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Preface

We started doing research in perceptual learning in 1997. At the time, only a handful of researchers were focused primarily on this topic. The field has transformed since then, and this book tells the story of what we came to know about both the phenomena and the theories. This transformation occurred because of the fantastic contributions of many active researchers, from sophisticated investigations of the phenomenology by psychophysicists to insightful modeling and physiology.

In the late 1990s, we were working on a new model of the human observer, the perceptual template model (PTM). Our intention was to use this model to understand how visual perception depended on signal patterns and two kinds of noise—the noise in the external stimulus and the variability in the internal sensory response. We were also interested in using this model to tease apart the effects of visual attention on human perception ("the observer") by distinguishing improvements due to filtering out external noise in the stimulus from enhancing or amplifying the signal stimulus itself—previously elusive mechanisms easily distinguished with external noise methods.

At some point, we realized that the same analysis applied equally well to a major field of performance improvement—perceptual learning. Improvements with practice had been reported from the very beginning of experimental psychology in the late 1890s and were popularized in the 1950s by Eleanor Gibson as part of her interest in the early perceptual development of children. The role of experience in the performance of perceptual tasks in adults had been documented in numerous task domains, including acuity, motion, and stereopsis. Some of the best psychophysicists in the field of visual perception had studied learning, and sometimes the specificity of that learning to some aspect(s) of the task or the stimuli.

Then, in the late 1990s, prominent work by a number of scientists (Avi Karni, Dov Sagi, Merav Ahissar, Shaul Hochstein, Aniek Schoups, Robert Sekuler, and others) demonstrated a very curious form of specificity. Learned improvements in a task practiced in one location on the retina sometimes failed to transfer to new locations in the visual field. Specificity indeed! These observations led many researchers to attribute experience-dependent changes in performance to plasticity in the early visual cortex, a brain area long thought to be stable after the early years of development. Soon, the most prominent theory of

perceptual learning involved plastic alterations of the sensory tuning in the early retinotopic visual cortex. Bolstered by similar reports in other modalities, a significant set of studies (by Rufin Vogel, Guy Orban, Geoff Ghose, John Maunsell, Charles Gilbert, Joshua Gold, Wu Li, and many others) began to investigate how learning affected the properties of cellular responses in the earliest levels of visual coding. How early in the visual cortex did learning reach? We have been avid followers of these physiological investigations.

Our first study of perceptual learning was a systematic analysis of the phenomenon using external noise methods and the PTM model. From the very beginning, we suspected that the dominant retuning theory of perceptual learning could only be one part of the picture; in order to influence behavior, sensory information must also be connected to decision. If the sensory system encoded the stimulus, this evidence also needed to be decoded. Even at this early stage, we developed an alternative reweighting theory in which changing how sensory information is weighted in a decision (changed readout) was perhaps the dominant mode of learning. If the early visual areas were the encoders of sensory information, then the brain also needed decoders to interpret the encoded information, and these decoders must also be key to learning. Based on this insight, we developed a reweighting (readout) theory in which evidence in many early visual channels determined how a decision was changed through reweighting. This was in 1998. Not until later did we realize that Mollon and Danilova had developed the same theoretical idea independently.

It wasn't until a few years later, with the help of a gifted postdoc, Alex Petrov, that we started work on a multichannel model of perceptual learning, the augmented Hebbian reweighting model (AHRM). This model built on network models of visual learning (by Tomaso Poggio, Shimon Edelman, Manfred Fahle, Michael Herzog, and others) from the 1990s and took advantage of significant recent developments in the field of neural networks. We joined this model to a physiologically inspired signal-processing front end. Experiments also became more complex in order to examine specificity in those situations where the two major learning theories (retuning and reweighting) made contrasting predictions. This pure reweighting model has subsequently been shown to be able to account for many of the major phenomena in visual perceptual learning. With another talented postdoc, Jiajuan Liu, and with insightful experimental work by graduate student Pam Jeter, the AHRM was extended in 2013 to form the integrated reweighting theory (IRT). This theory explains how certain forms of transfer occur when they do. This model has in turn been modified and taken further by other researchers (Aaron Seitz, Peggy Seriès, and others) in very clever ways. It is this story of models of perceptual learning that we tell in the Models section of this book.

Over the past 20 years, the field of perceptual learning has evolved significantly. There are now many studies that challenge the specificity of perceptual learning (by Cong Yu and others). Now, the ideas about the role of reweighting, or readout, in learning have become a prominent component of the integrated models by Takeo Watanabe and others that have positioned the field of perceptual learning within the broader considerations of human brain

imaging. Models other than our own have either used or advanced the principle of multilevel reweighting in learning that we put forward. Meanwhile, the study of learning has increasingly made its way toward a substantial set of practical applications, from education to visual remediation, thanks to the laboratories of Michael Murzenich, Dennis Levi, Krystel Huxlin, John Anderson, Chang-Bing Huang, Uri Polat, Robert Hess, Ben Thompson, and many others.

By the mid-2010s, the field had reached a point where a systemic exploration of its recent development seemed to be called for. We began a detailed survey of the sometimes disparate literature on perceptual learning. Our goal was to evaluate the state of the various theories, understand the implications of the findings in physiology, and point toward possible fruitful directions for research. This book is the result of our efforts. It is meant for researchers of perceptual learning as well as scientists from other related fields. We have tried to discuss perceptual learning at several levels, hoping to be thorough yet concise, inclusive but not exhaustive.

Over the years, the many advances in the field, and our work in particular, were moved forward by key contributions from many prominent scientists in perceptual learning. In addition to reading papers and attending conference presentations, we have especially benefited from attendance at the International Workshop in Perceptual Learning, a smaller group that meets every two years to talk through exciting new ideas and methods. We certainly have personally and individually benefited from these open exchanges. One of the remarkable things about the study of perceptual learning—despite, or perhaps even because of, the highly divergent theoretical views of the participants—is that the field has remained collegial, cooperative, and committed to working together to advance the science.

These major contributions of many individuals and laboratories have now established perceptual learning as a major field, with a wide recognition that learning and plasticity play critical roles in human adaptation and must be accounted for in any investigation of the mechanisms of perception or, for that matter, learning.

Writing this book has taken us a number of years for a variety of reasons. During this period, we have had the support, both intellectual and personal, of many people, from colleagues and friends to family, who we wish to thank profusely.

Barbara Dosher comments, after 23 years of collaboration, it is still a pleasure to talk about science with my coauthor and friend Zhong-Lin Lu. The stimulating environment of the Cognitive Sciences Department at the University of California, Irvine, with smart and supportive colleagues, has contributed materially to work on this book. I am also thankful for the significant contributions of graduate students and postdocs in my laboratory (the Memory Attention Perception Lab), including Pam Jeter, Alex Petrov, Wilson Chu, Shiau-Hua Liu, Nate Blair, Richard Hetley, Emelien Tlapale, and many undergraduate students and assistants, including Anchit Roy, who assisted in the production of some figures for this book. I am still inspired by the theoretical vision of my graduate advisor, Wayne Wickelgren. I am also thankful to the colleagues and friends who first introduced me to vision science:

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Zhong-Lin Lu comments, the publication of this book is a major milestone in our more than 20 years of collaboration. It is also the beginning of many new, exciting joint research projects. I really appreciate Barbara's friendship and the opportunity to work with her. Many thanks go to my wife, Wei Sun; son, James; and daughter, Mae. This book would not have been possible without their understanding and support. I have learned so much from my PhD advisors Samuel J. Williamson and Lloyd Kaufman, and my postdoc advisor, George Sperling. Their scientific spirit still inspires me today. For their contributions to the research program, I want to take this opportunity to thank members of the Laboratory of Brain ProcessES (LOBES), originally at the University of Southern California, then the Ohio State University, and now at NYU Shanghai and New York University, including Luis A. Lesmes, Wilson Chu, Simon Jeon, Debbie Dao, Jiajuan Liu, Chang-Bing Huang, Xiangrui Li, Gui Xue, Miao Wei, Fang Hou, Jongsoo Kim, Carlos Cabrera, Zhicheng Lin, Yukai Zhao, Pan Zhang, and Pengjing Xu. I would also like to thank C. Shawn Green, Daphne Bavelier, Alex Pouget, Tianmiao Hua, and Jinrong Li for collaborating with me on perceptual learning, and I thank organizers of the International Workshop on Perceptual Learning, Cong Yu, Dov Sagi, Takeo Watanabe, Merav Ahissar, Uri Polat, Shaul Hochstein, Yuka Sasaki, Mitsuo Kawato, Michael Herzog, Miguel Eckstein, Aaron Seitz, and Michael Silverman, for providing the opportunities for us to come together as a research community. I would also like to acknowledge my colleagues Irving Biederman, Adrian Raine, Antonio Damasio, Hanna Damasio, Michel Baudry, Judith Hirsh, James Todd, Roger Ratcliff, Brandon Turner, Deyue Yu, Alex Petrov, Tony Movshon, Paul Glimcher, Marisa Carrasco, Joanna Waley-Cohen, and Anqi Qian, as well as friends and colleagues I lost over the years: Patrick Suppes, Bosco Tjan, Stephen Madigan, and Richard F. Thompson.

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