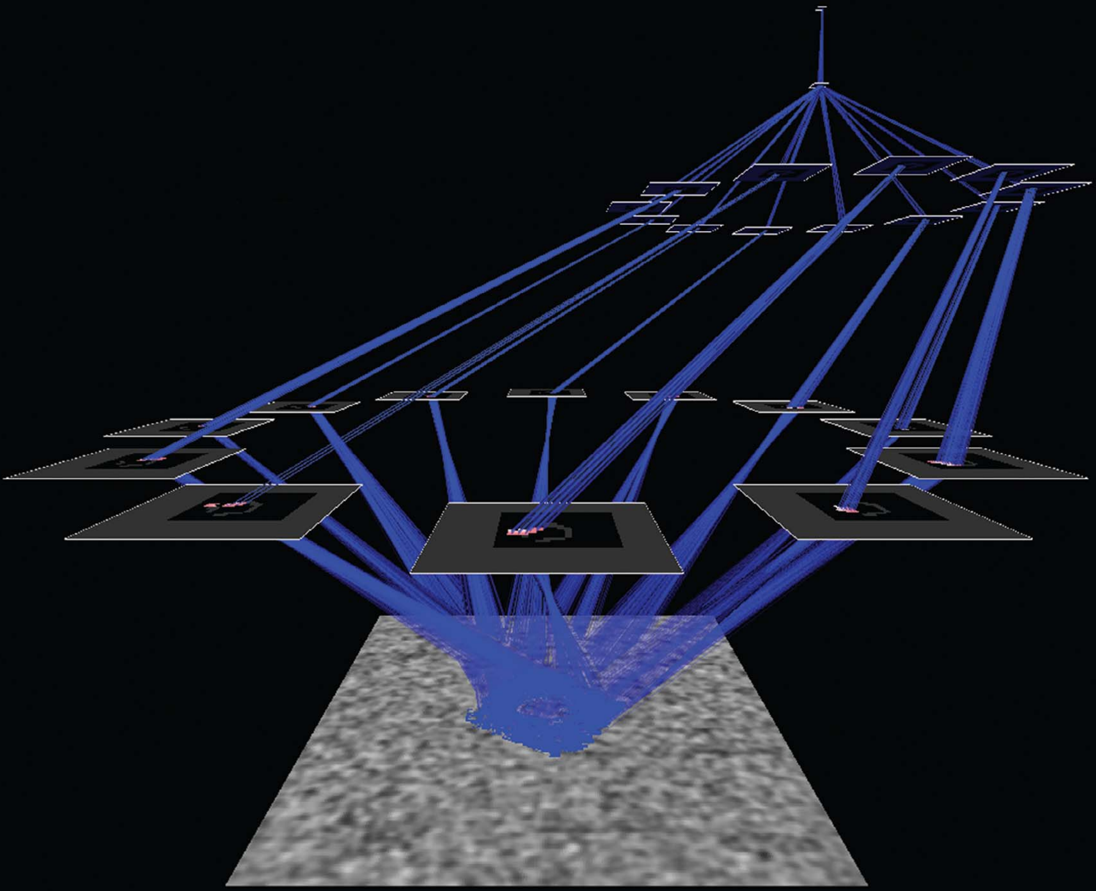
A Computational Perspective on Visual Attention

John K. Tsotsos



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The MIT Press
Cambridge, Massachusetts
London, England

For information about special quantity discounts, please email special_sales@mitpress.mit.edu

This book was set in Times Roman by Toppan Best-set Premedia Limited. Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Tsotsos, John K.
A computational perspective on visual attention / John K. Tsotsos.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-262-01541-7 (hardcover : alk. paper)
1. Vision. 2. Visual perception–Mathematical models. 3. Computer vision—Mathematical models. 4. Attention—Mathematical models. I. Title.
QP475.T875 2011
612.8′4—dc22
2010036050

10 9 8 7 6 5 4 3 2 1

I dedicate this to my children,
Lia and Konstantine,
who inspire me daily

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Preface

Attention in vision is something that I think has fascinated me since my undergraduate days at the University of Toronto. That is pretty surprising because I went to university wanting to be an aerospace engineer or maybe a physicist. In my first year, I subscribed to *Scientific American*, and in 1971 two papers caught my fancy: "Advances in Pattern Recognition" by R. Casey and G. Nagy and "Eye Movements and Visual Perception" by D. Noton and L. Stark. The first dealt in part with optical character recognition by computer, defining algorithms that might capture the process of vision and allow a computer to see. The second described the possible role of eye movements in vision and how they might define our internal representations of what we see. There had to be a connection! I have been trying to understand vision and what the connection between machine and biological vision might be since about 1974.

All through my graduate research, attention found its way into my work in some way. Back in the mid-1970s, there was a critical need for it in any large computer system: computing power was ridiculously meager by today's standards. I implemented my PhD thesis on a DEC PDP-11/45 with 256 kilobytes of memory! As a result, anything one could do to "focus" resources was a good thing. Similarly, if one looks at the computer vision research of the period (for that matter all of the artificial intelligence research, too), the inclusion of a "focus of attention" mechanism was not questioned.

But then in the early 1980s something happened, and, at least in the computational vision community, attention disappeared. I recall giving a seminar at a major U.S. university (nameless of course) where I spoke on my vision work, which included attention. I was taken aside by a very good friend afterward who apologized that many of the faculty did not attend my talk because, he said, they don't believe in attention at this school. I was surprised and disappointed, determined to "prove" that they were wrong. But how? These were really smart people, researchers for whom I had great respect. Could I really accomplish this? Maybe it was I who was mistaken? Within a couple of years of this event, 1985, as luck would have it, I became part of an amazing organization, the Canadian Institute for Advanced Research. Its president, J. Fraser Mustard, believed that to tackle a difficult problem such as artificial intelligence, one really had to look at it from many perspectives: computation, engineering, neuroscience, psychology, philosophy, robotics, society, and more. It was this connection that appealed to me and that eventually led me to a path for approaching my goal. This superb collection of scientists from all these disciplines pushed me, and in my 10 years as a fellow of the institute, I learned more from them all than I can possibly acknowledge. The lessons were sometimes direct but most often indirect, absorbed simply by observation or through casual conversations. The most important lessons were abstracted from watching how the disciplines interacted with one another. Which was ready to absorb the results of the other? What were the barriers to communication? How does one transform theories from one domain into something useful for another? How could one convince one discipline that another had any utility for it? These, and more questions, made me think about how one might better conduct truly interdisciplinary research. Specifically, the perspectives of multiple disciplines became ingrained in me, and I eagerly embarked on trying to understand those different viewpoints and how they may complement and build on one another. The first papers from which the contents of this volume emerged were directly due to the influence of the Canadian Institute for Advanced Research and its Artificial Intelligence and Robotics program.

Looking at the field of computer vision or computational visual neuroscience today, attention is no longer invisible and seems to be playing an increasingly larger role. The push to develop models and systems that are biologically plausible is prominent. Still, attention is most often thought of as either selection of a region of interest to guide eye movements or as single-neuron modulation. Few seem interested in considering how these two processes might be related, and certainly not many seem interested in an overarching theory of attention.

Such a theory of attention, especially for vision, is what this book proposes, at least with respect to some of its foundations. Whether those foundations are successful in the long term will depend on how well their implications and predictions provide a basis for new insights into how the brain processes visual input and how well the resulting representations and computational constructs contribute to new computational vision systems. As with all scientific endeavors, time will tell.

The audience for which this book is intended is a broad and varied one, mirroring the diversity of research efforts into this domain. The book is intended not only for those embarking on research on visual attention and for its current practitioners but also for those who study vision more broadly, as it is central to the thesis of this volume that without attention, vision as we know it would not be possible. The list of interested disciplines is large: visual neuroscience, visual psychology, cognitive psychology, computational vision, computational neuroscience, engineering, computer science, artificial intelligence, robotics, and more. It would be beyond the scope of any book to provide sufficient background so that anyone would find the book self-contained. To be sure, some background is presented in an abbreviated and certainly incomplete manner. Hopefully, enough pointers to relevant literature are included so the interested reader can track down what he or she might need. Those who have completed senior undergraduate or graduate-level courses in visual perception, computer vision, computational complexity, basic neuroanatomy of the visual system, and computational neuroscience will perhaps find the material more accessible than it will be to those who have not.

To provide a bit of assistance to some readers, the mathematical elements are confined to chapters 2 and 5 and appendixes B and C. Skipping these will of course lead to some gaps, but it shouldn't be too hard to follow the balance—unless you ask questions like "Why is he doing things this way?" In that case, you may have to simply bite the bullet and look at the math. Those who wish to see only the overview of the model can do so by reading chapters 4, 6, 7, and 8 and giving the early chapters less attention. For those who seek background on the main subject—visual attention—chapter 3 (and chapter 1 in a more general manner) is intended to be a comprehensive overview of attention theories and models. This literature is so large that gaps and unintentional omissions—for which I apologize—seem inevitable.

Those readers who identify with computer vision as their "home discipline" will undoubtedly be disappointed. But the current research directions in computer vision are not so compatible with the intent of this book. I am interested in using the language of computation, broadly speaking, to formalize and push forward our understanding of the mechanisms of vision and attention—both biological and artificial. Although I fully acknowledge the strong strides made by the computer vision community on the empirical and practical side of the discipline, that work is not covered in this book. Trust me, I may be more disappointed in this disconnect than you.

Many of the figures are better shown in color or as movies. There is a website associated with this book, <http://mitpress.mit.edu/Visual_Attention>, where one can see all color figures and movies. Where these are available, the citation in the book will be suffixed by "W." For example, if figure 7.3 has a color version, it can be found at the website as figure 7.3W, and it is referred to as such in this book. Movies are referred to as "movie 7.5W," not only pointing out that it is a movie but also that it is only available at the website. Although figures will be referred to with or without the "W" as appropriate, movies are only referred to with the "W" suffix.

Earlier, I wrote that two 1971 papers motivated my studies of vision and attention, but those were not my only motivation. My children played important roles, too, and it is for those roles that this book is dedicated to them. When my daughter, Lia (short for Ioulia), was born in 1985 (the same year that I joined the Canadian

Institute for Advanced Research, as I note in the preface—a fortuitous conjunction!), I was in the delivery room with my wife, Patty. I was the first to hold Lia on her birth and looked into her beautiful eyes—and was surprised! They did not seem to move in a coordinated manner; they gazed around apparently independently! The first thought in my head was, "What is going on in there to cause this? Is she okay?" After I was assured that there was nothing wrong, it occurred to me that I have to figure this out! Well I wound up not quite working on that side of the problem, but I do think this helped push me because the first paper that led to this book was written during the coming year. My son, Konstantine, was born in 1989, and this time I was better prepared for a birth, so no great surprises. However, about a year and a half later, he and I were lazing around at home on a Saturday morning looking for some cartoons on television to watch together. I found a program on robotics instead and was curious. It showed a disabled little boy operating a robotic toy-manipulation system. It was a very tedious system, and the juxtaposition of my healthy son playing on the floor beside me while watching the other little boy on television was actually painful to me. I thought that we should be able to do better, to build better systems to help. That was early 1991. My first paper on active vision was written as a result, appearing in 1992, and led to a robotic wheelchair project I named Playbot, intended to assist disabled children in play. So Lia and Konstantine, you were totally unaware of it at the time, but it is clear to me that if it weren't for you, my path would not be what it is today. And as I really like the research path that I am on, I thank you! You continue to inspire me every day with the wonder of how you are growing and becoming so much more than I will ever be.

My journey as a scientist has always had a modest goal. I have always viewed science as a race to solve a puzzle, a puzzle where the size, shape, and color of the pieces are unknown. Even the number of pieces and the eventual picture are unknown. Yet it is known that a picture exists, so we must discover what those puzzle pieces are and how they may fit together. My goal was always to be lucky enough to discover one or two of those puzzle pieces and to know where they fit within the full landscape that the puzzle represents. I think that every other scientist also has this as a goal. Only time will tell who discovers the right pieces for visual attention at the right time so that the picture is complete.

Acknowledgments

The theory presented in this volume was only possible because of the terrifically good fortune of having many talented people around me all of who contributed to the overall body of work (listed alphabetically). I thank each and every one:

- superb postdoctoral fellows—Neil Bruce, Xin Chen, Florin Cutzu, Daniel Loach, Julio Martinez-Trujillo, Pietro Parodi, Marc Pomplun, and Michael Tombu;
- gifted graduate students and research assistants—Neil Bruce, Sean Culhane, David Dolson, Brian Down, Yuhzong Lai, Randi Lanciwicki, Yueju Liu, Fernando Nuflo, Antonio Rodriguez-Sanchez, Albert Rothenstein, Xun Shi, Ksenia Shubina, Eugene Simine, Ankur Vijh, Winky Wai, David Wilkes, Yiming Ye, Andrei Zaharescu, and Kunhao Zhou;
- talented and generous colleagues and collaborators, some are coauthors, others may have provided a key conversation or pointer at the right time—Ruzena Bajcsy, Nico Boehler, Jochen Braun, Doug Cheyne, Sven Dickinson, Gregory Dudek, Mazyar Fallah, Olivier Faugeras, Fred Hamker, Hans-Joachim Heinze, Jens-Max Hopf, Laurent Itti, Michael Jenkin, Allan Jepson, Pierre Kornprobst, Evangelos Milios, John Mylopoulos (my first and continuing mentor), Zenon Pylyshyn, John Reynolds, Ariel Schoenfeld, Iannis Tourlakis, Anne Treisman, Stefan Treue, Jeremy Wolfe, Richard Wildes, Hugh Wilson, and the one who by far contributed the most, Steven Zucker.

I especially thank Eugene Simine for his programming assistance and for preparing many of the figures.

I also need to thank those who took the time to read drafts of this book and give me feedback and suggestions—Alexander Andreopoulos, Nico Boehler, Neil Bruce, Konstantinos Derpanis, Jens-Max Hopf, Marc Pomplun, Albert Rothenstein, Ehsan Fazl-Ersi, Lia Tsotsos, and Konstantine Tsotsos—and three anonymous referees arranged by The MIT Press. The presentation is much better as a result, but I take full ownership of any remaining errors or problems. Yes, my children did in fact read this and provided terrific feedback. Lia, being a PhD candidate in visual neuroscience, and Konstantine, being a senior engineering undergraduate who has

worked on visually guided robotics, are exactly the kinds of people for whom the book is intended and thus were ideal reviewers.

The staff of the MIT Press has been surprisingly easy to work with. I especially thank Susan Buckley, Katherine Almeida, and freelancer Chris Curioli. Finally, I thank Robert Prior for his encouragement, easygoing manner, and, above all, for his patience while I took my snail's pace toward completion. I also thank Sandy Pentland for starting me on this project long ago when he suggested that my 1990 paper in *The Behavioral and Brain Sciences* could form the basis for a good book.

I am grateful to the following main sources of funding that have made my work possible: the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Institute for Advanced Research, the Ontario Centres of Excellence (OCE), and the Canada Research Chairs Program, where I hold the Canada Research Chair in Computational Vision. I also thank my first home base where this research was initiated, the University of Toronto, for their support and the wonderful research environment in the Department of Computer Science. I thank Olivier Faugeras and the France-Canada Research Foundation for providing me with a few quiet weeks in a lovely setting in Provence, France, to focus on my writing. Finally, my current home base, York University, has provided the key elements of research environment and support for the past 10 years while the research program matured and enabled me to write this book. My department, Computer Science and Engineering, the Centre for Vision Research, and the office of the Vice-President of Research and Innovation (special thanks to V.P. Stan Shapson) have provided me with terrific infrastructure, institutional support, funding, and the intellectual playground that allowed me to pursue my research dreams.

As this is my first authored book, I believe the acknowledgments would be incomplete if I did not take the opportunity to thank my parents for the sacrifices of so many kinds, their love, unwavering support, and constant encouragement that formed the foundation for my life. My father taught me the meaning of idealism by his teachings of the ancient Greek ideals and with the romantic poetry he wrote. He always looked through the way the world really was to the way it should be, what he hoped it could become. And as John Polanyi said, idealism is the highest form of reasoning. My mother taught me how to take that idealism and put it into practice. Hard work, perseverance, single-mindedness, focus, and then when you think you have worked hard enough, more hard work. Thomas Edison said that genius is 1% inspiration and 99% perspiration—my mother knew this because I really perspired!

My family has been very supportive while I worked on this book. They realized that while I was focused on this writing, I was at my happiest scientifically! Especially to my wife Patty—the one I celebrate with, the one whose shoulder I cry on, the one with whom I share the trials and joys of raising our beautiful children, my soul mate for over 30 years now—thank you!

1 Attention—We All Know What It Is

But Do We Really?

The title of this chapter is adapted from the classic words of William James (1890), who wrote what has become perhaps the best-known plain language description of attention:

> Everyone 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.

James specified two domains in which these objects occur: sensory and intellectual. He listed three physiologic processes that he believed played a role in the implementation of attention: the accommodation or adjustment of the sensory organs, the anticipatory preparation from within the ideational centers concerned with the object to which attention is paid, and an afflux of blood to the ideational center. With these processes, he set up a good deal of modern attention research including functional magnetic resonance imaging (fMRI) studies. However, since the time of James—and because of the myriad experimental findings exploring each of James' three processes—things have become less and less clear, and it is important to consider the many subsequent points of view.

A book on attention, computational or otherwise, needs to define what it means by attention. It would have been so convenient to end the introduction to attention with James' description. But it is not to be so. Many over a long period of time have written on how difficult it has seemed to pin down this domain of inquiry. Compare James' statement with that of Pillsbury (1908)

> [A]ttention is in disarray . . . .

or that of Groos, who wrote in 1896 that

> To the question, 'What is Attention,' there is not only no generally recognized answer, but the different attempts at a solution even diverge in the most disturbing manner.

Four decades later, it seemed that little had changed. Spearman (1937) commented on the diversity of meanings associated with the word:

> For the word attention quickly came to be associated . . . with a diversity of meanings that have the appearance of being more chaotic even than those of the term ‘intelligence.’

Almost eleven decades after James, Sutherland (1998) suggested that:

> [A]fter many thousands of experiments, we know only marginally more about attention than about the interior of a black hole.

Taken together, these quotes make the situation seem bleak! The field is full of controversy, and it seems that a bit more care is required before moving on. A brief tour through some of the early thinking on the topic helps reveal sources of debate and key issues. A more detailed treatment can be found in Tsotsos, Itti, and Rees (2005). The first scientific reference to attention, even though its etymology is traced to ancient Rome, seems to be due to Descartes (1649), who connected attention to movements of the pineal body that acted on the animal spirit:

> Thus when one wishes to arrest one’s attention so as to consider one object for a certain length of time, this volition keeps the gland tilted towards one side during that time.

Keeping with the idea that body organs are involved, Hobbes (1655) believed:

> While the sense organs are occupied with one object, they cannot simultaneously be moved by another so that an image of both arises. There cannot therefore be two images of two objects but one put together from the action of both.

Leibnitz (1765) first linked attention to consciousness, a possibility that has received much debate recently, and attributed this to inhibition from competing ideas:

> In order for the mind to become conscious of perceived objects, and therefore for the act of apperception, attention is required.

Hebart (1824) was the first to develop an elaborate algebraic model of attention using differential calculus and may be considered the first attention modeler. His general view on attention, however, was still rather simple:

> He is said to be attentive, whose mind is so disposed that it can receive an addition to its ideas: those who do not perceive obvious things are, on the other hand, lacking in attention.

Since the 1800s, much genius has gone into experimental methods that were hoped to shed some light on the phenomenon of attention. Helmholtz (1860) believed that nervous stimulations are perceived directly, never the objects themselves, and there are mental activities that enable us to form an idea as to the possible causes of the observed actions on the senses. These activities are instantaneous, unconscious, and cannot be corrected by the perceiver by better knowledge—he called this **unconscious inference**, and thus he believed that attention is an unconscious phenomenon. On the other hand, Panum (1858) believed that attention is an activity entirely subservient to an observer's conscious will. Attention becomes difficult to hold once interest in an object fades. The greater the disparities between the intensities of two impressions, the harder it is to keep attention on the weaker one. Panum studied this in the specific context of binocular rivalry; but more generally, he observed that we are able to 'see' only a certain number of objects simultaneously. He therefore concluded that it makes sense that the field of view is first filled with the strongest objects. In studying an object, first attention, and then the eye, is directed to those contours that are seen by indirect vision.

Hamilton (1859) wondered about the span of attention:

> The doctrine that the mind can attend to, or be conscious of, only a single object at a time would in fact involve the conclusion that all comparison and discrimination are impossible. . . . Suppose that the mind is not limited to the simultaneous consideration of a single object, a question arises—how many objects can it embrace at once?

His last question is important even today. Brentano (1874) developed **act psychology,** where an act is a mental activity that affects percepts and images rather than objects. Examples include attending, picking out, laying stress on something, and similar actions. This was the first discussion of the possibility that a subject's actions play a dominant role in perception. Metzger (1974) lists aspects of action that contribute to perception: bringing stimuli to receptors, enlarging the 'accessible area,' **foveation** (the act of centering the central, highest-resolution part of the retina onto an object), optimization of the state of receptors, slowing down of fading and local adaptation, exploratory movement, and finally the search for principles of organization within visual stimuli.

Wundt (1874) further linked attention and consciousness, suggesting that attention, as an inner activity, causes ideas to be present in consciousness to differing degrees. The focus of attention can narrow or widen, reflecting these degrees of consciousness. For Titchener (1908), attention was an intensive attribute of a conscious experience equated with 'sensible clearness.' He compared attention to a wave, but with only one peak (corresponding with one's focus). He argued that the effect of attention is to increase clarity, whereas Kulpe (1902) suggested that attention enhanced not clarity but discriminability. Petermann (1929) argued against the subject being a passive perceiver of stimuli. He proposed an **attention-direction theor**y, based on actions, as the mechanism for an active attentive process. As will become apparent, this theme keeps reappearing. These and other ideas were never formalized in any way and remained conceptual, yet interesting, viewpoints on the issue.

Helmholtz (1896) introduced the idea of **covert attention**, independent of eye movements:

> The electrical discharge illuminated the printed page for a brief moment during which the image of the sheet became visible and persisted as a positive after-image for a short while. Hence, perception of the image was limited to the duration of the after-image. Eye movements of measurable size could not be performed during the duration of the flash and even those performed during the short persistence of the after-image could not shift its location on the retina. Nonetheless, I found myself able to choose in advance which part of the dark field off to the side of the constantly fixated pinhole I wanted to perceive by indirect vision. Consequently, during the electrical illumination, I in fact perceived several groups of letters in that region of the field. . . . The letters in most of the remaining part of the field, however, had not reached perception, not even those that were close to the point of fixation.

In other words, Helmholtz was able to attend to different portions of an image on his retina without eye movements. Such a demonstration is compelling and represents powerful evidence for the existence of attention independent of gaze change.

Even though experimental evidence supporting a variety of phenomena attributed to attention mounted, the field was not without its nonbelievers. The Gestalt school did not believe in attention. Köhler only barely mentions attention (Köhler, 1947). Gestaltists believed that the patterns of electrochemical activity in the brain are able to sort things out by themselves and to achieve an organization that best represents the visual world, reconciling any conflicts along the way. The resulting internal organization includes portions that seem more prominent than others. Attention, to them, was an emergent property and not a process in its own right. In this sense, Gestaltism was the precursor of the modern Emergent Attention theories that will be described in chapter 3. Figure-ground concerns loomed larger for them, the figure would dominate perceptions within a scene, thus emerging as the focus of attention rather than being explicitly computed as such. Berlyne (1974) tells us that Edgar Rubin, known for his vase/profile illusion of figure-ground perception, actually presented a paper at a meeting in Jena, Germany, in 1926 titled “On the Nonexistence of Attention.” More recently, Marr basically discounted the importance of attention by not considering the time intervals of perception where attentive effects appear even though his goal was clearly to propose a theory for full vision. Describing grouping processes and the full primal sketch, he said:

> [O]ur approach requires that the discrimination be made quickly—to be safe, in less than 160 ms—and that a clear psychophysical boundary be present. (Marr, 1982, p. 96)

Attention has been viewed as **Early Selection** (Broadbent, 1958), using **Attenuator Theory** (Treisman, 1964), as a **Late Selection** process (Deutsch & Deutsch, 1963; MacKay, 1973; Moray, 1969; Norman, 1968), as a two-part process, **preattentive fol-**

lowed by attentive processing (Neisser, 1967), as a result of **neural synchrony** (Milner, 1974), using the metaphor of a **spotlight** (Shulman, Remington, & McLean, 1979), within **Feature Integration Theory** (Treisman & Gelade, 1980), as an **object-based** phenomenon (Duncan, 1984), as a **shrink-wrap** process (Moran & Desimone, 1985), using the **Zoom Lens** metaphor (Eriksen & St. James, 1986), as a **Premotor Theory** subserving eye movements (Rizzolatti, Riggio, Dascola, & Umilta, 1987), as **Guided Search** (Wolfe, Cave, & Franzel, 1989), as **Biased Competition** (an extension of the shrink-wrap interpretation; Desimone & Duncan, 1995), as **Feature Similarity Gain** (Treue & Martinez-Trujillo, 1999), and more. These are all defined and discussed in later chapters, and they are listed here to show the diversity of opinion on the nature of attention. The field is rich with ideas, but can they all be right?

We have seen how Helmholtz provided a convincing demonstration for the existence of covert attention. Yet eye movements are the most obvious external manifestation of a change of visual attention. Yarbus' classic work (Yarbus, 1979) showed how task requirements affected fixation scan paths for an image. Given the same picture of a family in a Victorian living room scene, Yarbus asked subjects to either freely view the picture or to answer one of the following six questions about the people and situation depicted in the picture:

1. What is their economic status?
2. What were they doing before the visitor arrived?
3. What clothes are they wearing?
4. Where are they?
5. How long is it since the visitor has seen the family?
6. How long has the unexpected visitor been away from the family?

He recorded subject's eye movements while freely viewing and for the period of time before subjects provided a reply to a question. Each recording lasted 3 minutes. The surprise was the large differences among the summary scan paths demonstrating that the reason for looking at a picture plays a strong role in determining what was looked at. In fact, this was a nice extension of the basic Posner cueing paradigm that has played such a large role in experimental work (Posner, Nissen, & Ogden, 1978). Instead of providing a spatial cue that directed attention, Yarbus' questions directed attention. Posner (1980) suggested how overt and covert attentional fixations may be related by proposing that attention had three major functions: (1) providing the ability to process high-priority signals or alerting; (2) permitting orienting and overt foveation of a stimulus; and (3) allowing search to detect targets in cluttered scenes. This is the **Sequential Attention Model:** Eye movements are necessarily preceded by covert attentional fixations. Other views have also appeared. Klein put forth another hypothesis (Klein, 1980), advocating the **Oculomotor Readiness Hypothesis:** Covert and overt attention are independent and co-occur because they are driven by the same visual input. Finally, the aforementioned Premotor Theory of Attention also has an opinion: Covert attention is the result of activity of the motor system that prepares eye saccades, and thus attention is a by-product of the motor system (Rizzollati et al., 1987). However, as Klein more recently writes (Klein, 2004), the evidence points to three conclusions: that overt orienting is preceded by covert orienting; that overt and covert orienting are exogenously (by external stimuli) activated by similar stimulus conditions; and that endogenous (due to internal activity) covert orienting of attention is not mediated by endogenously generated saccadic programming.

What role do stimuli themselves play in attentional behavior? What is the role of the salience of the visual stimuli observed (see Wolfe, 1998a)? Just about everything someone may have studied can be considered a feature or can capture attention. Wolfe presents the kinds of features that humans can detect efficiently and thus might be considered salient within an image: color, orientation, curvature, texture, scale, vernier offset, size, spatial frequency, motion, shape, onset/offset, pictorial depth cues, and stereoscopic depth. For most, subjects can select features or feature values to attend in advance. Saliency has played a key role in many models of attention, most prominently those of Koch and Ullman (1985) and Itti, Koch, and Niebur (1998).

Modern techniques in neurophysiology and brain imaging have led to major advances in the understanding of brain mechanisms of attention through experiments in awake, behaving animals and in humans. It is not possible to do justice to the large and impressive body of such research here (but see Itti, Rees, & Tsotsos, 2005). Suffice it to say that evidence abounds for how attention changes perception, and it seems manifested as both enhancement as well as suppression of signals. We also have a better idea about where attentional computations may be taking place in the brain.

How can it be that so many different and sometimes opposing views can be held all for the same “we all know what it is” phenomenon? One possibility is that the nature of a purely experimental discipline lends itself to fragmented theories. Most of the theories and models described earlier are constructed so that they provide explanations for some set of experimental observations with a focus being on the experiments conducted by each researcher. To be sure, each attempts to be as consistent with past work as possible so to build upon the past and not to continually reinvent. However, the explanations are almost always stated in natural language, using the ambiguous terminology of attention. In other words, there is no quantitative or formal statement of the theory such that it is unambiguous and not open to different interpretations. For many of the main theories of attention, it is easy to find subsequent interpretations that seem rather unjustified. As a result, a large part of the controversy in the field may have two main sources: a vocabulary that has never been defined unambiguously and a theoretical framework that is not formal in a mathematical sense and thus open to interpretation.

Moving Toward a Computational Viewpoint

Although attention is a human ability we all intuitively think we understand, the computational foundations for attentive processes in the brain or in computer systems are not quite as obvious. Notions such as those of capacity limits pervade the attention literature but remain vague. Within all of the different viewpoints and considerations of the previous section, the only real constant—something that everyone seems to believe and thus the only logical substitute for James' original statement—is that attentional phenomena seem to be due to inherent limits in processing capacity in the brain. But if we seek an explanation of attentional processing, even this does not constrain the possible solutions. Even if we all agree that there is a processing limit, what is its nature? How does it lead to the mechanisms in the brain that produce the phenomena observed experimentally?

This presentation, focusing on vision and sensory perception mostly, attempts to make these more concrete and formal. Through mathematical proofs, it is possible to derive the necessity of attentive processes, and through algorithmic approximations and processing optimizations it is possible to discover realizations given either biological or computational resource constraints. Perhaps the most important conclusion is that the brain is not solving some generic perception problem and, by extension, a generic cognition problem. Rather, the generic problem is reshaped—changed—through approximations so that it becomes solvable by the amount of processing power available in the brain.

The human cognitive ability to attend has been widely researched in cognitive and perceptual psychology, neurophysiology, and in computational systems. Regardless of discipline, the core issue has been identified to be **information reduction**. Humans, and many other animals as well, are faced with immense amounts of sensory input, and the size of the brain limits its ability to process all of this input. This is the qualitative statement that has appeared many times in the literature. It is not simply that there is too much input; the problem is that each component of each stimulus can be matched to many different objects and scenes in memory resulting in a combinatorial explosion of potential interpretations, as is caricatured in figure 1.1.

Perhaps the bulk of all perceptual research has focused on how the brain decomposes the visual signal into manageable components. Individual neurons are selective for oriented bars, for binocular disparity, for speed of translational motion, for color opponency, and so on. We know that individual neurons also exist that are

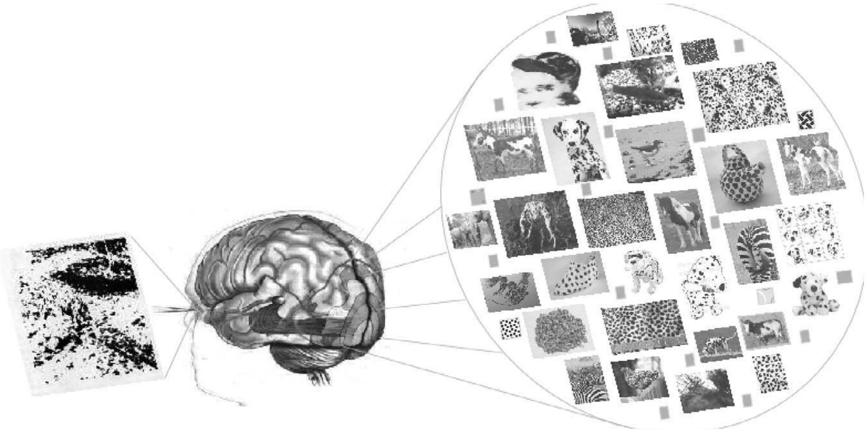

Figure 1.1
The classic "Dalmatian sniffing at leaves" picture (attributed to Richard Gregory) is sufficiently complex to activate an enormous number of possible interpretations. Each small piece of it has similarities (some strong, some weaker) to many other possible objects and scenes. The combinatorial explosion of possibilities that results is what any system—brain or machine—must effectively deal with to perceive successfully and act on the world.

tuned to particular faces or other known objects. But how can we deal with unknown scenes and objects? The neural decomposition of a visual scene gives the brain many, many pieces of information about a scene. It is in effect a *Humpty-Dumpty*-like problem—we know how the visual image may be decomposed, but how is it reassembled into percepts that we can use to guide our day-to-day lives? It is here where the combinatorial explosion has greatest impact.

This combinatorial view is the one that is central to the theory presented in this book. However, it is not the only view. For example, Tishby, Pereira, and Bialek (1999), using information theory, view the relevant information in a signal as being the information that it provides about some other signal. They formalize this problem as that of finding a short code that preserves the maximum information about the other signal, squeezing information through a 'bottleneck' formed by a limited set of code words (the **information bottleneck method**). Clearly, they address information reduction and do it in a principled and well-defined manner. Although an interesting and important perspective, it seems difficult to understand how it may relate to brain processing because it does not address what sort of process may be responsible for determining what those code words may be; Tishby et al.'s major concern is the amount of information not its content or how it is processed. The issues cannot be separated if one wishes to develop a theory of human attention.

The basic idea that humans can be viewed as limited-capacity information processing systems was first proposed by Broadbent (Broadbent, 1958). In computational systems, attention appears in early artificial intelligence (AI) systems explicitly as a focus of attention mechanism or implicitly as a search-limiting heuristic motivated primarily by practical concerns—computers were not powerful enough, and one had to do whatever possible to limit the amount of processing required so that resources could be allocated to the most relevant tasks. This kind of strategy and its heuristic nature is what Marr objected to. As he wrote:

> The general trend in the computer vision community was to believe that recognition was so difficult that it required every possible kind of information. (Marr, 1982, p. 35)

When describing the modular organization of the human visual processor, he added:

> [A]lthough some top-down information is sometimes used and necessary it is of only secondary importance . . . . evidence . . . was willfully ignored by the computer vision community. (Marr, 1982, p. 100)

As will become clear, top-down information is hardly secondary, and a heuristic strategy is really the only one possible. But, in contrast with what Marr thought, one *can* execute it in a principled manner.

All search methods that involve ordering or pruning of the search space perform information reduction. Information reduction is needed because the size of the full search space for a problem does not match the computing resources and system performance requirements, and thus a brute-force search scheme is not sufficient.

Motivation from cognitive psychology also made an important impact with the early appearance of a number of systems. The **Adaptive Character of Thought** (ACT) system was intended as a general model of cognition (Anderson, 1976). ACT has a focus of attention that changes as nodes in long-term memory are activated and put in working memory and as other nodes are pushed out of working memory. Focus is implemented with a small working memory (capacity limit), with strategies for determining which productions are applicable at any time. Along a very different application domain, Barstow's automatic programming system PECOS uses intermediate-level grouping to focus attention on the relevant and to ignore detail (Barstow, 1979). LIBRA was a system developed for efficient analysis of computer code (Kant, 1979). LIBRA has explicit attention and resource management rules. Rules determine how LIBRA's own resources are to be allocated on the basis of greatest utility. A landmark in AI, the 1980 HEARSAY-II system for speech understanding (Erman, Hayes-Roth, Lesser, & Reddy, 1980) ranked concepts using goodness-of-fit to focus in on the strongest and those with greatest utility. Several computer vision systems also included attention strategies to limit the region of interest that is processed in an image [the earliest being Kelly (1971) in the context of face outline detection] or even the window in time for video sequence input [the first being Tsotsos (1980) for heart motion analysis]. There are many more examples that help make the point that efficient matching of input, processing methods, and resources has played a major role in the development of computer systems whose performance attempts to match that of humans.

What Is Attention?

The study of attention has a long history, has been examined from many different disciplines, and there is a wealth of ideas, theories, and mechanisms that have been proposed. The bulk of this chapter was devoted to a brief tour through the development of the subject with the goal of searching for a definition. Is there anything within this enormous body of work that may be considered common, basic, or foundational? Perhaps this is the common thread:

> Attention is the process by which the brain controls and tunes information processing.

The perspective in this book is that attention seeks to find a satisficing configuration of processes so that at least the minimum requirements of a goal can be achieved. This configuration may approach optimal; but optimality is not the primary objective. Attention adapts the visual system to its dynamic needs that are dictated by current input and task so that it may perform as well as possible within its capacity. But this is not yet a formal definition of attention; it is a qualitative one in the same style as the other proposals mentioned thus far. The remainder of this volume attempts to provide a formal foundation for this statement and to provide particular mechanisms that accomplish this. The overriding goal is to provide a computational explanation for visual attention in the human brain and visual system with the hope that this may also lead to more effective computational vision systems. And this will begin with an investigation of what the brain's visual processing capacity might be.

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