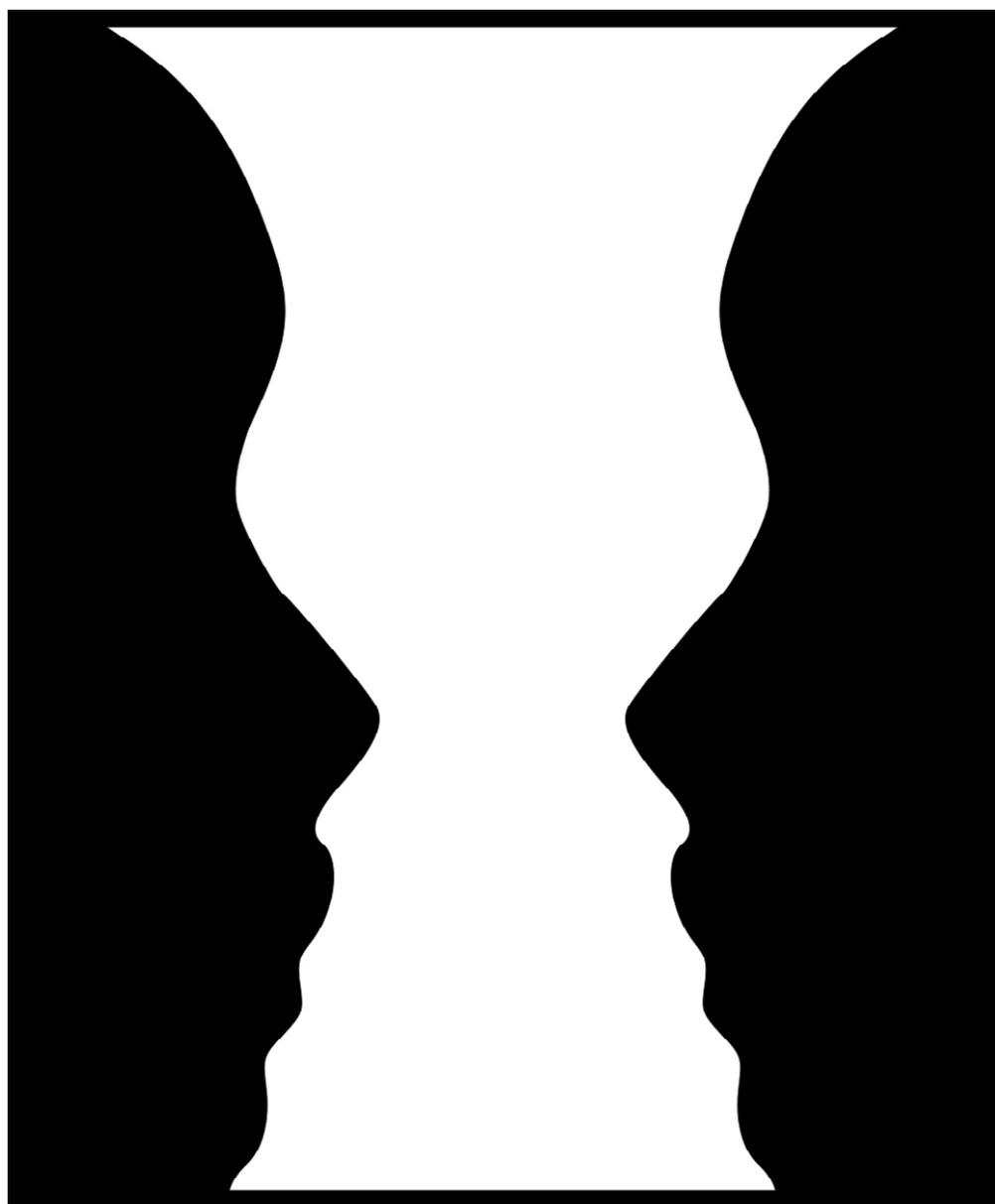
Neurons in a slice of neocortex

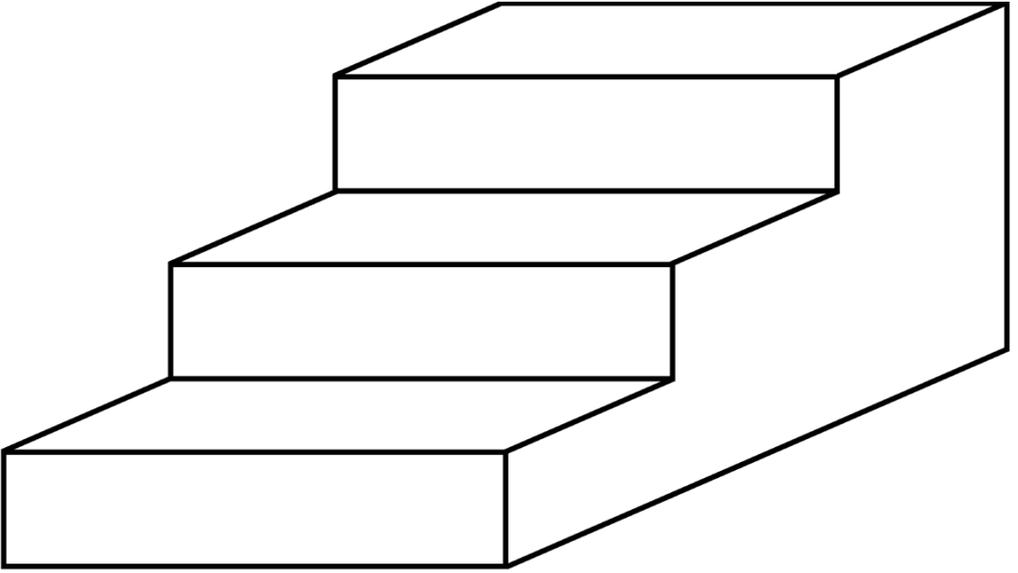


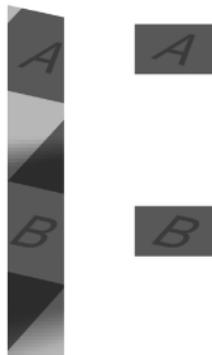
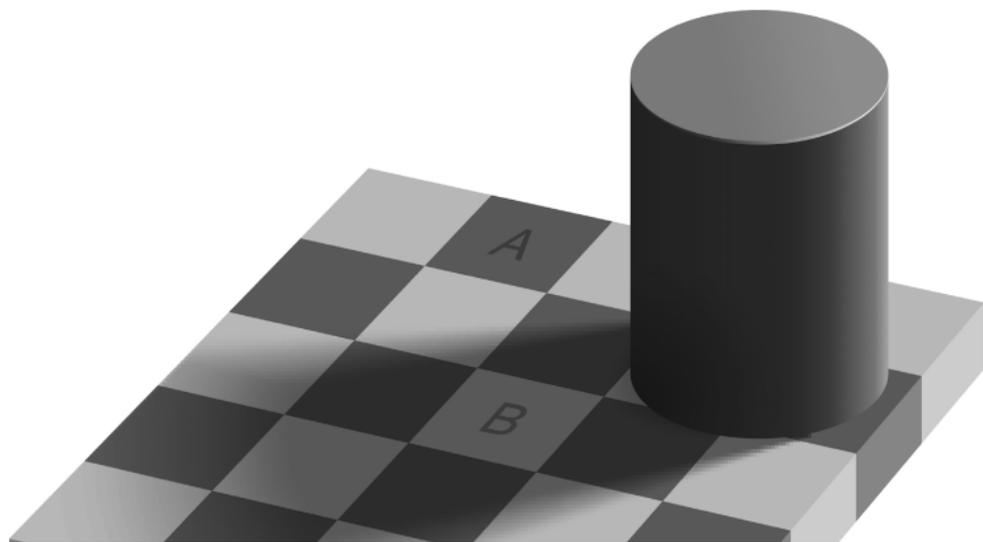
A typical neuron



A model of a cortical column







Suggested Readings

People who have heard about our work often ask me what I recommend reading to learn more about the Thousand Brains Theory and the related neuroscience. This usually prompts a deep sigh from me, because there isn't a simple answer, and to be honest, it is hard to read neuroscience papers. Before I give you specific reading recommendations, I have some general suggestions.

Neuroscience is such a large field of study that even if you are a scientist intimately familiar with one subfield you might have trouble reading the literature in a different one. And if you are completely new to neuroscience it can be difficult to get started.

If you want to learn about a specific topic—say, cortical columns or grid cells—and you are not already fluent in that topic, then I recommend starting with a source such as Wikipedia. Wikipedia usually has multiple articles on any topic, and you can quickly jump between them by following links. It is the quickest way I know to get a feel for terminology, ideas, themes, etc. You will often find that different articles disagree or use different terminology. You will find similar disagreements in peer-reviewed scientific papers. As a rule, you need to read multiple sources to get a sense of what is known about a topic.

To dig deeper, the next thing I recommend are review articles. Review articles appear in peer-reviewed academic journals, but, as their name implies, they present an overview of a topic, including areas where

Suggested Readings

scientists disagree. Review articles are usually easier to read than typical papers. The citations are also valuable because they present most of the important papers related to a topic in one list. A good way to find review articles is to use a search engine such as Google Scholar and type in something like “review article for grid cells.”

Only after you have learned the nomenclature, history, and concepts of a topic would I recommend reading individual scientific papers. The title and abstract of a paper are rarely sufficient to know if it has the information you are looking for. I typically read the abstract. Then I scan the images, which in a well-written paper should tell the same story as the text. Then I jump to the discussion section at the end. This section is often the only place where the authors plainly describe what the paper is about. Only after these preliminary steps will I consider reading the paper from beginning to end.

Below are suggested readings by topic. There are hundreds to thousands of papers on each subject, so I can only give you a few suggestions to help you get started.

Cortical Columns

The Thousand Brains Theory is built upon Vernon Mountcastle’s proposal that cortical columns have similar architectures and perform similar functions. The first reference below is Mountcastle’s original essay where he proposed the idea of a common cortical algorithm. The second reference is a more recent paper by Mountcastle in which he lists numerous experimental findings that support his proposal. The third reference, by Buxhoeveden and Casanova, is a relatively easy to read review. Although it is mostly about minicolumns, it discusses various arguments and evidence related to Mountcastle’s claim. The fourth reference, by Thomson and Lamy, is a review article on cortical anatomy. It is a thorough review of cellular layers and the prototypical connections between them. It is complicated, but it is one of my favorite papers.

Mountcastle, Vernon. “An Organizing Principle for Cerebral Function: The Unit Model and the Distributed System.” In *The Mindful Brain*, edited by Gerald M. Edelman and Vernon B. Mountcastle, 7–50. Cambridge, MA: MIT Press, 1978.

Mountcastle, Vernon. “The Columnar Organization of the Neocortex.” *Brain* 120 (1997): 701–722.

Buxhoeveden, Daniel P., and Manuel F. Casanova. “The Minicolumn Hypothesis in Neuroscience.” *Brain* 125, no. 5 (May 2002): 935–951.

Thomson, Alex M., and Christophe Lamy. “Functional Maps of Neocortical Local Circuitry.” *Frontiers in Neuroscience* 1 (October 2007): 19–42.

Cortical Hierarchy

The first paper below, by Felleman and Van Essen, is the one I mentioned in Chapter 1, which first described the hierarchy of regions in the macaque neocortex. I include it mostly for its historical interest. Unfortunately, it is not open-access.

The second reference, by Hilgetag and Goulas, is a more current look at issues of hierarchy in the neocortex. The authors list various problems of interpreting the neocortex as a strict hierarchy.

The third reference, a paper by Murray Sherman and Ray Guillery, argues that the primary way two cortical regions talk to each other is through a part of the brain called the thalamus. Figure 3 in the paper nicely illustrates this idea. Sherman and Guillery’s proposal is often ignored by other neuroscientists. For example, neither of the first two references mention the connections through the thalamus. Although I did not talk about the thalamus in this book, it is so intimately connected to the neocortex that I consider it an extension of the neocortex. My colleagues and I discuss a possible explanation of the thalamic pathway in our 2019 “Frameworks” paper, which is discussed below.

Felleman, Daniel J., and David C. Van Essen. “Distributed Hierarchical Processing in the Primate Cerebral Cortex.” *Cerebral Cortex* 1, no. 1 (January–February 1991): 1.

Hilgetag, Claus C., and Alexandros Goulas. “‘Hierarchy’ in the Organization of Brain Networks.” *Philosophical Transactions of the Royal Society B: Biological Sciences* 375, no. 1796 (April 2020).

Sherman, S. Murray, and R. W. Guillery. “Distinct Functions for Direct and Transthalamic Corticocortical Connections.” *Journal of Neurophysiology* 106, no. 3 (September 2011): 1068–1077.

What and Where Pathways

In Chapter 6, I described how cortical columns based on reference frames can be applied to what and where pathways in the neocortex. The first paper, by Ungerleider and Haxby, is one of the original papers on this topic. The second paper, by Goodale and Milner, is a more modern description. In it, they argue that a better description of what and where pathways is “perception” and “action.” This paper is not open-access. The third paper, by Rauschecker, is perhaps the easiest to read.

Ungerleider, Leslie G., and James V. Haxby. “‘What’ and ‘Where’ in the Human Brain.” *Current Opinion in Neurobiology* 4 (1994): 157–165.

Goodale, Melvyn A., and A. David Milner. “Two Visual Pathways—Where Have They Taken Us and Where Will They Lead in Future?” *Cortex* 98 (January 2018): 283–292.

Rauschecker, Josef P. “Where, When, and How: Are They All Sensorimotor? Towards a Unified View of the Dorsal Pathway in Vision and Audition.” *Cortex* 98 (January 2018): 262–268.

Dendritic Spikes

In Chapter 4, I discussed our theory that neurons in the neocortex make predictions using dendritic spikes. Here I list three review papers that discuss this topic. The first, by London and Häusser, is perhaps the easiest to read. The second, by Antic et al., is more directly relevant to our theory, as is the third reference, by Major, Larkum, and Schiller.

London, Michael, and Michael Häusser. “Dendritic Computation.” *Annual Review of Neuroscience* 28, no. 1 (July 2005): 503–532.

Antic, Srdjan D., Wen-Liang Zhou, Anna R. Moore, Shaina M. Short, and Katerina D. Ikonomu. “The Decade of the Dendritic NMDA Spike.” *Journal of Neuroscience Research* 88 (November 2010): 2991–3001.

Major, Guy, Matthew E. Larkum, and Jackie Schiller. “Active Properties of Neocortical Pyramidal Neuron Dendrites.” *Annual Review of Neuroscience* 36 (July 2013): 1–24.

Grid Cells and Place Cells

A key part of the Thousand Brains Theory is that every cortical column learns models of the world using reference frames. We propose that the neocortex does this using mechanisms that are similar to what is used by grid cells and place cells in the entorhinal cortex and hippocampus. To get an excellent overview of place cells and grid cells, I recommend reading or listening to the O’Keefe and the Mosers’ Nobel lectures, in the order they gave them. The three of them worked together to give a coordinated set of lectures.

O’Keefe, John. “Spatial Cells in the Hippocampal Formation.” Nobel Lecture. Filmed December 7, 2014, at Aula Medica, Karolinska Institutet, Stockholm. Video, 45:17. www.nobelprize.org/prizes/medicine/2014/okeefe/lecture/.

Moser, Edvard I. “Grid Cells and the Entorhinal Map of Space.” Nobel Lecture. Filmed December 7, 2014, at Aula Medica, Karolinska Institutet, Stockholm. Video, 49:23. www.nobelprize.org/prizes/medicine/2014/edvard-moser/lecture/.

Moser, May-Britt. “Grid Cells, Place Cells and Memory.” Nobel Lecture. Filmed December 7, 2014, at Aula Medica, Karolinska Institutet, Stockholm. Video, 49:48. www.nobelprize.org/prizes/medicine/2014/may-britt-moser/lecture/.

Grid Cells in the Neocortex

We are only beginning to see evidence of grid-cell mechanisms in the neocortex. In Chapter 6, I described two fMRI experiments that showed evidence of grid cells in humans performing cognitive tasks. The first two papers—by Doeller, Barry, and Burgess, and Constantinescu, O’Reilly, and Behrens—describe these experiments. The third paper, by Jacobs et al., describes similar results from humans undergoing open-brain surgery.

Doeller, Christian F., Caswell Barry, and Neil Burgess. “Evidence for Grid Cells in a Human Memory Network.” *Nature* 463, no. 7281 (February 2010): 657–661.

Suggested Readings

Constantinescu, Alexandra O., Jill X. O'Reilly, and Timothy E. J. Behrens. "Organizing Conceptual Knowledge in Humans with a Gridlike Code." *Science* 352, no. 6292 (June 2016): 1464–1468.

Jacobs, Joshua, Christoph T. Weidemann, Jonathan F. Miller, Alec Solway, John F. Burke, Xue-Xin Wei, Nanthia Suthana, Michael R. Sperling, Ashwini D. Sharan, Itzhak Fried, and Michael J. Kahana. "Direct Recordings of Grid-Like Neuronal Activity in Human Spatial Navigation." *Nature Neuroscience* 16, no. 9 (September 2013): 1188–1190.

Numenta's Papers on the Thousand Brains Theory

This book provides a high-level description of the Thousand Brains Theory, but it does not go into many details. If you are interested in finding out more, you can read my lab's peer-reviewed papers. They contain detailed descriptions of specific components, often including simulations and source code. All our papers are open-access. Here are the most relevant ones, with a brief description of each.

The following is our most recent paper, and also the easiest to read. It is the best place to start if you want to get a more in-depth description of the full theory and some of its implications.

Hawkins, Jeff, Marcus Lewis, Mirko Klukas, Scott Purdy, and Subutai Ahmad. "A Framework for Intelligence and Cortical Function Based on Grid Cells in the Neocortex." *Frontiers in Neural Circuits* 12 (January 2019): 121.

This next paper introduced our proposal that most dendritic spikes act as predictions, and that 90 percent of the synapses on pyramidal neurons are dedicated to recognizing contexts for predictions. The paper also described how a layer of neurons organized into minicolumns creates a predictive sequence memory. The paper explains many aspects of biological neurons that cannot be explained by other theories. It is a detailed paper that includes simulations, a mathematical description of our algorithm, and a pointer to source code.

Hawkins, Jeff, and Subutai Ahmad. "Why Neurons Have Thousands of Synapses, a Theory of Sequence Memory in Neocortex." *Frontiers in Neural Circuits* 10, no. 23 (March 2016): 1–13.

Next is the paper where we first introduced the idea that every cortical column can learn models of entire objects. This paper also introduced the concept of column voting. The mechanisms in this paper are extensions of the predictive mechanisms introduced in our 2016 paper. We also speculate that grid-cell representations might form the basis for the location signal, though we had not yet worked through any details. The paper includes simulations, capacity calculations, and a mathematical description of our algorithm.

Hawkins, Jeff, Subutai Ahmad, and Yuwei Cui. “A Theory of How Columns in the Neocortex Enable Learning the Structure of the World.” *Frontiers in Neural Circuits* 11 (October 2017): 81.

The following paper extends our 2017 paper by working through in detail how grid cells can form a representation of location. It explains how such locations can predict upcoming sensory input. The paper proposes a mapping between the model and three of the six layers in the neocortex. The paper includes simulations, capacity calculations, and a mathematical description of our algorithm.

Lewis, Marcus, Scott Purdy, Subutai Ahmad, and Jeff Hawkins. “Locations in the Neocortex: A Theory of Sensorimotor Object Recognition Using Cortical Grid Cells.” *Frontiers in Neural Circuits* 13 (April 2019): 22.

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- 16 Santiago Ramón y Cajal
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Jeff Hawkins is the cofounder of Numenta, a neuroscience research company, founder of the Redwood Neuroscience Institute, and one of the founders of the field of handheld computing. He is a member of the National Academy of Engineering and author of *On Intelligence*.