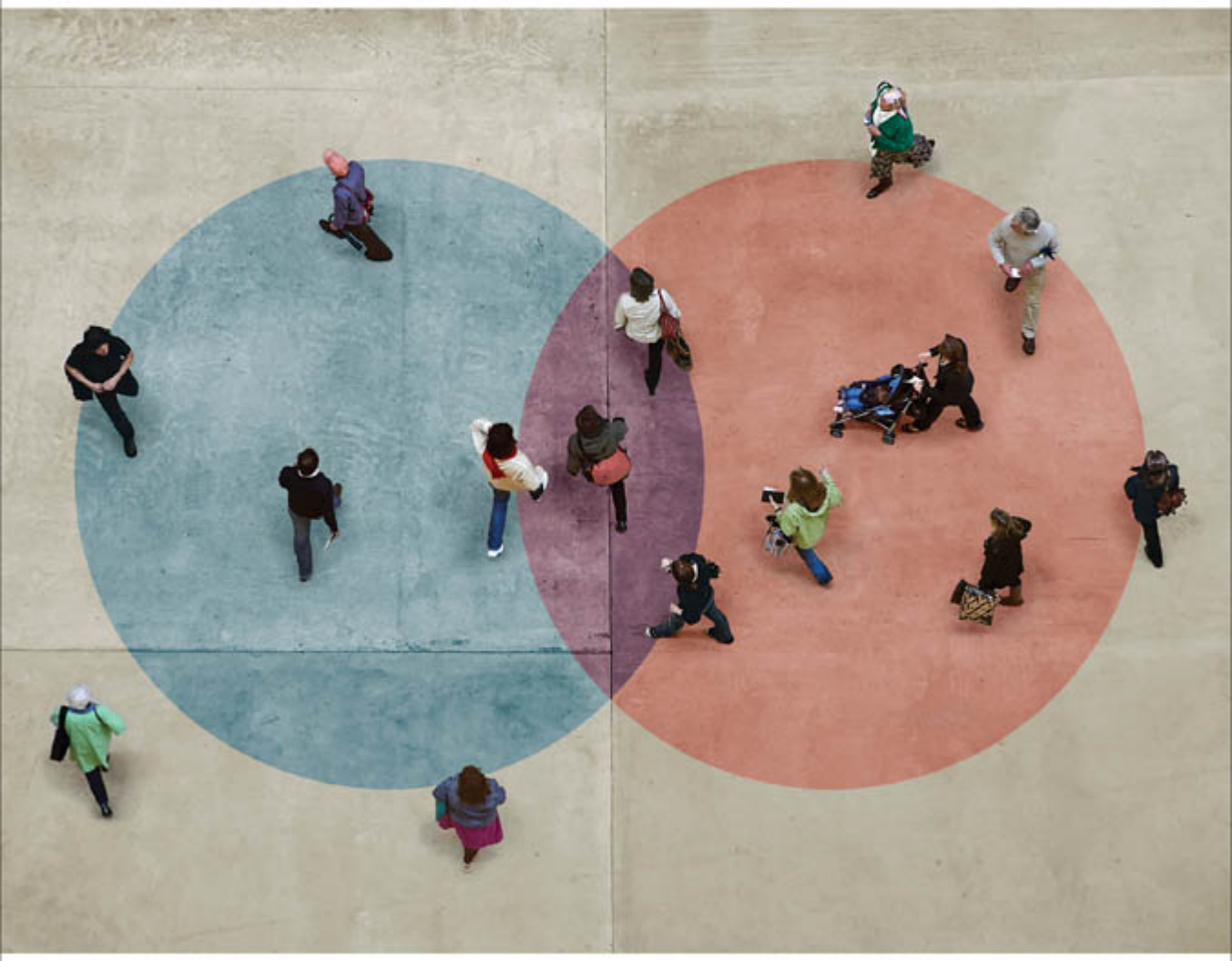
CLASSIFICATION IN THE WILD

The Science and Art of Transparent Decision Making



Konstantinos V. Katsikopoulos, Özgür Şimşek,
Marcus Buckmann, and Gerd Gigerenzer

Classification in the Wild

Classification in the Wild

The Science and Art of Transparent Decision Making

Konstantinos V. Katsikopoulos, Özgür Şimşek, Marcus Buckmann, and Gerd Gigerenzer

The MIT Press
Cambridge, Massachusetts
London, England

Library of Congress Cataloging-in-Publication Data

Names: Katsikopoulos, Konstantinos V., author.
Title: Classification in the wild : the science and art of transparent decision making / Konstantinos V. Katsikopoulos, Özgür Şimşek, Marcus Buckmann, and Gerd Gigerenzer.
Description: Cambridge, Massachusetts : The MIT Press, [2020] | Includes bibliographical references and index.
Identifiers: LCCN 2020015193 | ISBN 9780262045155 (hardcover)
Subjects: LCSH: Categorization (Psychology)—Case studies. | Classification—Case studies. | Uncertainty—Case studies.
Classification: LCC BF445 .K38 2020 | DDC 001.01/2—dc23
LC record available at https://lccn.loc.gov/2020015193

10 9 8 7 6 5 4 3 2 1

To our families

Contents

Acknowledgments

This book benefited greatly from the input provided by many colleagues. We are grateful to David Aikman, Jerome Busemeyer, Jean Czerlinski Whitmore, Uwe Czienskowski, Dan Goldstein, Panagiotis Katsikopoulos, Niklas Keller, Jan Malte Lichtenberg, Shenghua Luan, Laura Martignon, Douglas Medin, Nancy Montgomery, Christophe Mues, Nathaniel Phillips, Lael Schooler, Leonidas Spiliopoulos, and Leighton Vaughan Williams. We are indebted to Gisela Henkes for administrative help and Rona Unrau for suggestions on the writing. Finally, we would like to extend a big thanks to Philip Laughlin, Judy Feldmann, and Alex Hoopes, our editorial support at the MIT Press.

Introduction: Why Classification in the Wild?

> The demand for certainty is one which is natural to man, but is nevertheless an intellectual vice. If you take your children for a picnic on a doubtful day, they will demand a dogmatic answer as to whether it will be fine or wet, and be disappointed in you when you cannot be sure.
>
> —Bertrand Russell

The desire to assign a person to a class—friend or foe, trustworthy or not—is inherent to human nature. It provides the bricks from which intelligence is built. Without forming classes, we would notice only the particular, and any general idea would be out of reach. But how do we make classifications? And how should we?

Psychologists tend to focus on well-defined situations, where all characteristics of the entities to be classified are known with certainty, including probabilities. To achieve the goal of experimental control, the typical lab experiment requires people to allocate to classes artificial objects, such as circles and triangles that vary in color and size, that is, in terms of a precisely known, fixed number of dimensions.

Classification in the Wild, in contrast, exits the certainty of the lab and looks at fundamental uncertainty. *In the wild* refers to real-world situations where, unlike in the typical psychological experiment, the future is not knowable, and uncertainty cannot be meaningfully reduced to probability.[1] Such uncertainty does not necessarily apply to all real-world situations. A player in a casino, for instance, can calculate the probabilities of winning. In the great majority of other situations, however, uncertainty prevails—be it choosing the financial products in which one should invest or the most

appropriate partner to marry. Jimmie Savage, the father of modern Bayesian decision theory, argued that even planning a picnic lies outside his theory because one cannot know in advance all events that could possibly happen.[2] The relevant information may not be available in the first place or may even change from day to day. That raises the question whether classification in the wild can actually be based on science. Our answer is affirmative. This book introduces precise, *formal* models of classification that are often absent in otherwise interesting and useful work in applied psychology.[3] As we will see, these formal models combine well with the expertise of practitioners, thus the "science and art" in the book's subtitle.

Researchers in machine learning also address classification. They have developed tools such as neural networks and random forests for complex situations that go beyond the lab experiment. These tools are able to deal with complexity and uncertainty but are typically not transparent.[4] For instance, when systems based on these tools are used in financing or in courts of law, loan applicants and defendants are typically mystified about why they are classified as untrustworthy and denied a loan or bail. Often such systems fail to be transparent not only to the bank or the judge but also to the engineers who created them.

Classification in the Wild is committed to increasing transparency in situations of uncertainty. It provides tools that are easy to understand, memorize, teach, and execute. These tools allow practitioners to make fast and accurate decisions when no fancy machine learning program is at hand, as at the site of an accident or suicide attack. It also informs machine learning in how to construct transparent algorithms in the first place, rather than trying to explain opaque algorithms after the fact.

Another deep difference exists between cognitive psychology and machine learning. Psychology is mostly descriptive, answering the question of how people actually make classifications. Machine learning is prescriptive, answering the question of how one should make classifications. *Classification in the Wild* integrates the "is" and the "ought." It deals with heuristics that often are both descriptive and prescriptive; that is, they describe what experienced practitioners actually do, while also suggesting how their practices can be improved.

The classification tools we present in this book are known under the rubric of *bounded rationality*, a term coined in the 1950s by Herbert Simon,[5] one of the founders of artificial intelligence (AI) and a pioneer of the

cognitive revolution. The modern study of bounded rationality in Simon's tradition is the program of *fast-and-frugal heuristics*, on which these classification tools are based.[6] Fast-and-frugal heuristics are useful additions to existing models in cognitive psychology and machine learning, allowing for fast, transparent, and accurate classifications under uncertainty.

Classification in the Wild provides points of contact where cognitive psychology and machine learning can meet. It shows how to extend the psychological study of classification to the real world of uncertainty. It also shows how to derive simple and accurate classification rules from first cognitive principles, the human abilities of *counting* and *ordering*. Additionally, the book contributes to the goal of interpretable machine learning. Fast-and-frugal classification rules can be easily understood and applied.

In *Classification in the Wild*, we make two key arguments:

Simple rules do well in the wild. In stable situations such as the games of chess and Go or face recognition, complex algorithms outperform fast-and-frugal heuristics if large amounts of data are available. In the wild, by contrast, where the future is uncertain and may differ from the past in unpredictable ways, simple heuristics can outperform complex methods regardless of whether the available data are big or small. We call this the *unstable-world principle*.

Transparency is a key value. More and more our lives are influenced by algorithms that classify citizens according to their creditworthiness, health conditions, and social and political attitudes. The underlying logic of these algorithms is often opaque, be it inherently or with the aim to protect trade secrets. Fast-and-frugal heuristics, on the other hand, are transparent by design. In sensitive domains such as health, wealth, and justice, the ability to understand algorithms is indispensable for citizens in a participatory democracy. Contrary to common wisdom in parts of machine learning, which assume that the most accurate algorithms must be inherently complicated and uninterpretable, we show that transparent algorithms are often as accurate as black-box models. We call this the *transparency-meets-accuracy principle*.

In this book, we show that these two arguments go together. The choice is not between using complex algorithms that are hard to understand and simple ones that are hardly accurate. In the wild, simplicity and transparency are not enemies of accuracy.

Bibliography

Admati, Anat, and Martin Hellwig. *The Bankers' New Clothes: What's Wrong with Banking and What to Do about It*. Princeton, NJ: Princeton University Press, 2014.

Aikman, David, Mirta Galesic, Gerd Gigerenzer, Sujit Kapadia, Konstantinos V. Katsikopoulos, Amit Kothiyal, Emma Murphy, and Tobias Neumann. "Taking Uncertainty Seriously: Simplicity versus Complexity in Financial Regulation." *Industrial and Corporate Change*, in press.

Allen, Michael. "Preschool Children's Taxonomic Knowledge of Animal Species." *Journal of Research in Science Teaching* 52, no. 1 (2015): 107–134.

Almeida, Tiago A., José M. G. Hidalgo, and Akebo Yamakami. "Contributions to the Study of SMS Spam Filtering: New Collection and Results." *Proceedings of the 11th ACM Symposium on Document Engineering* (2011): 259–262.

Anderson, John R., and Lael J. Schooler. "Reflections of the Environment in Memory." *Psychological Science* 2, no. 6 (1991): 396–408.

Antman, Elliott M., Marc Cohen, Peter J. L. M. Bernink, Carolyn H. McCabe, Thomas Horacek, et al. "The TIMI Risk Score for Unstable Angina/Non-ST Elevation MI: A Method for Prognostication and Therapeutic Decision Making." *Journal of the American Medical Association* 284, no. 7 (2000): 835–842.

Artinger, Florian, Nikita Kozodi, Florian von Wangenheim, and Gerd Gigerenzer. "Recency: Prediction with Smart Data." In *2018 AMA Winter Academic Conference: Integrating Paradigms in a World Where Marketing Is Everywhere*, ed. Jacob Goldenberg, Juliano Laran, and Andrew Stephen, 2–6. Chicago: American Marketing Association, 2018.

Ashby, Gregory F., and Leola A. Alfonso-Reese. "Categorization as Probability Density Estimation." *Journal of Mathematical Psychology* 39, no. 2 (1995): 216–233.

Åstebro, Thomas, and Samir Elhedhli. "The Effectiveness of Simple Decision Heuristics: Forecasting Commercial Success for Early-Stage Ventures." *Management Science* 52, no. 3 (2006): 395–409.

Backlund, Lars G., Johan Bring, Ylva Skånér, Lars-Erik Strender, and Henry Montgomery. "Improving Fast and Frugal Modeling in Relation to Regression Analysis: Test of 3 Models for Medical Decision Making." *Medical Decision Making* 29, no. 1 (2009): 140–148.

Bagwell, Randall. "The Threat Assessment Process." *Army Lawyer*. Department of the Army pamphlet 27-50-419 (2008), 5–16.

Baucells, Manel, Juan A. Carrasco, and Robin M. Hogarth. "Cumulative Dominance and Heuristic Performance in Binary Multiattribute Choice." *Operations Research* 56, no. 5 (2008): 1289–1304.

Bishop, Michael A., and John D. Trout. *Epistemology and the Psychology of Human Judgment*. New York: Oxford University Press, 2005.

Blank, Laurie R., and Amos N. Guiora. "Updating the Commander's Toolbox: New Tools for Operationalizing the Law of Armed Conflict." *Prism* 1, no. 3 (2010): 59–78.

Breiman, Leo. "Statistical Modeling: The Two Cultures (with Comments and a Rejoinder by the Author)." *Statistical Science* 16, no. 3 (2001): 199–231.

Breiman, Leo, Jerome Friedman, Charles J. Stone, and Richard A. Olshen. *Classification and Regression Trees*. Boca Raton, FL: CRC Press, 1984.

Brown, Thomas. *Lectures on the Philosophy of the Human Mind*. London: William Tait, 1838.

Bröder, Arndt. "The Quest for Take-the-Best." In *Ecological Rationality: Intelligence in the World*, ed. Peter M. Todd, Gerd Gigerenzer, and the ABC Research Group, 216–240. New York: Oxford University Press, 2012.

Bruner, Jerome S., Jacqueline J. Goodnow, and George A. Austin. *A Study of Thinking*. New York: John Wiley and Sons, 1956.

Buckmann, Marcus, and Özgür Şimşek. "Decision Heuristics for Comparison: How Good Are They?" *Proceedings of the NIPS 2016 Workshop on Imperfect Decision Makers*, in *PMLR* 58 (2017): 1–11.

Buckmann, Marcus, and Özgür Şimşek. *Learning Interpretable Models*. Berlin: Working Paper, 2019.

Busemeyer, Jerome R., and Adele Diederich. *Cognitive Modeling*. Thousand Oaks, CA: Sage, 2014.

Chevaleyre, Yann, Frédéric Koriche, and Jean-Daniel Zucker. "Rounding Methods for Discrete Linear Classification." In *Proceedings of the 30th International Conference on International Conference on Machine Learning*, 651–659 (Atlanta: JMLR.org, 2013).

Chou, Roger, Laurie Hoyt Huffman, Rongwei Fu, Ariel K. Smits, and P. Todd Korthuis. "Screening for HIV: A Review of the Evidence for the US Preventive Services Task Force." *Annals of Internal Medicine* 143, no. 1 (2005): 55–73.

Cohen, Andrew L., and Robert M. Nosofsky. "An Extension of the Exemplar-Based Random-Walk Model to Separable-Dimension Stimuli." *Journal of Mathematical Psychology* 47, no. 2 (2003): 150–165.

Cohen, William H. "Fast Effective Rule Induction." In *Proceedings of the Twelfth International Conference on Machine Learning*, 115–123 (New York: ACM, 1995).

Converse, Philip E. "The Nature of Belief Systems in Mass Publics." In *Ideology and Discontent*, ed. David Apter, 206–261. New York: Free Press, 1964.

Cook, Louis. "The World Trade Center Attack: The Paramedic Response; An Insider's View." *Critical Care* 5, no. 6 (2001): 301–303.

Cook, Samantha, Corrie Conrad, Ashley L. Fowlkes, and Matthew H. Mohebbi. "Assessing Google Flu Trends Performance in the United States during the 2009 Influenza Virus A (H1N1) Pandemic." *PloS One* 6, no. 8 (2011): e23610.

Czerlinski, Jean, Gerd Gigerenzer, and Daniel G. Goldstein. "How Good Are Simple Heuristics?" In *Simple Heuristics That Make Us Smart*, by Gerd Gigerenzer, Peter M. Todd, and the ABC Research Group, 97–118. New York: Oxford University Press, 1999.

Dantzig, Tobias. *Number, the Language of Science: A Critical Survey Written for the Cultured Non-Mathematician*. London: Penguin, 1954.

Davies, Nathan, Jill Manthorpe, Elizabeth L. Sampson, Kethakie Lamahewa, Jane Wilcock, Rammya Mathew, and Steve Iliffe. "Guiding Practitioners through End of Life Care for People with Dementia: The Use of Heuristics." *PLOS One* 13, no. 11 (2018): e0206422.

Dawes, Robyn M. "The Robust Beauty of Improper Linear Models in Decision Making." *American Psychologist* 34, no. 7 (1979): 571–582.

Dawes, Robyn M., and Bernard Corrigan. "Linear Models in Decision Making." *Psychological Bulletin* 81, no. 2 (1974): 95–106.

Dawson, Robert J. MacG. "The 'Unusual Episode' Data Revisited." *Journal of Statistics Education* 3, no. 3 (1995).

DeMiguel, Victor, Lorenzo Garlappi, and Raman Uppal. "Optimal versus Naive Diversification: How Inefficient Is the 1/N Portfolio Strategy?" *Review of Financial Studies* 22, no. 5 (2007): 1915–1953.

Dhami, Mandeep K. "Psychological Models of Professional Decision Making." *Psychological Science* 14, no. 2 (2003): 175–180.

Dhami, Mandeep K., and Peter Ayton. "Bailing and Jailing the Fast and Frugal Way." *Journal of Behavioral Decision Making* 14, no. 2 (2001): 141–168.

Dhami, Mandeep K., and Clare Harries. "Information Search in Heuristic Decision Making." *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition* 24, no. 4 (2010): 571–586.

Djulbegovic, Benjamin, Iztok Hozo, and William Dale. "Transforming Clinical Practice Guidelines and Clinical Pathways into Fast-and-Frugal Decision Trees to Improve Clinical Care Strategies." *Journal of Evaluation in Clinical Practice* 24, no. 5 (2018): 1247–1254.

Douglas, Vanja C., Christine S. Hessler, Gurpreet Dhaliwal, John P. Betjemann, Keiko A. Fukuda, Lama R. Alameddine, Rachael Lucatorto, et al. "The AWOL Tool: Derivation and Validation of a Delirium Prediction Rule." *Journal of Hospital Medicine* 8, no. 9 (2013): 493–499.

Doyle, Nora M., Judy E. Levinson, and Michael O. Gardner. "Rapid versus Enzyme-Linked Immunosorbent Assay Screening in a Low-Risk Mexican American Population Presenting in Labor: A Cost-Effectiveness Analysis." *American Journal of Obstetrics and Gynecology* 193, no. 5 (2005): 1280–1285.

Dressel, Julia, and Hany Farid. "The Accuracy, Fairness, and Limits of Predicting Recidivism." *Science Advances* 4, no. 1 (2018): eaao5580.

Dyson, Freeman. "A Meeting with Enrico Fermi." *Nature* 427 (January 2004): 297.

Einhorn, Hillel J., and Robin M. Hogarth. "Unit Weighting Schemes for Decision Making." *Organizational Behavior and Human Performance* 13, no. 2 (1975): 171–192.

Estes, William K. *Classification and Cognition*. New York: Oxford University Press, 1994.

Esteva, Andre, Brett Kuprel, Roberto A. Novoa, Justin Ko, Susan M. Swetter, Helen M. Blau, and Sebastian Thrun. "Dermatologist-Level Classification of Skin Cancer with Deep Neural Networks." *Nature* 542, no. 7639 (2017): 115.

Federal Bureau of Investigation. *FBI Criminal Justice Information Services 2016 Annual Report*. 2016.

Ferguson, Neal M., Derek A. T. Cummings, Simon Cauchemez, Christophe Fraser, Steven Riley, Aronrag Meeyai, et al. "Strategies for Containing an Emerging Influenza Pandemic in Southeast Asia." *Nature* 437, no. 7056 (2005): 209–214.

Fernández-Delgado, Manuel, Eva Cernadas, Senén Barro, and Dinani Amorim. "Do We Need Hundreds of Classifiers to Solve Real World Classification Problems?" *Journal of Machine Learning Research* 15, no. 1 (2014): 3133–3181.

Fific, Mario, Daniel R. Little, and Robert M. Nosofsky. "Logical-Rule Models of Classification Response Times: A Synthesis of Mental-Architecture, Random-Walk, and Decision-Bound Approaches." *Psychological Review* 117, no. 2 (2010): 309–348.

Fischer, Joachim E., Felicitas Steiner, Franziska Zucol, Christoph Berger, Laura Martignon, Walter Bossart, Martin Altwegg, and David Nadal. "Use of Simple Heuristics to Target Macrolide Prescription in Children with Community-Acquired Pneumonia." *Archives of Pediatrics and Adolescent Medicine* 156, no. 10 (2002): 1005–1008.

Forbes, William P., Aloysius Obinna Igboekwu, and Shabnam Mousavi. *A Fast and Frugal Finance: Bridging Contemporary Behavioral Finance and Ecological Rationality*. Cambridge: Academic Press, 2019.

Ford, Kevin J., Neal Schmitt, Susan L. Schechtman, Brian M. Hults, and Mary L. Doherty. "Process Tracing Methods: Contributions, Problems, and Neglected Research Questions." *Organizational Behavior and Human Decision Processes* 43, no. 1 (1989): 75–117.

Geman, Stuart, Elie Bienenstock, and René Doursat. "Neural Networks and the Bias/Variance Dilemma." *Neural Computation* 4, no. 1 (1992): 1–58.

German Advisory Council for Consumer Affairs. *Consumer-Friendly Scoring*. 2019.

Gigerenzer, Gerd. "The Bias Bias in Behavioral Economics." *Review of Behavioral Economics*, no. 5 (2018): 303–336.

Gigerenzer, Gerd. *Calculated Risk: How to Know When Numbers Deceive You*. New York: Simon and Schuster, 2002.

Gigerenzer, Gerd. "From Tools to Theories: A Heuristic of Discovery in Cognitive Psychology." *Psychological Review* 98, no. 2 (1991): 254–267.

Gigerenzer, Gerd. *Gut Feelings: The Intelligence of the Unconscious*. New York: Penguin, 2007.

Gigerenzer, Gerd. "The Heuristics Revolution: Rethinking the Role of Uncertainty in Finance." In *The Behavioral Finance Revolution: A New Approach to Financial Policies and Regulations*, ed. Riccardo Viale, Shabnam Mousavi, Barbara Alemanni, and Umberto Filotto, 115–134. Cheltenham: Edward Elgar, 2018.

Gigerenzer, Gerd. "Ideas in Exile: The Struggles of an Upright Man." In *The Essential Brunswik: Beginnings, Explications, Applications*, ed. Kenneth R. Hammond and Tom R. Stewart, 445–452. Oxford: Oxford University Press, 2001.

Gigerenzer, Gerd. *Risk Savvy: How to Make Good Decisions*. New York: Viking, 2014.

Gigerenzer, Gerd. "What Is Bounded Rationality?" In *Routledge Handbook of Bounded Rationality*, ed. Riccardo Viale. London: Routledge, in press.

Gigerenzer, Gerd, and Henry Brighton. "Homo Heuristicus: Why Biased Minds Make Better Inferences." *Topics in Cognitive Science* 1, no. 1 (2009): 107–143.

Gigerenzer, Gerd, and Daniel G. Goldstein. "Reasoning the Fast and Frugal Way: Models of Bounded Rationality." *Psychological Review*, no. 103 (1996): 650–669.

Gigerenzer, Gerd, Ralph Hertwig, and Thorsten Pachur, eds. *Heuristics: The Foundations of Adaptive Behavior*. New York: Oxford University Press, 2011.

Gigerenzer, Gerd, and David J. Murray. *Cognition as Intuitive Statistics*. London: Psychology Press, 2015.

Gigerenzer, Gerd, and Reinhard Selten, eds. *Bounded Rationality: The Adaptive Toolbox*. Cambridge, MA: MIT Press, 2001.

Gigerenzer, Gerd, and Thomas Sturm. "How (Far) Can Rationality Be Naturalized?" *Synthese*, no. 187 (2012): 243–268.

Gigerenzer, Gerd, Peter M. Todd, and the ABC Research Group. *Simple Heuristics That Make Us Smart*. New York: Oxford University Press, 1999.

Ginsberg, Jeremy, Matthew H. Mohebbi, Rajan S. Patel, Lynnette Brammer, Mark S. Smolinski, and Larry Brilliant. "Detecting Influenza Epidemics Using Search Engine Query Data." *Nature* 457, no. 7232 (2009): 1012–1014.

Glymour, Clark. "Osiander's Psychology." *Behavioral and Brain Sciences* 34, no. 4 (2011): 200.

Goel, Sharad, Jake M. Hofman, Sébastien Lahaie, David M. Pennock, and Duncan J. Watts. "Predicting Consumer Behavior with Web Search." *Proceedings of the National Academy of Sciences* 107, no. 41 (2010): 17486–17490.

Green, Lee, and David R. Mehr. "What Alters Physicians' Decisions to Admit to the Coronary Care Unit?" *Journal of Family Practice* 45, no. 3 (1997): 219–226.

Gregg, Lee W., and Herbert A. Simon. "Process Models and Stochastic Theories of Simple Concept Formation." *Journal of Mathematical Psychology* 4, no. 2 (1967): 246–276.

Grimes, Derek I., John Rawcliffe, Jeannine Smith, LTC Eugene Baime, LTC Michael Benjamin, MAJ James Dorn, MAJ Chris Fredrikson, et al. *Operational Law Handbook*. Charlottesville, VA: International and Operational Law Department, Judge Advocate General's Legal Center and School, 2006.

Haldane, Andrew G., and Vasileios Madouros. "The Dog and the Frisbee." *Revista de Economia Institucional*, no. 14 (2012): 109–110.

Hamlin, Robert P. "The Gaze Heuristic: Biography of an Adaptively Rational Decision Process." *Topics in Cognitive Science* 9, no. 2 (2017): 264–288.

Hammond, D. "The Effects of Remand." *Prison Service Journal*, no. 69 (1988): 19.

Härle, Philipp, Erik Lüders, Theo Pepanides, Sonja Pfetsch, Thomas Poppensieker, and Uwe Stegemann. "Basel III and European Banking: Its Impact, How Banks Might Respond, and the Challenges of Implementation." McKinsey Working Papers on Risk no. 26 (November 2010).

Hertwig, Ralph, Jennifer Nerissa Davis, and Frank J. Sulloway. "Parental Investment: How an Equity Motive Can Produce Inequality." *Psychological Bulletin* 128, no. 5 (2002): 728–745.

Hertwig, Ralph, Ulrich Hoffrage, and the ABC Research Group. *Simple Heuristics in a Social World*. New York: Oxford University Press, 2013.

Hertwig, Ralph, Timothy J. Pleskac, Thorsten Pachur, and the Center for Adaptive Rationality. *Taming Uncertainty*. Cambridge, MA: MIT Press, 2019.

Hogarth, Robin M. "When Simple Is Hard to Accept." In *Ecological Rationality: Intelligence in the World*, by Peter M. Todd, Gerd Gigerenzer, and the ABC Research Group, 61–79. New York: Oxford University Press, 2012.

Holewinski, Sarah. "Escalation of Force: The Civilian Perspective." In *Escalation of Force Handbook*, 81–82. Fort Leavenworth, KS: Center for Army Lessons Learned, 2007.

Human Rights Watch. *China: Police "Big Data" Systems Violate Privacy, Target Dissent*. 2017.

Hunter, David A. "The Conservation and Demography of the Southern Corroboree Frog." MA thesis, University of Canberra, 2000.

Hutchinson, John M. C., and Gerd Gigerenzer. "Simple Heuristics and Rules of Thumb: Where Psychologists and Behavioural Biologists Might Meet." *Behavioural Processes* 69, no. 2 (2005): 97–124.

Jenny, Mirjam A., Niklas Keller, and Gerd Gigerenzer. "Assessing Minimal Medical Statistical Literacy Using the Quick Risk Test: A Prospective Observational Study in Germany." *British Medical Journal Open* 8, no. 8 (2018): e020847.

Jenny, Mirjam A., Thorsten Pachur, S. Lloyd Williams, Eni Becker, and Jürgen Margraf. "Simple Rules for Detecting Depression." *Journal of Applied Research in Memory and Cognition* 2, no. 3 (2013): 149–157.

Karaliopoulos, Merkourios, Konstantinos V. Katsikopoulos, and Lambros Lambrinos. "Bounded Rationality Can Make Parking Search More Efficient: The Power of Lexicographic Heuristics." *Transportation Research Part B: Methodological* 101 (2017): 28–50.

Karaliopoulos, Merkourios, and Iordanis Koutsopoulos. "Mobile App User Choice Engineering Using Behavioral Science Models." In *2018 IEEE 19th International*

Workshop on Signal Processing Advances in Wireless Communications (Piscataway: IEEE, 2018): 1–5.

Katsikopoulos, Konstantinos V. "How to Model It: Review of 'Cognitive Modeling.'" *Journal of Mathematical Psychology* 55, no. 2 (2011): 198–201.

Katsikopoulos, Konstantinos V. "Psychological Heuristics for Making Inferences: Definition, Performance, and the Emerging Theory and Practice." *Decision Analysis* 8, no. 1 (2011): 10–29.

Katsikopoulos, Konstantinos V., Ian N. Durbach, and Theodor J. Stewart. "When Should We Use Simple Decision Models? A Synthesis of Various Research Strands." *Omega* 81 (2018): 17–25.

Katsikopoulos, Konstantinos V., and Laura Martignon. "Naive Heuristics for Paired Comparisons: Some Results on Their Relative Accuracy." *Journal of Mathematical Psychology* 50, no. 3 (2006): 488–494.

Kay, John, and Mervyn King. *Radical Uncertainty: Decision-Making Beyond the Numbers*. New York: W. W. Norton, 2020.

Keller, Niklas, and Konstantinos V. Katsikopoulos. "On the Role of Psychological Heuristics in Operational Research; and a Demonstration in Military Stability Operations." *European Journal of Operational Research* 249, no. 3 (2016): 1063–1073.

Kirchner, Lauren. "Traces of Crime: How New York's DNA Techniques Became Tainted." *New York Times*, September 4, 2017.

Kirchner, Lauren. "Where Traditional DNA Testing Fails, Algorithms Take Over." *ProPublica*, November 4, 2016.

Klein, Gary A. *Sources of Power: How People Make Decisions*. Cambridge, MA: MIT Press, 1998.

Knight, Frank. *Risk, Uncertainty and Profit*. Boston, MA: Houghton Mifflin, 1921.

Kocher, Mininder S., Rahul Mandiga, David Zurakowski, Carol Barnewolt, and James R. Kasser. "Validation of a Clinical Prediction Rule for the Differentiation between Septic Arthritis and Transient Synovitis of the Hip in Children." *Journal of Bone and Joint Surgery* 86, no. 8 (2004): 1629–1635.

Kruschke, John K. "Models of Categorization." In *The Cambridge Handbook of Computational Psychology*, ed. Ron Sun. New York: Cambridge University Press, 2008.

Kumar, Neeraj, Alexander C. Berg, Peter N. Belhumeur, and Shree K. Nayar. "Attribute and Simile Classifiers for Face Verification." In *2009 IEEE 12th International Conference on Computer Vision* (Piscataway: IEEE, 2009), 365–372.

Lake, Brenden M., Tomer D. Ullman, Joshua B. Tenenbaum, and Samuel J. Gershman. "Building Machines That Learn and Think Like People." *Behavioral and Brain Sciences* 40 (2017): e253.

Larsen, Peter Thal. "Goldman Pays the Price of Being Big." *Financial Times*, March 13, 2007.

Larson, Christina. "China's AI Imperative: The Country's Massive Investments in Artificial Intelligence Are Disrupting the Industry—and Strengthening Control of the Populace." *Science* 359, no. 6376 (2018): 628–630.

Larson, Jeff, Surya Mattu, Lauren Kirchner, and Julia Angwin. "How We Analyzed the COMPAS Recidivism Algorithm." *ProPublica*, May 23, 2016, 5–9.

Lazer, David, Ryan Kennedy, Gary King, and Alessandro Vespignani. "The Parable of Google Flu: Traps in Big Data Analysis." *Science* 343, no. 6176 (2014): 1203–1205.

LeCun, Yann, Léon Bottou, Yoshua Bengio, and Patrick Haffner. "Gradient-Based Learning Applied to Document Recognition." *Proceedings of the IEEE* (1998).

Lessmann, Stefan, Bart Baesens, Hsin-Vonn Seow, and Lyn C. Thomas. "Benchmarking State-of-the-Art Classification Algorithms for Credit Scoring: An Update of Research." *European Journal of Operational Research* 247, no. 1 (2015): 124–136.

Letham, Benjamin, Cynthia Rudin, Tyler H. McCormick, and David Madigan. "Interpretable Classifiers Using Rules and Bayesian Analysis: Building a Better Stroke Prediction Model." *Annals of Applied Statistics* 9, no. 3 (2015): 1350–1371.

Liang Fan, Vishnupriya Das, Nadiya Kostyuk, and Muzammil M. Hussain. "Constructing a Data- Driven Society: China's Social Credit System as a State Surveillance Infrastructure." *Policy and Internet* 4 (2018).

Lichtman, Alan J. *Predicting the Next President: The Keys to the White House*. Lanham, MD: Rowman and Littlefield, 2016.

Lim, Wei S., Menno M. Van der Eerden, Richard T. R. Laing, Wim G. Boersma, Noel Karalus, George I. Town, et al. "Defining Community Acquired Pneumonia Severity on Presentation to Hospital: An International Derivation and Validation Study." *Thorax* 58, no. 5 (2003): 377–382.

Luan, Shenghua, and Jochen Reb. "Fast-and-Frugal Trees as Noncompensatory Models of Performance-Based Personnel Decisions." *Organizational Behavior and Human Decision Processes* 141 (2017): 29–42.

Luan, Shenghua, Lael J. Schooler, and Gerd Gigerenzer. "A Signal-Detection Analysis of Fast-and-Frugal Trees." *Psychological Review* 118, no. 2 (2011): 316–338.

Marcus, Gary, and Ernest Davis. "How to Build Artificial Intelligence We Can Trust." *New York Times International Edition*, September 11, 2019.

Martignon, Laura, Konstantinos V. Katsikopoulos, and Jan K. Woike. "Categorization with Limited Resources: A Family of Simple Heuristics." *Journal of Mathematical Psychology* 52, no. 6 (2008): 352–361.

Martignon, Laura, Oliver Vitouch, Masanori Takezawa, and Malcolm R. Forster. "Naive and Yet Enlightened: From Natural Frequencies to Fast and Frugal Decision Trees." In *Thinking: Psychological Perspectives on Reasoning, Judgment, and Decision Making*, ed. Laura Macchi and David Hardman, 189–211. Hoboken, NJ: John Wiley and Sons, 2003.

Medin, Douglas L., and Marguerite M. Schaffer. "Context Theory of Classification Learning." *Psychological Review* 85, no. 3 (1978): 207–238.

Montgomery, Nancy. "U.S. Seeks to Reduce Civilian Deaths at Iraq Checkpoints." *Stars and Stripes*, March 18, 2006.

Morgan, James N., and John A. Sonquist. "Problems in the Analysis of Survey Data, and a Proposal." *Journal of the American Statistical Association* 58, no. 302 (1963): 415–434.

Moyer, Virginia A. "Screening for HIV: US Preventive Services Task Force Recommendation Statement." *Annals of Internal Medicine* 159, no. 1 (2013): 51–60.

Musgrave, Alan. "Logical versus Historical Theories of Confirmation." *British Journal for the Philosophy of Science* 25, no. 1 (1974): 1–23.

Naik, Aanand D., Felicia Skelton, Amber B. Amspoker, Russell A. Glasgow, and Barbara W. Trautner. "A Fast and Frugal Algorithm to Strengthen Diagnosis and Treatment Decisions for Catheter-Associated Bacteriuria." *PLOS One* 12, no. 3 (2017): e0174415.

Nosofsky, Robert M., and Thomas J. Palmeri. "An Exemplar-Based Random Walk Model of Speeded Classification." *Psychological Review* 104, no. 2 (1997): 266–300.

Nosofsky, Robert M., Thomas J. Palmeri, and Stephen C. McKinley. "Rule-Plus-Exception Model of Classification Learning." *Psychological Review* 101, no. 1 (1994): 53–79.

Olson, Donald R., Kevin J. Konty, Marc Paladini, Cecile Viboud, and Lone Simonsen. "Reassessing Google Flu Trends Data for Detection of Seasonal and Pandemic Influenza: A Comparative Epidemiological Study at Three Geographic Scales." *PLOS Computational Biology* 9, no. 10 (2013): e1003256.

Payne, John W., James R. Bettman, and Eric J. Johnson. *The Adaptive Decision Maker*. Cambridge: Cambridge University Press, 1993.

Phillips, Nathaniel D., Hansjörg Neth, Jan K. Woike, and Wolfgang Gaissmaier. "FFTrees: A Toolbox to Create, Visualize, and Evaluate Fast-and-Frugal Decision Trees." *Judgment and Decision Making* 12, no. 4 (2017): 344–368.

Pisters, Ron, Deirdre A. Lane, Robby Nieuwlaat, Cees B. De Vos, Harry J. G. M. Crijns, and Gregory YH Lip. "A Novel User-Friendly Score (HAS-BLED) to Assess 1-Year Risk of Major Bleeding in Patients with Atrial Fibrillation: The Euro Heart Survey." *Chest* 138, no. 5 (2010): 1093–1100.

Pitt, Mark A., and In Jae Myung. "When a Good Fit Can Be Bad." *Trends in Cognitive Sciences* 6, no. 10 (2002): 421–425.

Pollan, Michael. *Food Rules: An Eater's Manual*. New York: Penguin, 2009.

Pozen, Michael W., Ralph B. D'Agostino, Harry P. Selker, Pamela A. Sytkowski, and William B. Hood Jr. "A Predictive Instrument to Improve Coronary-Care-Unit Admission Practices in Acute Ischemic Heart Disease: A Prospective Multicenter Clinical Trial." *New England Journal of Medicine* 310, no. 20 (1984): 1273–1278.

Prasad, Vinay, Jeanne Lenzer, and David H. Newman. "Why Cancer Screening Has Never Been Shown to 'Save Lives'—and What We Can Do about It." *British Medical Journal* 352 (2016): h6080.

Prinz, Roman, Markus Feufel, Gerd Gigerenzer, and Odette Wegwarth. "What Counselors Tell Low-Risk Clients about HIV Test Performance." *Current HIV Research* 13, no. 5 (2015): 369–380.

Quinlan, J. Ross. *C4.5: Programs for Machine Learning*. Amsterdam, Netherlands: Elsevier, 1993.

Quinn, Paul C. "Beyond Prototypes." In *Advances in Child Development and Behavior*, ed. R. V. Kai and H. W. Reese, 161–193. San Diego: Academic Press, 2002.

Quinn, Paul C., Peter D. Eimas, and Michael J. Tarr. "Perceptual Categorization of Cat and Dog Silhouettes by 3- to 4-Month-Old Infants." *Journal of Experimental Child Psychology* 79, no. 1 (2001): 78–94.

Rakison, David H., and Lisa M. Oakes, eds. *Early Category and Concept Development: Making Sense of the Blooming, Buzzing Confusion*. Oxford: Oxford University Press, 2003.

Rivest, Ronald L. "Learning Decision Lists." *Machine Learning* 2, no. 3 (1987): 229–246.

Roberts, Seth, and Harold Pashler. "How Persuasive Is a Good Fit? A Comment on Theory Testing." *Psychological Review* 107, no. 2 (2000): 358–367.

Romig, Lou E. "Pediatric Triage: A System to JumpSTART Your Triage of Young Patients at MCIs." *Journal of Emergency Medical Services* 27, no. 7 (2002): 52–58.

Rubinstein, Reuven. "The Cross-Entropy Method for Combinatorial and Continuous Optimization." *Methodology and Computing in Applied Probability* 1, no. 2 (1999): 127–190.

Rudin, Cynthia, and Joanna Radin. "Why Are We Using Black Box Models in AI When We Don't Need To? A Lesson from an Explainable AI Competition." *Harvard Data Science Review* 1, no. 2 (2019).

Sanborn, Adam N., and Nick Chater. "Bayesian Brains without Probabilities." *Trends in Cognitive Sciences* 20, no. 12 (2016): 883–893.

Savage, Leonard J. *The Foundations of Statistics*. Mineola, NY: Dover, 1954.

Schroff, Florian, Dmitry Kalenichenko, and James Philbin. "Facenet: A Unified Embedding for Face Recognition and Clustering." In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 815–823 (Piscataway: IEEE, 2015).

Seymour, Christopher W., Vincent X. Liu, Theodore J. Iwashyna, Frank M. Brunkhorst, Thomas D. Rea, André Scherag, Gordon Rubenfeld et al. "Assessment of Clinical Criteria for Sepsis for the Third International Consensus Definitions for Sepsis and Septic Shock (Sepsis-3)." *Journal of the American Medical Association* 315, no. 8 (2016): 762–774.

Silver, David, Thomas Hubert, Julian Schrittwieser, Ioannis Antonoglou, Matthew Lai, Arthur Guez, Marc Lanctot et al. "A General Reinforcement Learning Algorithm That Masters Chess, Shogi, and Go through Self-Play." *Science* 362, no. 6419 (2018): 1140–1144.

Silver, David, et al. "Mastering the Game of Go without Human Knowledge." *Nature* 550, no. 7676 (2017): 354–359.

Simon, Herbert A. *Models of Bounded Rationality: Empirically Grounded Economic Reason*. Cambridge, MA: MIT Press, 1997.

Simon, Herbert A. "Rational Choice and the Structure of the Environment." *Psychological Review* 63, no. 2 (1956): 129–138.

Simonoff, Jeffrey S. *Analyzing Categorical Data*. New York: Springer, 2003.

Şimşek, Özgür. "Linear Decision Rule as Aspiration for Simple Decision Heuristics." *Advances in Neural Information Processing Systems* (2013): 2904–2912.

Şimşek, Özgür, and Marcus Buckmann. "Learning from Small Samples: An Analysis of Simple Decision Heuristics." In *Advances in Neural Information Processing Systems* 28 (2015): 3159–3167.

Sinha, Pawan, Benjamin J. Balas, Yuri Ostrovsky, and Richard Russell. *Face Recognition: Models and Mechanism*. Cambridge, MA: Academic Press, 2003.

Smith, Jack W., J. E. Everhart, W. C. Dickson, W. C. Knowler, and R. S. Johannes. "Using the ADAP Learning Algorithm to Forecast the Onset of Diabetes Mellitus." In *Proceedings of the Annual Symposium on Computer Application in Medical Care* (American Medical Informatics Association, 1988), 261.

Smith, Liz, and Ken Gilhooly. "Regression versus Fast and Frugal Models of Decision-Making: The Case of Prescribing for Depression." *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition* 20, no. 2 (2006): 265–274.

State Council. "Planning Outline for the Construction of a Social Credit System (2014–2020)." *China Copyright and Media*, June 14, 2014.

Sterelny, Kim. *Thought in a Hostile World: The Evolution of Human Cognition*. Hoboken, NJ: Wiley Blackwell, 2003.

Stiglitz, Joseph E. *Freefall: America, Free Markets, and the Sinking of the World Economy*. New York: W. W. Norton, 2010.

Super, Gary. *START: A Triage Training Module*. Newport Beach, CA: Hoag Memorial Hospital Presbyterian, 1984.

Taleb, Nassim Nicholas. *Skin in the Game: Hidden Asymmetries in Daily Life*. New York: Allen Lane, 2018.

Tan, Jolene H., Shenghua Luan, and Konstantinos V. Katsikopoulos. "A Signal-Detection Approach to Modeling Forgiveness Decisions." *Evolution and Human Behavior* 38, no. 1 (2017): 27–38.

Tanner, Wilson P., Jr., and John A. Swets. "A Decision-Making Theory of Visual Detection." *Psychological Review* 61, no. 6 (1954): 401–409.

Thompson, William C., Franco Taroni, and Colin G. G. Aitken. "How the Probability of a False Positive Affects the Value of DNA Evidence." *Journal of Forensic Science* 48, no. 1 (2003): 1–8.

Todd, Peter M., Gerd Gigerenzer, and the ABC Research Group. *Ecological Rationality: Intelligence in the World*. New York: Oxford University Press, 2012.

Trafimow, David. "Hypothesis Testing and Theory Evaluation at the Boundaries: Surprising Insights from Bayes's Theorem." *Psychological Review* 110, no. 3 (2003): 526–535.

Tukey, John Wilder. *Exploratory Data Analysis*. Boston, MA: Addison-Wesley, 1970.

Tversky, Amos. "Elimination by Aspects: A Theory of Choice." *Psychological Review* 79, no. 4 (1972): 281–299.

Tversky, Amos, and Daniel Kahneman. "Judgment under Uncertainty: Heuristics and Biases." *Science* 185, no. 4157 (1974): 1124–1131.

United Nations Assistance Mission to Afghanistan. *Human Rights' Group Annual Report on the Protection of Civilians in Armed Conflict*. Kabul, Afghanistan, 2012.

US Preventive Services Task Force. "Screening for Skin Cancer: US Preventive Services Task Force Recommendation Statement." *Annals of Internal Medicine* 150, no. 3 (2009): 429.

van Rooij, Tibor, Mary Roederer, Todd Wareham, Iris van Rooij, Howard L. McLeod, and Sharon Marsh. "Fast and Frugal Trees: Translating Population-Based Pharmacogenomics to Medication Prioritization." *Personalized Medicine* 12, no. 2 (2015): 117–128.

Wald, Abraham. *Statistical Decision Functions*. New York: Wiley, 1950.

Welch, Gilbert H., Steven Woloshin, and Lisa M. Schwartz. "Skin Biopsy Rates and Incidence of Melanoma: Population-Based Ecological Study." *British Medical Journal* 331, no. 7515 (2005): 481.

Woike, Jan K., Ulrich Hoffrage, and Jeffrey S. Petty. "Picking Profitable Investments: The Success of Equal Weighting in Simulated Venture Capitalist Decision Making." *Journal of Business Research* 68, no. 8 (2015): 1705–1716.

Wübben, Markus, and Florian V. Wangenheim. "Instant Customer Base Analysis: Managerial Heuristics Often 'Get It Right.'" *Journal of Marketing* 72, no. 3 (2008): 82–93.

Zhao, Sihai Dave, Giovanni Parmigiani, Curtis Huttenhower, and Levi Waldron. "Más-o-Menos: A Simple Sign Averaging Method for Discrimination in Genomic Data Analysis." *Bioinformatics* 30, no. 21 (2014): 3062–3069.

Zięba, Maciej, Sebastian K. Tomczak, and Jakub M. Tomczak. "Ensemble Boosted Trees with Synthetic Features Generation in Application to Bankruptcy Prediction." *Expert Systems with Applications* 58 (2016): 93–101.