Nebraska Symposium on Motivation

Michael D. Dodd
John H. Flowers *Editors*

The Influence of Attention, Learning, and Motivation on Visual Search

Springer

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Debra A. Hope
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Preface

The volume editors for this 59th volume of the Nebraska Symposium on Motivation are Michael Dodd and John Flowers. The volume editors coordinated the symposium that led to this volume including selecting and inviting the contributors. My thanks go to Professors Dodd and Flowers and to our contributors for their outstanding presentations and chapters. As we learned during the Symposium, visual search is part of our daily experience. A better understanding of the underlying processes and limitations helps us solve everything from minor everyday problems we all face to security problems that could pose a threat to our way of life.

At the Symposium we honored Professor Flowers as he retired in 2011 following a long and distinguished career at the University of Nebraska-Lincoln. This volume helps round out a fruitful scientific career as well as marks the passing of the torch to the next generation of cognitive psychologists in our department, including Professor Dodd.

This Symposium series is supported by funds provided by the Chancellor of the University of Nebraska-Lincoln, Harvey Perlman, and by funds given in memory of Professor Harry K. Wolfe to the University of Nebraska Foundation by the late Professor Cora L. Friedline. We are extremely grateful for the Chancellor's generous support of the Symposium series and for the University of Nebraska Foundation's support via the Friedline bequest. This symposium volume, like those in the recent past, is dedicated to the memory of Professor Wolfe, who brought psychology to the University of Nebraska. After studying with Professor Wilhelm Wundt in Germany, Professor Wolfe returned to Nebraska, his native state, to establish the first undergraduate laboratory in psychology in the nation. As a student at Nebraska, Professor Friedline studied psychology under Professor Wolfe.

Lincoln, Nebraska
USA

Debra A. Hope
Series Editor

Acknowledgements

As is the case with any large scale event, the 59th annual Nebraska Symposium on Motivation and accompanying volume would not have been possible were it not for the tireless efforts of numerous individuals. We are truly grateful for everyone's investment and would like to acknowledge a number of people for the critical role they played. First, the Department of Psychology staff, particularly Claudia Price-Decker, Roxanne Earnest, Jamie Longwell, and Jodi Wiser. In addition to their normal role in ensuring that the day-to-day operations of the Psychology Department run smoothly, each of these individuals took time out of their busy schedules to assist in a number of tasks that were critical to the success of the event. These included, but are not limited to, arranging speaker travel, hotel and conference room accommodations, conference registration and administration, program and gift-bag preparation, and the scheduling of meals and refreshments during breaks in the day. Mark Mills, a cognitive area graduate student, volunteered his time to schedule and assist in ground travel for all speakers both to-and-from the airport and to-and-from the conference. Peter Levitov was also very helpful in terms of informing the administrative work and protocol we needed to follow to bring in our international speakers. Chancellor Harvey Perlman is to be thanked for the introductory remarks he offered at the beginning of the Symposium which acknowledged not just the great history of the event itself, but also celebrated the career of Symposium co-organizer, John Flowers who retired in 2011 after 39 years as a major contributor to our faculty.

It goes without saying that we are incredibly indebted to our speakers, all of whom were eager and willing to take part in the Symposium and clearly put a great deal of time into their talks—all of which were dynamic, informative, and interesting—and their subsequent chapters appearing in this volume. These chapters fully capture the spirit of their Symposium presentation while also allowing them to go into more depth on specific issues which are currently at the forefront of the study of visual search. Moreover, many of the speakers brought along their graduate students to present posters at the end of the first day of the conference. The poster session also featured UNL students and a number of other graduate student participants from out-of-state, making it one of the larger poster sessions in recent memory with representatives from a number of different regions of the country doing research related to visual search at a variety of levels. These individuals are to be thanked not only for the time and effort they put into their presentations, but also for taking the Symposium speakers out to lunch on the second day of the conference, allowing for additional intellectual exchange.

The 59th Nebraska Symposium on Motivation was also the first to be webcast live meaning that anyone in the world could watch the presentations in real time as they were occurring in addition to being able to send questions in via e-mail for the speakers to address. On the first day of the conference alone, more than 300 individuals logged in from around the world to view the talks and we received very positive feedback from people who were unable to travel to the Symposium but thrilled to have the opportunity to view the talks nonetheless. We anticipate that this will now be the standard for all future symposia. This also allowed us to make the talks available to the speakers when it came time for them to write their chapters which is a huge benefit given how quickly the event unfolds. We are very appreciative of Mark Hendricks and his team in UNL Educational Media for their outstanding efforts with the web streaming.

Finally, we would like to highlight and give thanks to the contributions of Deb Hope, Series Editor for the Nebraska Symposium on Motivation. Were it not for Deb, we would not have known where to begin in organizing an event and volume of this magnitude. Her willingness to share her expertise and her experiences with past events made it very easy for us to address every issue that arose during the course of planning and execution of the event and the volume that now follows.

Contributors

Stephen H. Adamo completed his B.S. in Psychology in 2010 at the University of Arizona. Under the guidance of Dr. Mary Peterson, he investigated visual awareness in figure-ground perception through the use of binocular rivalry. After graduation, he joined the laboratory of Dr. Stephen R. Mitroff at Duke University, where he has since focused on exploring the spatial and temporal aspects of visual attention. Stephen uses eye tracking and a battery of individual-differences measures to study the mechanisms of visual search and the attentional blink.

Brian A. Anderson is a Ph.D. student in the Department of Psychological and Brain Sciences at Johns Hopkins University, where he studies the interplay between attention and reward learning under the direction of Steven Yantis. He received an M.S. in Psychology from Villanova University in 2009, where he studied top-down control of attention with Charles Folk. Brian is originally from Maine and received his undergraduate degree from the University of Maine at Augusta.

Matthew S. Cain received his S.B. in Brain and Cognitive Science from the Massachusetts Institute of Technology in 2002 and his Ph.D. in Psychology from the University of California, Berkeley in 2009. His graduate work in the laboratory of Dr. Arthur P. Shimamura investigated cognitive control, attention, and task switching and the effects of factors such as sleep and video-game experience on these processes. As a postdoctoral researcher in Dr. Stephen R. Mitroff's laboratory, Matthew has investigated how visual search and visual attention are influenced by local factors such as anxiety, environmental statistics, and stroboscopic training as well as by more global factors such as media exposure and other individual differences.

Kait Clark completed her B.S. in Psychology in 2008 at Saint Joseph's University, where she worked with Drs. Patrick Garrigan and John Jewell investigating visual memory and change detection. She then pursued graduate studies at Duke University under the mentorships of Drs. Stephen R. Mitroff and Marty G. Woldorff. Over the course of her graduate career, Kait has focused on the influences on visual search performance from a variety of directions. She has explored how certain forms of training and experience (lab-based practice, video-game experience, and radiological expertise) may augment search performance and how individual differences between subjects and motivational factors impact search speed and accuracy.

Michael Dodd received his Ph.D. in Cognitive Psychology from the University of Toronto in 2005 and was a Killam postdoctoral fellow at the University of British Columbia before joining the University of Nebraska faculty in 2007. His research encompasses many different aspects of human cognition, with a particular focus on visual attention (e.g., visual search; inhibition of return; object-based attention; apparent motion; sensory processing; scene perception; oculomotor programming; task-induced changes in eye movements), memory (false memory, retrieval-induced forgetting, directed forgetting), individual differences (influences of political temperament on cognition) and goal-directed activity, as well as the interactions between these cognitive.

Dr. John H. Flowers jointed the UNL faculty in 1972. He received his Ph.D. from Yale University in 1972 in experimental psychology. His primary research interests are in the general area of human information processing, particularly attention, implicit learning, and the perception of structure. His interest in the perception of structure has recently led to a research program on the use of sound as a means for representing data.

Andrew Hollingworth received his Ph.D. from Michigan State University in 2000 and is currently a professor at the University of Iowa. He studies how humans select, store, and use visual information to support efficient behavior. His research program is composed of projects involving multiple visual/cognitive systems, with a focus on how these systems are coordinated during visual tasks, including: eye movements and saccade target selection, attention capture, visual search, transaccadic memory and integration, visual working memory, object correspondence and updating, long-term memory for object and scenes, and spatial cognition.

Yoko Ishigami is a postdoctoral fellow at Brain Repair Centre (Dalhousie University). Yoko completed her Ph.D. and M.Sc. at Dalhousie University and her undergraduate studies at University of Victoria. Her research interests include: visual attention, its development/aging, its disorders, and its individual differences. She is specifically interested in exploring their roles, interactions, and limitations in different contexts.

Raymond M. Klein is a University Research Professor and chair of the Department of Psychology & Neuroscience at Dalhousie University. He is an experimental psychologist and cognitive neuroscientist whose research strategies are most strongly influenced by those of D. O. Hebb, Donald Broadbent and Michael Posner. His research interests include: Visual attention and its disorders, reading and dyslexia; applied cognitive psychology.

Patryk Laurent is a Postdoctoral Researcher in the Yantis Laboratory at Johns Hopkins University. He earned his Ph.D. in Neuroscience at the University of Pittsburgh in 2009, while using computational modeling and fMRI to study how reinforcement leads to the coordination of perception, cognition, and action. His current research focuses on understanding the neural circuits involved in reward learning.

Stephen R. Mitroff is an associate professor in the Department of Psychology & Neuroscience and the Center for Cognitive Neuroscience at Duke University. He is originally from the San Francisco Bay Area and received his undergraduate degree in Cognitive Science from the University of California, Berkeley. He received a Masters degree and his Ph.D. in Cognitive Psychology from Harvard University. He completed three years of postdoctoral research at Yale University prior to joining the faculty at Duke University in 2005. Dr. Mitroff's research interests focus on the study of visual cognition, examining the nature of visual memory, perception, and attention. He is currently working with the Department of Homeland Security and the Army Research Office to explore how experiences influence vision and attention. A primary focus is on individual differences to reveal how it is that some individuals can outperform others, how can we quickly and easily identify the best performers, and how can we then train those individuals to make them even better.

Jan Theeuwes is professor and head of the Department of Cognitive Psychology at the Vrije Universiteit Amsterdam. He is a member of the Royal Dutch Academy of Science (KNAW) and received the Bertelson Award in recognition for outstanding psychological research from the European Society for Cognitive Psychology. He has published more than 185 peer-reviewed journal articles on attention, working memory, face processing, cross-modal integration and eye movements. He is widely known for his work on attentional and oculomotor capture. In addition to his basic research, he is an expert in traffic behavior and one of the principal advisors to the Dutch Department of Transportation.

Nicholas Turk-Browne is Assistant Professor and Lawrence S. Brodie Preceptor of Psychology at Princeton University. His NIH-funded research uses brain imaging and behavioral studies to explore interactions between multiple aspects of cognition in an effort to develop an integrated understanding of the mind and brain. In particular, he examines the interaction between perception (how we represent the current environment) and memory (how we store this experience for future use). As an example, he has published extensively on visual statistical learning, our ability to unconsciously extract regularities from experience. These and other studies have been published in journals such as Psychological Science, Neuron, and Proceedings of the National Academy of Sciences. Turk-Browne is the recipient of the James B. Grossman Dissertation Prize from Yale University and the Early Researcher Award from the American Psychological Association.

Emma Wampler is a graduate student in the Department of Psychology at the University of Washington. She received her B.A. in Neuroscience at the Kenyon College in 2009. Her research interests focus on language learning and learning to read.

Jeremy Wolfe graduated summa cum laude from Princeton in 1977 with a degree in Psychology and went on to obtain his Ph.D. in 1981 from MIT, studying with Richard Held. His PhD thesis was entitled "On Binocular Single Vision." Wolfe remained at MIT until 1991. During that period, he published papers on binocular rivalry, visual aftereffects, and accommodation. In the late 1980s, the focus of the lab shifted to visual attention. Since that time, his research has focused on visual search and visual attention with a particular interest in socially important search tasks in areas such as medical image perception (e.g. cancer screening) and security (e.g. baggage screening). In 1991, Wolfe moved to Brigham and Women's Hospital where he is Director of the Visual Attention Lab and the Center for Advanced Medical Imaging. At Harvard Medical School, he is Professor of Ophthalmology and Professor of Radiology. His work is currently funded by the US National Institutes of Health, the Office of Naval Research, Toshiba Corboration, and Google. He has published 127 peer-reviewed papers, 1 textbook, and 31 book chapters. Dr. Wolfe has taught Psychology courses at MIT & Harvard and is Past-President of the Eastern Psychological Association, President of Division 3 of the American Psychological Association, and editor of the journal Attention, Perception and Psychophysics. He won the Baker Memorial Prize for teaching at MIT in 1989. He is a fellow of the AAAS, the American Psychological Association (Div. 3 & 6), the American Psychological Society, and a member of the Society for Experimental Psychologists. He lives in Newton, Mass.

Steven Yantis is Professor and Chair of the Department of Psychological and Brain Sciences at Johns Hopkins University. He received a Ph.D. in Experimental Psychology at the University of Michigan in 1985, and following a year as postdoctoral fellow at Stanford University, he joined the JHU faculty in 1986. His research interests include selective attention and cognitive control.

Contents

Introduction

Michael D. Dodd and John H. Flowers

Abstract The 59th Annual Nebraska Symposium on Motivation (The Influence of Attention, Learning, and Motivation on Visual Search) took place April 7–8, 2011, on the University of Nebraska–Lincoln campus. The symposium brought together leading scholars who conduct research related to visual search at a variety levels for a series of talks, poster presentations, panel discussions, and numerous additional opportunities for intellectual exchange. The Symposium was also streamed online for the first time in the history of the event, allowing individuals from around the world to view the presentations and submit questions. The present volume is intended to both commemorate the event itself and to allow our speakers additional opportunity to address issues and current research that have since arisen. Each of the speakers (and, in some cases, their graduate students and post docs) has provided a chapter which both summarizes and expands on their original presentations. In this chapter, we sought to a) provide additional context as to how the Symposium came to be, b) discuss why we thought that this was an ideal time to organize a visual search symposium, and c) to briefly address recent trends and potential future directions in the field. We hope you find the volume both enjoyable and informative, and we thank the authors who have contributed a series of engaging chapters.

Given that the Nebraska Symposium on Motivation is considered one of the most influential and well revered symposium series in psychology and beyond, it will not come as a surprise to the reader to discover that the topics covered often reflect not just significant areas of research within the sciences, but also issues that are widely relevant and of interest to the public at large. A cursory examination of the titles of the symposia over the past decade reveals a number of gripping and instantly relatable topics: false memory, ethnicity and youth health disparities, emotion and the law,

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nicotine use, lesbian/gay/bisexual identity, prejudice and racism. As such, the goal of any symposium organizer and volume editor is to propose a topic that is substantial, interesting and easily relatable. To this end, there was never any question in our mind as to what the focus should be for the 59th annual Nebraska Symposium. Visual search is one of the most well researched topics of the past few decades and is one of the most, if not the most, ubiquitous behaviors that we engage in on a daily basis. Despite the importance of search to everyday functioning, however, it is noteworthy that the term "visual search" has not permeated the vocabulary of the public at large in any substantive way. Whereas numerous researchers across disciplines can immediately identify what visual search is, how important it is to our understanding of attention, and how it can be used to examine and inform numerous aspects of behavior, the term "visual search" does not have that same cache outside of the sciences. Despite this, everyone can instantly relate to the concept of visual search if you provide examples such as searching for your keys which you have misplaced; searching for a ripe piece of fruit in a supermarket; attempting to locate your car when you have forgotten where you have parked, and the nostalgia that accompanies the memory of searching for Waldo as a child (one of our volume contributors and Symposium speakers, Raymond Klein, was the first to use Where's Waldo displays when studying visual search in the laboratory). This creates an interesting conundrum: how can you convince an audience of the tremendous importance of visual search when very few people will actually be familiar with that term or realize that they engage in this behavior repeatedly throughout each day for the entire duration of their life?

At least part of the reason that the term "visual search" may not have caught on beyond the laboratory could be attributed to the fact that the earliest experimental paradigms for studying search could seem quite artificial. Participants would search for a sideways T amidst upright Ts and sideways Ls; or participants could be asked to detect whether a target letter appears in a stream of letters presented one at a time in a very rapid manner; alternatively it could be your goal to detect a red square in a display consisting of blue squares and red circles. These are not tasks that we ever find ourselves engaged with in the real world yet these early tasks provided important demonstrations of how attention and search success are influenced by factors such as target salience, the number and type of distractors in a display, and the relationship between targets and distractors. These concepts easily generalize to the real world even if they do not appear to at first blush: finding the ripest banana is quite easy if the majority of other bananas you are searching through are green but this task becomes considerably more difficult if most of the bananas you are looking through are yellow; finding a car in a parking lot is daunting if you have no idea where you parked, but will be considerably easier if you can remember the general area in which you parked and narrow your efforts to that specific region. It will be easier still if your car is bright red and the majority of other cars in the parking lots are black or blue. The reason Where's Waldo tasks are both challenging and rewarding is that they are designed to be particularly difficult based on what we have previously learned about search from these laboratory paradigms: the greater the number of distractors, the more difficult it will be to find Waldo; as the similarity between the target (Waldo) and the distractors (everything else) increases, so too does task difficulty (which explains why so many other characters and background items in a Where's Waldo book appear in the colors red and white... if everything else was purple and green it would be easy to detect our bespectacled friend). As such, the vast majority of individuals are intuitively aware of the factors that can make search easy or difficult, even if they have not heard the term "visual search" before.

Though the earliest visual search paradigms could seem artificial, they were exceptionally well controlled and provided a great deal of invaluable information into the factors that can influence search. Over time, various advancements have afforded researchers the opportunity to study search in a variety of different contexts. These include *technological* advances that allow much greater control of the timing and complexity of visual displays, and the simultaneous collection of multiple streams of behavioral and brain activity data. They also include advancement in our understanding of the relationship between *neurological processes and behavior* that point to potentially important relationships between such factors as motivation, memory, and reinforcement history and the manner in which visual search is carried out. As a consequence of these developments, search displays will now routinely consist of more realistic scenes, both static and dynamic, that are more akin to what we experience in the real world. Eyetracking technology has made it possible to study the manner in which individuals search in more naturalistic settings whereas advancements in neuroimaging have made it possible to determine the biological and cognitive processes engaged during search. With each new advancement and each new study, however, it has become increasingly clear that a staggering number of factors influence attention and search beyond those that were identified in earlier research. Moreover, it has also become clear that the importance of attention and search extends beyond the target-directed examples we have provided above. At a basic level, visual search is the process through which attention is allocated throughout the environment in order to process information that is relevant to an individual's goals or interests while simultaneously ignoring information that is irrelevant at best and potentially distracting at worst. In this way, the vast majority of visual tasks we perform are some form of search task. Watching television requires the viewer to focus attention on task relevant stimuli (the television) while ignoring irrelevant stimuli. The act of driving requires continuous shifts of attention to relevant stimuli (such as traffic lights, pedestrians, and street signs) and an attempt to block out potentially distracting stimuli (e.g. billboards, one's cellphone). Even reading this introduction requires the continuous movement of attention to specific stimuli (the words on the page) so as to extract relevant information while simultaneously ignoring other items in your environment that could attract attention. In this way one could argue that the vast majority of all visual behaviors are a form of search and an understanding of these behaviors—and how to make them efficient—can only be gleaned by considering the many different factors that influence search at multiple levels.

Given that visual search encompasses a variety of behaviors and is influenced by a staggering number of variables, our goal in putting together the symposium was to not merely invite scholars who are best known for doing research on visual search. Rather, we sought to bring together individuals who engage in research at a number of different levels relevant to search. As such, we scholars who study attention and search in both laboratory and applied settings; individuals who do not study search per se but study factors that are highly related to search performance (e.g. motivation/reward, statistical learning); individuals who study cognitive mechanisms which greatly influence the manner in which search is conducted (e.g. eye movements, object representation, memory and knowledge). In this volume alone you will read about a number of factors relating to search which are currently being studied such as a) selection in space and time (Klein), b) automatic processes (Theeuwes), c) the role of scene perception, scene memory, and schematic knowledge (Hollingworth), d) motivation/reward (Yantis), e) statistical learning (Turk-Browne), and f) satisfaction of search (Mitroff), and g) search termination (Wolfe).

In summary, the goal of the symposium was twofold. We sought to take stock of where we currently are in the study of search and how our understanding can be increased across a variety of areas but we also hoped to provide some insight into how our understanding of search will be shaped by future research and what questions seem likely to develop in the future. It seems clear that emerging technology involving visual displays of information for a wide variety of applications will make the study of search processes an important topic for applied research. While the precise role that visual search tasks will play in future research in cognitive psychology and neuroscience is somewhat more difficult to predict, the presentations of this symposium suggest that studying search behavior, in conjunction with applying other tools for assessing cognitive and behavioral activity, will continue to be a useful endeavor.

Searching in Space and in Time

Raymond M. Klein and Yoko Ishigami

Abstract Our conception of attention is intricately linked to limited processing capacity and the consequent requirement to select, in both space and time, what objects and actions will have access to these limited resources. Seminal studies by Treisman (*Cognitive Psychology*, *12*, 97–136, 1980) and Broadbent (*Perception and Psychophysics*, *42*, 105–113, 1987; Raymond et al. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 849–860, 1992) offered the field tasks for exploring the properties of attention when searching in space and time. After describing the natural history of a search episode we briefly review some of these properties. We end with the question: Is there one attentional "beam" that operates in both space and time to integrate features into objects? We sought an answer by exploring the distribution of errors when the same participant searched for targets presented at the same location with items distributed over time (McLean et al. *Quarterly Journal of Experimental Psychology, 35A,* 171–186, 1982) and presented all at once with items distributed over space (Snyder *Journal of Experimental Psychology, 92,* 428–431, 1972). Preliminary results revealed a null correlation between spatial and temporal slippage suggesting separate selection mechanisms in these two domains.

Keywords Attention · Limited processing capacity · Selection · Space · Time · Attentional blink

The concept of attention is at the nexus of search behavior. Two related aspects of attention are critical: limited processing capacity and the consequent requirement to select in space and time where and when to allocate our limited resources. The concept of selective attention both entails and represents these two related ideas. Attention may be captured by the target or by salient distractors. Lacking capture by the target, attention may be allocated individually to potential targets to allow information processes to determine whether these items are what we are looking for. It is the sine qua non of "limited capacity" that when mental processes are allocated to some things (e.g., items during search) they become less available for other activities.

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The scientific study of search behavior is motivated by both basic and applied research questions. Basic research has been preoccupied by two inter-related efforts: Using studies of search to reveal the properties of attention and to reveal the nature of object recognition. Several "basic" questions are suggested by the combination of these efforts. For example, What is the nature of the limited capacity mechanisms that are captured or deliberately allocated when we search? What is the role of these mechanisms in the construction of object representations? And, What is the role of objects and object properties in the control of attention.

Basic research on search behavior has led to fundamental principles (Treisman and Gelade 1980; Wolfe et al. 1989) and empirical generalizations (e.g., Duncan and Humphreys 1989; Wolfe 1998) that can be used to characterize and improve real-world search behavior (e.g., Berbaum et al. 1990; Wolfe et al. 2007). This kind of applied psychological science was a pre-occupation of Donald Broadbent, who is inextricably linked to the archetypical theory of attention that often bears his name ("Broadbent's Filter Theory", Broadbent 1958). And while we know that his theory, which provides a departure point for so many subsequent theories of attention, is wrong in detail, it is a fitting tribute to Broadbent's applied inclinations that Neville Moray (1993) would later say of Broadbent's filter theory that: "Whatever the deep structure of attention may be, its surface performance is, in the vast majority of cases, well described by a single, limited capacity channel" (page 113). Consequently, from an applied perspective we can not only aim to improve search performance per se but also to decrease the demands it places on limited capacity resources.

A Taxonomy of Attention

With roots in a program of research begun by Michael **Posner** over 40 years ago (Posner and Boies 1971) three isolable functions of attention—alertness, orienting, and executive control—have been identified and linked to specific neural networks (Posner and Peterson 1990; Fan et al. 2005). In the domain of space, where selection has been referred to as orienting and most of the research has been on visual orienting, two important distinctions were first made by Posner (1980) and have since been highlighted in work from Klein's laboratory (for a review, see Klein 2009). One concerns whether selection is accomplished by an overt reorientation of the receptor surface (an eye movement) or by a covert reorientation of internal information processing mechanisms. The other concerns whether the eye movement system or attention is controlled primarily by exogenous (often characterized as bottom-up or reflexive) means or by endogenous (often characterized as top-down or voluntary) means.

Helmholtz provided the first demonstration that attention could be shifted covertly and consequently independently of the direction of gaze. When control is purely endogenous, (Klein 1980; Klein and Pontefract 1994) and others (e.g., Hunt and Kingstone 2003; Schall and Thompson 2011) have demonstrated that such shifts of

Fig. 1 A taxonomy of attention proposed by Klein and Lawrence (2011)

		Mode of allocation	
		Exogenous	Endogenous
Domain of allocation	Space		
	Time		
	Sense		
	Task		

attention are not accomplished via sub-threshold programming of the oculomotor system. On the other hand, when orienting is controlled exogenously, by bottom-up stimulation, it is difficult to disentangle activation of covert orienting from activation of the oculomotor programs.

In the domain of covert orienting, Klein has emphasized the importance of distinguishing between whether control is (primarily) endogenous or exogenous because different resources or mechanisms seem to be recruited to the selected location or object when the two different control systems are employed. This assertion was first supported by the following double dissociation: (1) When exogenously controlled, attention interacts with opportunities for illusory conjunctions and is additive with non-spatial expectancies, and (2) when endogenously controlled, attention is additive with opportunities for illusory conjunctions and interacts with non-spatial expectancies (Briand and Klein 1987; Briand 1998; Handy et al. 2001; Klein and Hansen 1990; Klein 1994). Several other dissociations discovered by others reinforce Klein's conclusion that different resources are recruited when orienting is controlled endogenously versus exogenously (for reviews, see Klein 2004, 2009).

Thinking about the importance of this distinction in the world of orienting led Klein and Lawrence to propose an alternative taxonomy (Klein and Lawrence 2011), illustrated in Fig. 1, in which two modes of control (endogenous and exogenous) operate in different domains time, space, modality, task, etc.). Searching entails the endogenous and exogenous control of attention in space and time. In contrast to the literature using Posner's cuing paradigm, however, in typical search tasks the endogenous/exogenous distinction is often not made explicit. In spatial search, for example, perhaps this is because even when search is hard (the target does not exogenously capture attention) we typically do not experience volitional control of the search process—of the sequence of decisions about where to look next for the target. It has been suggested that these "decisions" are typically made by low-level subroutines (Klein and Dukewich 2006). It seems likely that the endogenous control of search is instantiated before the search episode begins based on the observer's knowledge about properties of the target (setting up a template matching process) and distractors (e.g. establishing attentional control settings to implement guided search).

Natural History of a Search Episode

A typical search episode begins with some specification of what the target is; usually some information about the nature of the material to be searched through for the target; perhaps some useful information on how to find it; and, critically, what to do when it is found. The human searcher is thought to incorporate these tasks- or goal-oriented elements into a mental set, program or strategy so that their performance will optimize their payoffs. In Broadbent's theory (1958) an important component of this process was "setting the filter" so that task-relevant items (targets) would have access to limited capacity processing mechanisms while task irrelevant items would be excluded. Duncan (1981) would later provide a useful recasting of Broadbent's ideas. Instead of "filtering" he referred to a "selection schedule" and, recognizing the many empirical demonstrations that an unselected stimulus could nevertheless activate complex internal representations, he suggested that the limitation has more to do with availability for reporting an item than the quality or nature of an item's internal representation. We see subsequently proposed endogenous control mechanisms such as attentional control settings (ACS) (Folk et al. 1992) and "task-set reconfiguration" (Monsel 1996) as firmly rooted in these earlier ideas.

During the search episode the efficient performer must represent the target and the feature(s) that will distinguish the target from the distractors. Representations activated by the spatial search array or temporal search stream are compared against these representations to determine if the target is present and if so to report its properties according to observer's goals. This comparison process might take place one at a time or in parallel across the items in the search array or stream.

Two paradigms for exploring the information processing dynamics of searching will be emphasized in this chapter. These paradigms were developed to study, in relatively pure form, searching in space and in time. Searching in space entails the allocation of attention to items distributed in space and presented at the same time. Searching in time entails the allocation of attention to items distributed in time and presented at the same location. With a few exceptions (e.g., Arend et al. 2009; Keele et al. 1988; McLean et al. 1982; Vul and Rich 2010) searching in space and time has been studied separately, usually in studies with a similar objective: understanding the role of attention in detecting, identifying, or localizing targets. We believe that it will be empirically fruitful and theoretically timely for these somewhat separate efforts to be combined. And, it will be useful, because in the real world searching often combines these two pure forms.

Searching in Space

There are many studies from before 1980 that used a wide variety of spatial search tasks, The spatial search paradigm emphasized here (see Fig. 2) was imbued with excitement by Anne **Treisman's** (Treisman and Gelade 1980; Treisman and Schmidt 1982) use of it to provide support for her feature integration theory in which spatial

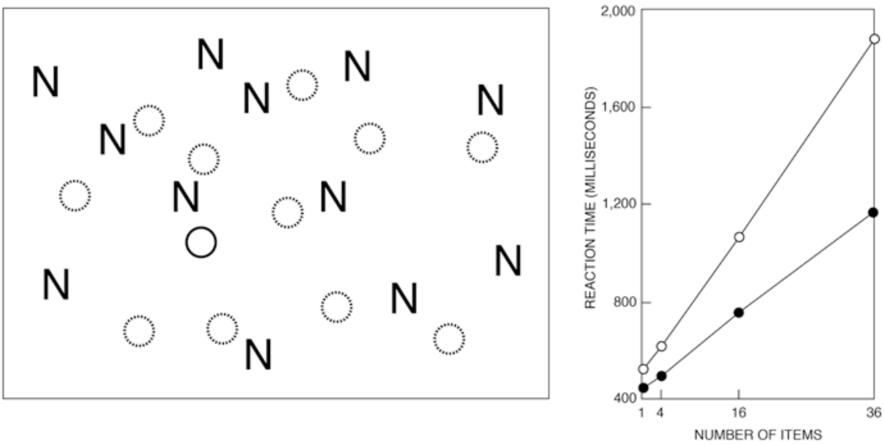

Fig. 2 A prototypical "present/absent" search task (is there a solid "O" in the display?) is illustrated on the *left*. Typical results illustrated on the *right* showing reaction time to make the decision (*open symbols* = target absent trials; *filled symbols* = target present trials) as a function of the number of items in the display. (Adapted from Treisman 1986)

attention is the binding agent for otherwise free-floating features. When observers are asked to indicate whether a target is present in an array of distractors, two dramatically different patterns are frequently reported. In one case (i.e., difficult search—target is not defined by a single unique feature), illustrated in Fig. 2, reaction time for both target absent and target present trials is a roughly linear function of the number of distractors and the slope for the target absent trials is approximately twice that of the present trials. This pattern is intuitively compatible with (indeed predicted by) a serial self-terminating search (SSTS) process in which each item (or small groups of items) is compared against a representation of the target and this process is repeated until a match is found or until the array has been exhausted. In the other case (not illustrated) (i.e., easy search—target is defined by a single unique feature), reaction time is unaffected by the number of distractor items. Phenomenologically, instead of having to search for the target, it "pops out" of the array.

This model task and the theory Treisman inferred from its use have been remarkably fruitful in generating: modifications of the model task (e.g., the preview-search paradigm of Watson and Humphreys 1997; the dynamic search paradigm of Horowitz and Wolfe 1998), theoretical debates (such as: are so-called "serial" search patterns like that illustrated in Fig. 2 caused by truly sequential or by parallel processes; and, when search is a sequential process of inspections, how much memory is there about rejected distractors, see Klein and Dukewich 2006, for a review), empirical generalizations (e.g., Wolfe's 1998, review; the search surface of Duncan and Humphreys 1989), and conceptual contributions (e.g., the guided search proposal of Wolfe et al. 1989; the foraging facilitator proposal of Klein 1988).

The model task and the theory of Treisman encouraged Klein and Dukewich (2006) to address the question whether search is primarily driven by serial or parallel mechanisms. While rooted in basic research on spatial search, we believe that their advice applies equally to searching in time and to real-world search behavior:

> When there is more than one good strategy to solve a problem it seems reasonable to assume that nature may have figured out a way to take advantage of both. . . .We recommend that future research seek to determine, rather than which strategy characterizes search, "when" and "how" the two strategies combine. (Klein and Dukewich 2006, p. 651)

Searching in Time

In the mid-1960's Molly **Potter** discovered that people could read when the text was presented using rapid serial visual presentation (RSVP), that is with words presented one after the other at the same location in a rapid sequence. A few decades later this mode of stimulus presentation began to be used as a tool for exploring the consequences of limited processing capacity, particularly for dealing with multiple "targets" in streams of unrelated items (Broadbent and Broadbent 1987; Weichselgartner and Sperling 1987). Broadbent and Broadbent (1987), for example, showed how difficult it is to identify two targets when they are in close succession.

The difficulty identifying subsequent items after successfully identifying an earlier one was subsequently named an "attentional blink" by Raymond et al. (1992). The blink and the task for exploring it that was developed by **Broadbent, Raymond** and **Shapiro** propelled this paradigm to the center stage of attention research. In the seminal paradigm of Raymond et al. (1992) (see Fig. 3, left/bottom), multiple letters are presented rapidly and sequentially at the same location (in RSVP). In the sequence of letters, all but one of which are black, there are two targets (separated by varying numbers of distractors) and the observer has two tasks: Report the identity of the white letter and report if there was an X in the stream of letters after the white letter.

One possible weakness of this particular paradigm (often called "detect X") is that the "blink" it generates and measures may have quite different sources: double speeded identification and switching the mental set (the selection schedule or filter setting) from color to form ("white" to "X"). A more general paradigm (that is more like Broadbent's) is often used to avoid such switching. Chun and Potter (1995) used one version of this paradigm (Fig. 3, right/top) in which the observers task is to report the identity of two letter targets that are embedded in a stream of digits.

As with the spatial search paradigm, these methods for exploring "searching in time" using one or more targets embedded in a stream of rapidly presented items, have been remarkably fruitful in generating: modifications of the model task, theoretical debates, empirical generalizations, and conceptual contributions (e.g., Dux and Marios 2009 for a review).

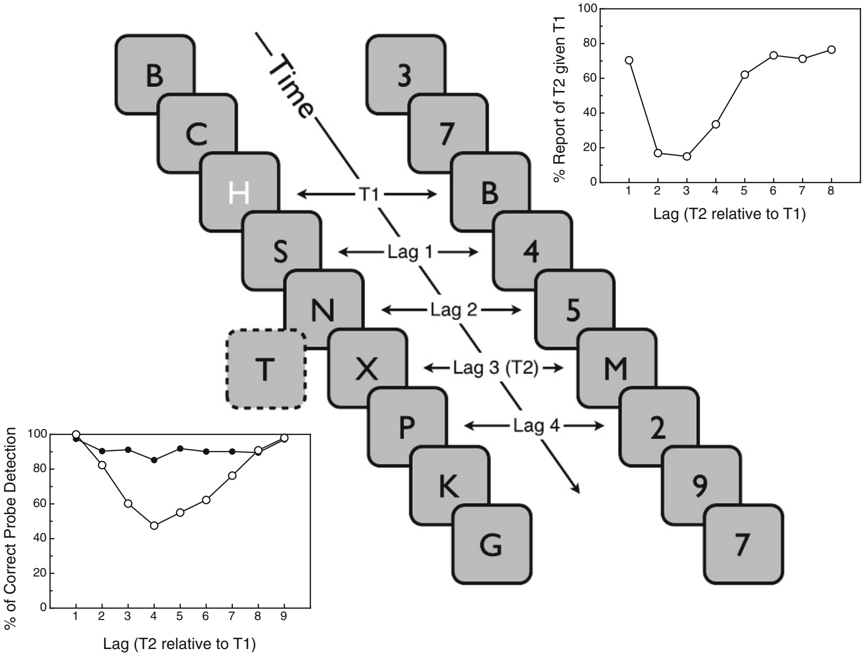

Fig. 3 Two different methods that have been used to explore the attentional blink. Both entail presenting a sequence of individual alphanumeric items using RSVP (with about 100 ms separating item onsets). The stream on the *left* illustrates the "detect-X" task pioneered by Raymond et al. (1992). After a random number of black letters the first target, a white letter (T1), is displayed. Then, at varying lags after the presentation of T1 an X (T2 or probe) might or might not (this alternative is shown in the *box* with the *dashed line*) be presented. At the end of the stream the observer reports the identity of the white letter and whether or not an X had appeared in the stream. Typical results from this task are shown in the inset at the bottom. *Open symbols* show the probability of correctly reporting that an X was present as a function of its position following a white letter when that letter had been correctly identified. *Filled symbols* show the same results when there was no requirement to report the white letter. The stream on the *right* illustrates the paradigm developed by Chun and Potter (1995) and used by many others. Here there is a stream of items in one category (digits) in which two targets from another category (letters) are embedded. At the end of the stream the observer's task is to report the identities of the two targets. Typical results (accuracy of T2 reports when T1 was identified correctly) are shown in the inset at the top

Searching in Space and Time: Some Comparisons

The Nature of the Stimuli

It seems likely that if a certain kind of stimulus pops out in a spatial search it might also do so in temporal search and vice versa. Duncan and Humphreys (1989) identified two principles that interact in determining the difficulty of searching in space for a target among distractors. One factor is: How similar is the target to the distractors?