CHAPTER 13

Visual Search

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WHY DO WE SEARCH?

Broadly defined, *visual search* is the act of looking for something or a number of things. It is reasonable, at the start of a survey of the topic, to ask why we have to search at all. Part of the answer is obvious, part is more involved, and all of the answer has to do with the fact that we are creatures with limitations. To begin with the obvious, our eyes are seeing only part of the world around us at the present moment. The world extends 360 degrees around our heads, but our eyes have a visual field of a bit over 180 degrees in the horizontal dimension and, depending on the configuration of our faces, about 90 degrees in the vertical dimension. If the target of search is outside the current visual field, we will need to move to point our eyes in the right direction.

Within that large visual field, processing is hugely uneven. In the fovea, each individual photoreceptor commands what amounts to its own optic nerve fiber. If there were one optic nerve fiber for every photoreceptor in the retina, the optic nerve would be too fat to be practical. This constraint and others result in extensive pooling of information in the peripheral visual field. As a result, visual resolution falls off dramatically as we move away from the fovea (Green, 1970). If detection requires more than very coarse processing—for example, if one wants to read any letter on this page—the target must be brought to the fovea by moving the eyes. It is important to note that while fixation of the targets of search is common and often necessary, it is not required in all cases. Targets can be detected in peripheral vision as long as their defining features can be resolved in peripheral vision. Indeed, many studies of search involve requiring observers to hold fixation at one point while targets and distractors are presented at peripheral locations (e.g., Braun & Julesz, 1998; Carrasco, Evert, Chang, & Katz, 1995; Wolfe, O'Neill, & Bennett, 1998). On the right side of Figure 13.1, if you fixate on the central "x," you should be able to search successfully for the letter "c" without moving your eyes. When a basketball player is praised for his peripheral vision, this does not mean that he can read the newspaper 15 degrees from fixation. It is more likely to mean that he has trained himself to fixate at one location while successfully searching for the receiver of his next pass by deploying his attention to his peripheral visual field.

The decline in resolution is only part of the problem in peripheral vision. Targets that are large enough to be resolved may still be difficult or impossible to identify in peripheral vision because of the crowding effects of other, nearby contours (Levi, Klein, & Aitsebaomo, 1985). If you look at the "x" at the center of the array on the left of

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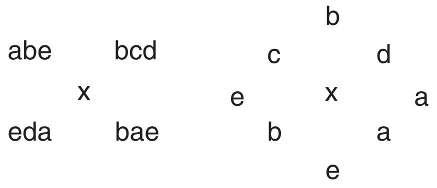

Figure 13.1 While fixating on the “x,” it is much easier to find the “c” in the right-hand display than in the left.

Figure 13.1, you will find it hard to find the letter “c.” If you look at the “x” on the right, you will find that it is much easier to find the “c.” In part this is because there are 12 letters on the left and only 8 on the right, but the primary cause is that the nearby flanking letters make the target “c” in peripheral vision difficult to resolve. There are a number of useful reviews of the phenomenon of crowding (Levi, 2008, 2011; Pelli & Tillman, 2008; Whitney & Levi, 2011). For present purposes, crowding represents another limitation on our processing abilities that makes it necessary to search (Rosenholtz, Huang, & Ehinger, 2012; Wertheim, Hooge, Krikke, & Johnson, 2006).

Perhaps the most interesting limitation on our capabilities emerges if we search for targets whose detectability is not limited by the borders of the visual field, distance from fixation, or crowding. This can be illustrated if you search in Figure 13.2 for the plus that has a green (darker) vertical component and a purple (lighter) horizontal component. Holding fixation on the central “x,” you should be convinced that you can find the target without needing to fixate on the item. At the same time, introspection should convince you that this task does require covert search. While it is immediately obvious that the display consists of green (darker) and purple (lighter) pluses, it is not clear how orientations and colors are bound together in any particular plus until that plus is scrutinized, even if it is scrutinized without fixating on it directly.

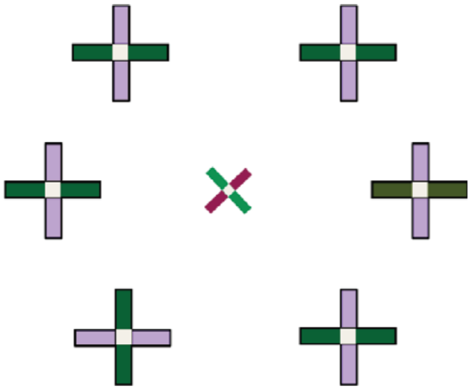

Figure 13.2 The binding problem: Search for the target with green (darker) vertical and purple (lighter) horizontal components.

The Binding Problem

Figure 13.2 is an illustration of the “binding problem” (Roskies, 1999; Treisman, 1986b, 1996; von der Malsburg, 1981; Wolfe & Cave, 1999). The idea that there might be a problem arose from the work that showed that different portions of the visual cortex appeared specialized for different functions (e.g., Hubel & Livingstone, 1987). If color was processed in one area and orientation was processed in another, how did the organism as a whole know that a region of a particular orientation possessed a particular color? Treisman argued that visual selective attention to a region was needed to bind the features together. Indeed, Treisman’s original thought was that, in the absence of attention, features were “free floating” (Treisman & Gelade, 1980). Illusory conjunctions were her classic evidence for this idea.

Figure 13.3 illustrates the phenomenon, albeit without appropriate experimental controls. Look briefly at the figure and then return to the text. Can you confirm the presence of a blue “D” or a green “C” or of an F in diamond? In fact, the green C is present but the D is red and the F is in a triangle.

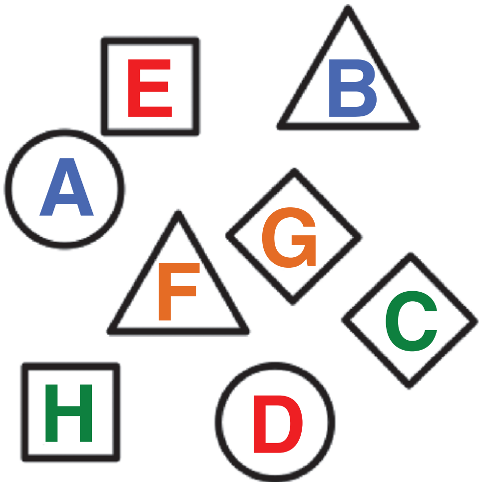

Figure 13.3 The binding problem: Look briefly at this figure and return to the text.

The colors will be available only online, but if you are reasonably convinced that you saw a D that was not red or a C that was not green or an F that was not in a triangle, you have experienced an illusory conjunction. For Treisman, illusory conjunctions were evidence that the features were unbound. Others argued that they might have been bound but then forgotten (Tsal, 1989). Others noted that these sorts of illusory conjunctions were not limited to basic features. They could be seen, for example, in word formation (Mozer, 1983) or in the attachment of colors to words (Virzi & Egeth, 1984). Though research has shown that the phenomenon is more complex (for a review see Burwick, 2014), illusory conjunctions do illustrate that the connections between attributes of an object are not necessarily clear before or after that object is the current focus of attention. Treisman's central observation about the binding problem remains valid; object identification generally requires an appreciation of the relationship of different attributes of that object. This binding of attributes requires attention. As a consequence, identification of a specific object requires that attention be directed to that object. Hence, we need to search. For much of the rest of this chapter, we will be concerned with explaining why, if this is so, we do not search at random. Given a need to search, much of the work of our human search engine is devoted to making that search as efficient as possible.

The need to bind is not the only reason that we need to search. Returning to Figure 13.2, if you are viewing this online and the color reproduction is good, you will be able to find the one plus showing a different, yellower shade of green. This was not obvious to you in the absence of attentional scrutiny and illustrates the fact that attention allows observers to appreciate more subtle perceptual distinctions (Yeshurun & Carrasco, 1998). It also improves spatial discrimination (Yeshurun & Carrasco, 1999) and allows for the individuation of items whose features might otherwise be averaged together (Intriligator & Cavanagh, 2001). Indeed, you may find that the very qualia of the stimuli change with the application of attention (Carrasco, Ling, & Read, 2004). These are not binding functions, but they, too, represent cases where search would be required to find a specific target (e.g., the item with that specific shade of green).

A WORD ABOUT ARCHITECTURE AND TERMINOLOGY

Preattentive

Consider Figure 13.2 once more. It is introspectively clear that, on first glance, we can perceive that the display consists of purple and green pluses. It is also clear that the identity of any one item as a purple-vertical or green-vertical version is not immediately available but requires search. This introspection is described at least as early as the 18th century by the French philosopher Condillac (1781). Several important conclusions follow.

First, given that it can take a measurable amount of time before a plus is selected by attention and identified as, say, a green vertical version, and given that *something* is seen at that location before attention arrives, it makes sense to talk about *preattentive* processing. Defined in this manner, the term is nearly tautological. If there is spatially selective attention and if there are items that have not yet been selected, there simply must be some sort of preattentive processing. Nevertheless, the term has been controversial (Di Lollo, 2012a; DiLollo, Kawahara, Zuvic, & Visser, 2001; Hochstein & Ahissar, 2002) because it often comes with other theoretical assumptions attached. Building on earlier ideas like those of Broadbent (1958), Neisser's (1967) formulation had two distinct stages: preattentive and attentive. With the rise of modern research on visual cortical physiology, there also arose an unfortunate, geographically concrete account in which it was assumed that some pieces of brain were "preattentive" processors of single basic features like color or orientation whereas other, later, areas were "attentive." The binding problem, as conceived by von der Malsburg (1981), could be described as the problem of binding together activity in two or more preattentive loci in the brain. As Di Lollo (2012a) points out, a strong form of this view cannot survive the evidence that many areas process multiple features simultaneously. Nor can preattentive geography survive the evidence that massive feedback connections make simple feed-forward, preattentive-to-attentive stories implausible. Attention modulates even the earliest stages of visual cortical processing (Gandhi, Heeger, & Boynton, 1998; Wurtz & Mohler, 1976). It is more profitable to use "preattentive" to describe the *type* of processing that occurs before selective attention is deployed and not to use the term to describe a preattentive piece of the brain. At the very least, it is important to acknowledge that the neural locus of preattentive processing may be a locus of attentive processing moments later.

If there is such a process as spatially selective visual attention, then the processing of an item is preattentive before it is selected, and, it is worth noting, the processing of that item will become "postattentive" once selective attention has moved on to another item or location (Wolfe, Klempen, & Dahlen, 2000). The nature of postattentive vision has been much less studied than the nature of the preattentive representation, but it is worth thinking about in the context of the framework discussed so far. If an object must be selected in order for its features to be bound and for the object to be recognized, does that binding survive the departure of attention? This topic will be considered later in this chapter.

Spatially Selective Visual Attention

Do we need the concept of spatially selective visual attention? Why not propose that binding of features and recognition of objects occurs everywhere at once, limited only by the limits on peripheral vision (acuity, crowding, etc.) and, perhaps, by the time required to accumulate enough information to support recognition? The answer is that we lack the capacity. Tsotsos argues that this is a fundamental computational constraint; that the brain is simply not big enough and cannot be big enough to process everything in parallel across the visual field (Tsotsos, 1990, 2011). Object recognition involves two massively parallel processes. As Condillac (1781) noted, we can process some visual attributes across the whole visual field in parallel. Object recognition must also represent a massively parallel process in which a representation of a visual object is matched against the vast set of representations of objects held in memory. What is not possible is the simultaneous matching of all items/regions in the visual world with all items in memory. In this context, binding can be thought of as part of this matching process, building a representation that can be matched against the contents of memory. A more primitive sort of binding seems to occur without attention (Houck and Hoffman, 1986). It can be thought of as the simple co-occurrence of two features (e.g., vertical and green) in the same place, perhaps activating the same neurons, but not supporting recognition in the absence of attention.

Between the parallel front end of visual processing and the parallel identification of an object, there is a very tight bottleneck that allows one or, perhaps, a small number of objects to be identified at one time. Selective attention is the name we give to the process that governs access to this bottleneck. Figure 13.4 gives an illustration of this bottleneck (albeit one that could be explained in other terms). If you fixate on each "x" from top to bottom, you can read either the words on the left or on the right or you can read both sides in succession. However, it should be clear that you cannot read both phrases simultaneously.

Global Attention and Multiple Attentions

Perhaps we can still dispense with the notions of preattentive and attentive processing if we label all vision as "attentive" and propose that what varies is only the degree to which attention is spread over more or less of the stimulus. Treisman and Gormican (1988) proposed something like this when they argued that "So-called preattentive search is really search in which attention is distributed widely over the whole display" (p. 43) (see also Nakayama & Joseph, 1998). This is a version of a "zoom-lens" theory of attention (Eriksen & St. James, 1986). However, when attention is directed to a specific item or location, the rest of the world does not vanish, so one would need to propose global and selective attention at the same time. Di Lollo (2012b) would argue that, at this point, one should simply "avoid the use of such a nebulous and ill-defined concept as 'attention'" (p. 308) and, with regard to the term *global attention* he may be right. More generally, however, it is useful to remember that attention is not a thing or a single process with a specific locus in the brain. It is what we call the family of selective processes in the nervous system. Just as we cannot recognize every visible object at once, we cope with a host of other capacity limitations by means of various different attentional processes. You cannot simultaneously process two speech streams at the same time (Cherry, 1953). Auditory attention mediates that limitation (Shamma, Elhilali, & Micheyl, 2011). Until it is mentioned here and now, you have not been aware of the point of contact between your body and whatever you are sitting on (if you are sitting). See Stein (2012) for an extended treatment of multisensory attention. Examples of the multiple forms of attention could be multiplied; see Chun, Golomb, and Turk-Browne (2011) for a fine taxonomy. In this chapter, unless otherwise specified, the term *attention* will be shorthand for the spatially selective visual attention that allows some visual information to be bound and allows objects to be recognized.

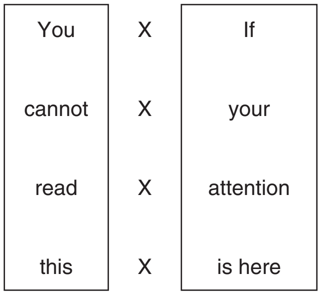

Figure 13.4 Move your eyes from x to x, top to bottom, while trying to read left and right phrases at the same time.

CLASSIC VISUAL SEARCH TASKS: STIMULI AND METHODS

To briefly recap, we have to search because we lack the capacity to simultaneously identify everything in the visual field in a single step. In the world, we search continuously for specific objects (Where is my iPhone?), for resources (e.g., dinner in the wild or in the supermarket), for threats (What path shall I pick through this dangerous-looking neighborhood?), and so forth. These complex tasks have been simplified and schematized into a family of laboratory visual search tasks.

Classic search tasks involve search for a target in an array of clearly individuated items presented on an otherwise blank background. In early experiments, these were often alphanumeric characters, presented in orderly arrays (Egeth, 1967; Green & Anderson, 1956; Neisser & Beller, 1965). We tend to think of alphanumeric characters as simple stimuli, but they are complex shapes, so when interest began to focus on the nature of preattentive visual processing, classic search displays became arrays of even simpler shapes (colored bars and the like), often presented in quasirandom arrays or on a circle at a fixed distance from fixation. Originally, these might be drawn by hand and presented in a tachistoscope (Treisman & Gelade, 1980). The advent of computer graphics vastly simplified the creation of experiments of this sort (Enns, Ochs, & Rensink, 1990).

Accuracy Methods

There are typically two behavioral measures of interest in classic search tasks: response time or reaction time (RT in either case) and accuracy. In a typical RT study, stimuli are presented until the observer responds. The number of items in the display (the set size) is varied from trial to trial, and the RT × set size function is analyzed (Treisman & Gelade, 1980). Accuracy is tracked but usually merely to ensure that the error rates are not so high that they would call the RTs into question. As error rates rise in these tasks, RTs decline: a "speed-accuracy trade-off" (SAT; Heitz, 2014; Henmon, 1911) that can distort the shape of RT × set size functions. In experiments that focus on accuracy, the stimuli are often presented very briefly, preventing any role for voluntary eye movements if the presentation is less than about 200 ms. In many cases, the stimuli are masked with another visual stimulus after presentation to strictly limit the amount of time that the stimulus is available. Again, set size can be varied and the accuracy × set size function becomes the measure of interest (Bergen & Julesz, 1983a, 1983b). Alternatively, the duration of the stimulus can be varied and accuracy can be measured as a function of that duration. Refining the latter method, one might determine how long the stimulus needs to be visible in order to obtain some threshold level of performance (e.g., 80% correct). That threshold could then be measured for different search tasks. For instance, using this method, Verghese and Nakayama (1994) measured the time required to detect a difference in orientation between target and distractor lines. The bigger the orientation difference, the smaller the required duration.

The great virtue of the brief-exposure–accuracy methods is the degree of control they offer over the visual input. For example, John Palmer performed experiments where a fixed set of items was presented on the screen. The effective set size was varied by identifying a relevant subset of locations at the start of each trial. In this way, every trial could have the same items in the same locations for the same length of time on each trial (J. Palmer, 1994, 1995; J. Palmer, Ames, & Lindsey, 1993) (see also Grindley & Townsend, 1968). These methods convert search tasks into well-controlled, two-alternative, forced-choice psychophysical experiments, making them amenable to analysis by the tools of signal detection theory (Verghese, 2001). The drawback is that the methods and stimuli are quite removed from real-world search tasks. All laboratory tasks are abstractions of some real-world question. These methods are, perhaps, more abstract than most. They are most effective in their ability to shed light on the effects of attention on the initial phase of processing.

One useful version of brief-exposure–accuracy methods is the speed-accuracy trade-off (SAT) approach. The SAT was mentioned previously as a problematic factor that could be distorting RT measures, but it can also be exploited deliberately. For instance, observers can be taught to respond within a narrow temporal window after the onset of the stimuli. The response window is indicated by a cue. By varying the timing of this response cue, an SAT function can be generated. It will rise from chance, when observers must respond too quickly to some asymptotic, best performance for that stimulus. The shape of this function is diagnostic of the type of processing occurring. For instance, models with serial components predict changes in the rising portion of the SAT curve. As set size increases, the curve rises more slowly because the chance of finding the target in some fixed time declines as set size increases (Dosher, 1976; Dosher, Han, & Lu, 2004; McElree & Carrasco, 1999), and the results have been generally consistent with parallel processing of multiple items in the initial milliseconds of search. The method is not well suited to seeing any subsequent serial deployments of attention.

RT Methods

Reaction time or response time (RT) methods come a bit closer to the normal experience of search. Typically, observers search for a target among a variable number of distractor items. The stimulus is usually present until response is made. The response might be a two-alternative, presence/absence judgment or a localization response in which the observer must indicate the location and not just the presence of a target. Observers are typically tested for several hundred trials. To conduct 50 trials per data point is not a bad rule of thumb. Thus, 3 set sizes × target present/absent yields 6 data points as shown in the RT × set size functions cartooned in Figure 13.5. A standard experiment might have 10 to 12 observers, each performing 300 trials (obviously, details vary).

Accuracy is measured, but usually in the hopes of being able to say that the error rates are low enough to have only modest impact on the RT × set size functions. In the classic analysis of these functions, the slope gives the most interesting information about search. It is a measure of the rate at which items can be processed. The intercept is a measure of the time required for nonsearch processes (e.g., the act of making a response) (Posner, 1978).

If all items can be processed in parallel without capacity limitations, the slope of the RT × set size function would be expected to be zero ms/item. If items are processed in series, one after the other, then the RT would increase linearly with the number of

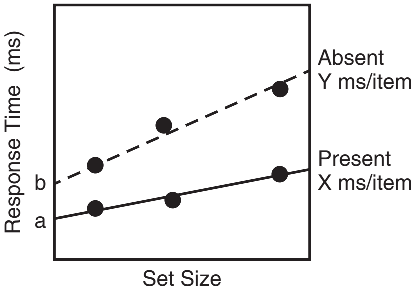

Figure 13.5 Hypothetical data from a search experiment using RT methods.

items in the display. In the simplest case of a serial, self-terminating search, the slope on the target-present trials would be half the time required to process as a single item. If items are sampled randomly, observers will, on average, sample half of the items before stumbling on the target. If target-absent trials require exhaustive search through all items, then the slope for target-absent trials would be twice that for target-present trials, a pattern that is seen quite frequently (Treisman & Gelade, 1980).

Unfortunately, whereas this is a quite straightforward account of RT × set size functions in search, there are many complications. First, and most important, although it is true that a parallel, infinite-capacity search will produce flat slopes and a serial, self-terminating search will produce linear slopes in a 2:1, absent:present ratio, it does not follow that this pattern of results proves this theoretical account of search. Many different processes can produce similar patterns of RT × set size functions (Townsend, 1971, 1976, 1990; Townsend & Wenger, 2004). Second, RT × set size functions are not always linear (e.g., Pashler, 1987). Third, as noted earlier, speed-accuracy trade-offs complicate analysis, especially since observers tend to make more "miss" errors at larger set sizes. This means that RTs will be more depressed at higher set sizes, artificially curving the functions and lowering the slopes (Dukewich & Klein, 2005, 2009). Given these concerns (especially the first), it is unwise to label a search task as "parallel" or "serial" on the basis of the slope of the RT × set size function. It is safer to use a theory-neutral term like "efficiency" to describe the meaning of a search slope (Wolfe, 1998). That is, whatever the underlying process, a search that produces an RT × set size function with a slope of 5 ms/item is more efficient than a search with a 30 ms/item slope. More items can be processed every second—somehow. Some researchers are very pessimistic about the use of RT methods to uncover underlying search processes (Kristjansson, 2015). Others are more sanguine, especially when information beyond the slope alone can be brought to bear. For instance, RT distributions can constrain the models that can account for the results of this class of search experiments (R. Moran, Zehetleitner, Liesefeld, Müller, & Usher, 2015; E. M. Palmer, Horowitz, Torralba, & Wolfe, 2011; Wolfe, Palmer, & Horowitz, 2010).

Eye Movement Methods

Once the visual display is present for an extended period of time, recording eye movements can be an instructive way to examine the process of search (Kowler, 2011; Sanders & Donk, 1996; Tatler, 2009). Eye tracking has been used as a method in search experiments for decades (Enoch, 1959a; L. G. Williams, 1966), and advances in technology have made it much more convenient in recent years. Modern eye trackers can record the point of the eyes' fixation with good resolution in space and time. The recorded scan path (Noton & Stark, 1971) of fixations certainly tells us something about the process of search. Attention and fixation are linked (McPeek, Maljkovic, & Nakayama, 1999). Programming a ballistic movement of the eyes, a "saccade" to a location has the effect of deploying attention to that location (Kowler, Anderson, Dosher, & Blaser, 1995), and it is very hard to program a deployment of the eyes to one location and attention to another (Kowler et al., 1995). Attention gets to the location of a planned fixation in advance of the actual fixation, and significant information can be picked up from that location before fixation (e.g., Melcher, 2007; B. Wolfe & Whitney, 2015), perhaps because some receptive fields are remapped to that location by the act of directing attention and/or a planned saccade to the location (Duhamel, Colby, & Goldberg, 1992). Pursuit eye movements, too, are linked to attention (Khurana & Kowler, 1987).

If there were a 1:1 mapping between the locus of selective attention and the point of fixation, eye movement recording might be the perfect way to study search, but, sadly, that is not the case. First, it is possible to perform search tasks without moving the eyes (refer back to your experience of Figure 13.4). Of more interest, if acuity and crowding do not interfere with processing of items away from fixation, it is possible to get essentially the same pattern of RT × set size data from observers who fixate and observers who are free to move their eyes (Zelinsky & Sheinberg, 1997). Second, for many classic search tasks, eye movements do not reveal which items have been selected by attention. This is a simple matter of timing. Humans make saccadic eye movements about 3–4 times per second. Even a classic inefficient search like a search for a letter T among Ls produces slopes consistent with a rate no slower than 10–20 letters per second (e.g., if the estimate were based on the unusually steep slope of about 50 ms/item in Huang, 2005). If the letters are made small enough to require fixation, then slopes will be on the order of 125 ms/item for target-present trials and 250 ms/item for target-absent trials. However, when acuity does not limit the search, more than one item per fixation is being processed. Regardless of whether one thinks that several items are being processed in parallel on each fixation (Hulleman & Olivers, 2017) or that covert attention is being deployed from one item to the next at a rate faster than of voluntary saccades (Wolfe, 2003), fixations must be revealing only some of the items that have been processed in a standard search task.

This does not make eye tracking data uninteresting in the least. There are search tasks where the main question of interest is how the target gets fixated. Arguably, this is true of many medical image perception studies (e.g., Bertram, Helle, Kaakinen, & Svedstrom, 2013; Kundel & La Follette, 1972; Kundel, Nodine, & Carmody, 1978) and some searches in continuous scenes (e.g., Ehinger, Hidalgo-Sotelo, Torralba, & Oliva, 2009; Henderson, Malcolm, & Schandl, 2009; Hwang, Wang, & Pomplun, 2011; Neider & Zelinsky, 2006). More artificial search tasks can be contrived where eye movements reveal how the observer is foraging for information (Najemnik & Geisler, 2005, 2008, 2009). There have also been efforts to use more rapid eye movements (microsaccades) as a measure of rapid deployments of attention (Engbert & Kliegl, 2003; Hafed & Clark, 2002) (but see Horowitz, Fencsik, Fine, Yurgenson, & Wolfe, 2007). Still, while eye movements are an invaluable tool, they cannot fully describe search.

Electrophysiological Measures

One of the disadvantages of RT measures and even of eye movements is that the behavior being measured lags hundreds of milliseconds behind the events of interest, the deployment of attention. Recording electrical activity directly from the brain is a possible solution to that problem. In animals, it is possible to monitor attentional effects in exquisite detail at the single neuron level. This chapter is focused on human behavioral data and will barely touch the animal literature. The interested reader can consult many good reviews (Buschman & Kastner, 2015; Eimer, 2014; Miller & Buschman, 2013; Nobre & Kastner, 2014; Reynolds & Chelazzi, 2004). In humans, visual event-related potentials (ERPs), recorded from the scalp, are among the most useful tools (Luck, 2014). Specific waveforms have been associated with the deployment of attention, notably the N2pc (Luck & Hillyard, 1994). ERP methods have been used to examine a wide range of questions in search. For instance, there is ERP evidence to support the notion of rapid serial deployment of attention (Woodman & Luck, 2003). ERPs have examined the guidance of attention by specific feature information (Tollner, Zehetleitner, Gramann, & Muller, 2010) and by object categories (Nako, Wu, Smith, & Eimer, 2014). The main drawback is that the relevant signals are small and many very similar trials must be averaged together to produce a meaningful result. Moreover, signals like the N2pc require that attention goes reliably to the same item on the bulk of these trials. This means that the methods are hard to use on classic search tasks where the observer is free to attend at random.

Functional magnetic resonance imaging (fMRI) has provided a variety of useful insights, mostly into the neural architecture of visual search. For instance, fMRI provides evidence that the right temporoparietal junction (TPJ) contributes to the search for conjunctions (Pollmann, Zinke, Baumgartner, Geringswald, & Hanke, 2014) and that different networks are involved when target features change (e.g., red to green) than when target dimensions change (e.g., color to orientation) (S. I. Becker, Grubert, & Dux, 2014). Other recent fMRI work suggests that attentional networks may not be the same in humans and other primates (Patel et al., 2015). The fMRI is less useful in uncovering the details of a specific search because the method lacks the spatiotemporal resolution to track attention from distractor to distractor to eventual target. That said, advances in fMRI like the work of Nishimoto et al. (2011) raise the possibility of being able to decode dynamic search from patterns of blood-oxygen-level dependent (BOLD) activity. Methods like magnetoencephalography (MEG) hold promise to provide the requisite resolution (Baldauf & Desimone, 2014), but we still await the imaging method that can track attention in visual search the way that an eye tracker registers fixations.

CLASSIC VISUAL SEARCH TASKS: WHAT DO THE DATA TELL US?

The Continuum of Search Efficiency

As discussed previously, in the most standard form of visual search experiments in the lab, observers are asked to look for a target in a display containing some number of distractor items. The total number of items in the display is the set size, and the function relating RT to set size is a prime measure of search efficiency, especially if error rates are kept low.

Treisman's original conception was that search tasks could be divided into two classes: *parallel* searches with slopes near zero, indicating that all items could be processed in parallel, and *serial* tasks with steeper slopes (around 20–40 ms/item, indicating that items were selected in series at a rate of 25–50 items/second) (Treisman & Gelade, 1980). In fact, slopes of search tasks form a continuum from very efficient to very inefficient (Wolfe, 1998). This is cartooned in a series of examples in Figure 13.6.

For illustrative purposes, we have divided the search continuum into four rough categories. Note that it is a bad idea to try to strictly define terms like *efficient* using precise slope values. It would not be reasonable, for example, to assert that 8 ms/item is officially efficient whereas 10 ms/item is officially inefficient. There is no categorical boundary between such labels; search efficiency is a continuous measure. Moreover, slopes tend to be quite variable, and it would not be helpful to declare that one observer was categorically different from another observer, based on a small slope difference.

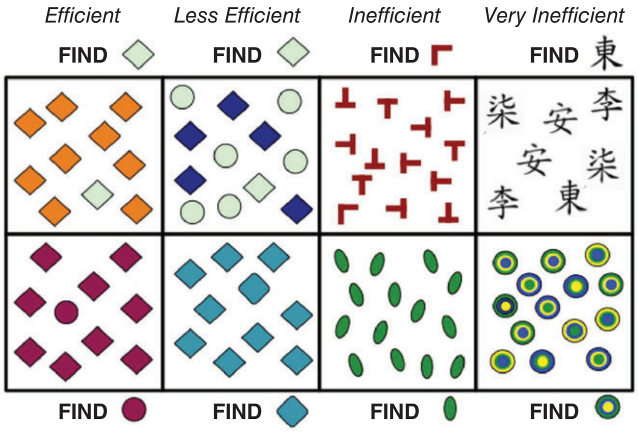

Figure 13.6 Two examples each of four rather loosely defined categories of search.

Slopes are best used comparatively to make statements such as “Looking at Figure 13.6, it is clear that the search for light green among darker orange diamonds is more efficient than search for the same light green diamond among darker blue diamonds and light green circles.”

Continuing with Figure 13.6 and starting with the most efficient searches, the shallowest RT × set size functions are found for searches where the target is defined by a salient difference from the distractors in a basic feature (features are discussed in more detail later) (Egeth, Jonides, & Wall, 1972). Here, the targets’ salient differences in shape and color immediately attract attention. Having a target that differs in a basic feature from the distractors does not necessarily guarantee an efficient search. If the target-distractor (TD) difference is smaller, search will be less efficient (Duncan & Humphreys, 1989; Foster & Ward, 1991b; Nagy & Sanchez, 1990). Thus, in the second column, the shape difference in the second row is not particularly subtle, but the slope for this search would probably be somewhat steeper than the shape search in column 1.

Of more theoretical import is the *conjunction* search, illustrated at the top of column 2. In a standard conjunction search, the target is defined by the presence of two features among distractors that each share one feature with the target. Here, a light green diamond shares color with light green circles and shape with dark blue diamonds. Treisman and Gelade (1980) originally reported that conjunction searches were inefficient—“serial” in their terms, with slopes greater than 20 ms/item on target-present trials. However, starting in the later 1980s, exceptions started to appear (McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986; Quinlan & Humphreys, 1987; Wolfe, Cave, & Franzel, 1989). Today, it is clear that conjunction searches tend to be less efficient than the easiest feature searches, but that there is no clear slope value that divides performance on the two different types of search task. Indeed, some conjunction tasks can produce slopes as shallow as most feature searches (Theeuwes & Kooi, 1994). Typically, a search for a conjunction target defined by two salient features will produce a slope of about 10–15 ms, always assuming that acuity is not a factor and the items can be recognized in near-peripheral vision (Wolfe, 1998). As will be discussed later, the efficiency of conjunction searches depends on the effectiveness with which feature information can guide attention to the target. In the

Figure 13.6 example, attention can be guided to light green items, eliminating the darker blue diamonds from consideration. Attention is probably guided somewhat more weakly to diamonds over the circle distractors.

In the third column we have inefficient searches. This is the category of what Treisman and Gelade called "serial" searches with target-present slopes in the neighborhood of 20–40 ms/item. Classic inefficient searches are often tasks where the targets and distractors have the same features in different spatial arrangements. Here the example is a search for an L (in any of four rotations) among Ts (likewise rotated). These "spatial configuration" searches tend to be inefficient. When they are not, it is often because some unexpected feature is complicating the results. For instance, search for an upright L among upright Ts can be quite efficient, probably because the convex hull of each character defines a triangle, and the target and distractor triangles are of different orientations. Feature searches can be inefficient, too. Here the example is search for a vertically oriented oval among ovals tilted 20 degrees to the left and right of vertical. Even though it is easy to identify a vertical item once it is attended, the search for a specific orientation is inefficient if the distractors flank it in orientation (Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). As with the previous examples, these inefficient searches would involve relatively large stimuli that can be identified without fixation.

In the study of classic visual search, it is sometimes forgotten that the search continuum does not end with what we are calling inefficient search. There are many instances of simple search tasks that will produce markedly steeper RT × set size functions. Here, we are calling all of these "very inefficient." Perhaps the most trivial examples are those where the search task requires foveation to identify the target. For example, if the Ts and Ls of the inefficient example were rendered in a small font, the RT × set size slope would be constrained by the rate of eye movements. A task that produces slopes of around 125 ms/item on target-present trials and 250 ms/items on target-absent trials is probably a serial, self-terminating search for an item that needs to be fixated. Slopes can be arbitrarily steep even with large, well-defined items if those items each take an arbitrarily long time to identify. Thus, in column 4, the top example would be very inefficient for non-Chinese readers who would take hundreds of milliseconds to identify each item and/or to try to match it to the designated target. Chinese readers would be faster, illustrating the obvious fact that expertise makes a difference in search. The second very inefficient example simply asks observers to look for a specific arrangement of the colored rings. This can be painfully slow. If you imagine adding rings, you can see how these very inefficient searches can be almost arbitrarily slow.

As an aside, in the third column, second example, if you did not notice that there are two vertical targets, you have fallen victim what is known as "satisfaction of search" (Berbaum et al., 1990; Berbaum et al., 2015; Cain & Mitroff, 2012; Fleck, Samei, & Mitroff, 2010; Nodine, Krupinski, Kundel, Toto, & Herman, 1992; Tuddenham, 1962), a phenomenon with potentially serious consequences if you are meant to find the second tumor or the unexpected broken rib. Factors from memory capacity to personality traits can influence susceptibility to these errors (Cain, Dunsmoor, LaBar, & Mitroff, 2011; Cain & Mitroff, 2012).

What Are the Guiding Attributes?

The continuum of search efficiency, shown in Figure 13.6, is governed by two factors: the ability to guide attention toward likely targets

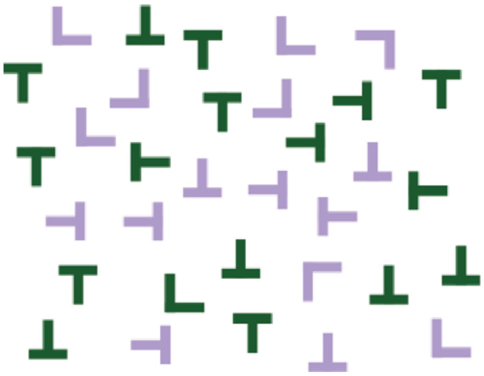

Figure 13.7 In search for a dark green L, attention will be guided to dark green.

and the speed with which distractors can be rejected. As discussed earlier, the fourth column of Figure 13.6 illustrates the distractor rejection factor. Here we will consider the attributes that guide attention toward a target. The basic idea of guidance is shown in Figure 13.7. If you search for a dark green L, you will need to perform an inefficient search for an L among Ts, but you will be able to restrict your search to the dark green items. If half the items are dark green, then the slope of the RT × set size function will be cut approximately in half, compared to the situation where all items are the same color (Egeth, Virzi, & Garbart, 1984). If only 25% of items were dark green, the slope would be cut to one fourth of its *unguided* value. In these terms, highly efficient searches like those shown in column 1 of Figure 13.6 can be thought of as searches in which attention is guided to the target item immediately, thus making the rest of the set size irrelevant.

Wolfe et al. (1989) introduced the use of the term *guidance* in this sense in the context of the guided search (GS) model, a modification of Treisman and Gelade's feature integration theory (FIT). FIT originally proposed that a limited set of basic features could be searched for in parallel and that all other searches, other than basic feature search, required serial, self-terminating search (Sternberg, 1966). Wolfe et al. (1989) modified the basic FIT idea, arguing that basic features could be processed in parallel and then used to guide the serial deployment of attention. It is worth noting that accepting the idea of feature guidance does not require acceptance of this FIT–GS commitment to serial deployments of covert attention. Returning to Figure 13.7, it would be possible that the role of guidance is to limit the parallel processing of items to just the dark green items, freeing up more resources for those items or otherwise allowing more rapid parallel processing of the relevant items. In neurophysiological work, for instance, it has been proposed that feature guidance (often called feature attention in that literature) "might allow the processing of all objects in parallel but bias activity in favor of those neurons that represent critical features of the target" (from the abstract of Bichot, Rossi, & Desimone, 2005).

Many years of work have failed to create a definitive list of the attributes that guide attention. That said, we do know a lot about guiding features. First, compared to the set of all possible attributes, the set of guiding attributes is very limited; between one and two dozen would be a plausible range. As will be described later, many important attributes, although readily processed by the visual system, do not guide search. If you think of guidance as a human search engine, the set of terms you can type into the search box is vastly smaller than the terms you can type into Google. Second, all attributes are not equal. It is not clear why one attribute should be more effective than another, but it is clear that color and motion guide attention more effectively than, say, orientation, and that orientation is more effective than various depth cues.

Tables 13.1 through 13.5 show the latest version of a list of attributes that appear to guide attention. This list is a modification

Table 13.1 The Undoubted Guiding Attributes: Almost Everyone Would Agree That These Features Guide Attention. Generally, There Is Converging Evidence from Multiple Paradigms

The Undoubted Guiding Attributes		
Color	(Bauer, Jolicoeur, & Cowan, 1996, 1998; Brawn & Snowden, 1999; Carter, 1982; Daoutis, Pilling, & Davies, 2006; Duncan, 1988; D'Zmura, 1991; Farmer & Taylor, 1980; Green & Anderson, 1956; Lindsey et al., 2010; Monnier & Nagy, 2001; Nagy & Sanchez, 1990; Nagy, Young, & Neriani, 2004; Smith, 1962; Treisman & Gormican, 1988; Treisman & Souther, 1985)	1
Motion	(Braddick & Holliday, 1991; Burr, Baldassi, Morrone, & Verghese, 2009; Dick, Ullman, & Sagi, 1987; Horowitz, Wolfe, DiMase, & Klieger, 2007; Kawahara, 1993; McLeod et al., 1988; Nakayama & Silverman, 1986; Nothdurft, 1993a; Rosenholtz, 2001; Takeuchi, 1997; von Muhlenen & Muller, 1999)	2
Orientation	(Bergen & Julesz, 1983a; Cavanagh, Arguin, & Treisman, 1990; Foster & Ward, 1991a; Moraglia, 1989a; Sagi, 1990; Wolfe & Friedman-Hill, 1992b; Wolfe, Friedman-Hill, et al., 1992; Wolfe, Klempen, & Shulman, 1999)	3
Size (including length and spatial frequency)	(Cavanagh et al., 1990; Found & Muller, 2001; Moraglia, 1989b; Sagi, 1988; Stuart, 1993; Treisman & Gormican, 1988; Verghese & Nakayama, 1994; Verghese & Pelli, 1994; Williams, 1966)	4

NOTES:

[1] Color is usually the first dimension that comes to mind, though it is not always the most powerful (Huang, 2015a). More recent work has focused on the nature of preattentive color processing. Thus, unique hues do not seem to have special status (Wool et al., 2015), though cardinal directions in color space might make some difference (Gunther, 2014).

[2] It is always a little difficult to know if a property like motion contains several preattentive dimensions (e.g., speed and direction), with possibly further divisions of direction in the third dimension (looming) (Franconeri, Hollingworth, & Simons, 2005; Skarratt, Cole, & Gellatly, 2009). Further complications arise if we consider rotational motions like rolling and spinning (Cain, Josephs, & Wolfe, 2015).

[3] Most of what we know about orientation search is derived from work about single lines or objects in isolation. We should remember that factors like collinearity have a strong effect on orientation search (Meigen, Lagreze, & Bach, 1994; Tseng & Jingling, 2015).

[4] As with motion, it is unclear if the attribute of size is a single thing or a collection of preattentive dimensions like spatial frequency (Bilsky & Wolfe, 1995). It is also possible that there are specific effects of the known real-world size of objects even if the mouse and the elephant subtend the same visual angle onscreen (Long, Konkle, Cohen, & Alvarez, 2016), though these effects may not be preattentive. Size search is also influenced by the apparent 3D layout of the display (Champion & Warren, 2010).

of the list found in the *Oxford Handbook of Attention* (Wolfe, 2014), and that list was an adaptation of an earlier version (Wolfe & Horowitz, 2004). Extensive references and notes are given for readers with a special interest in the topic. The more casual reader would be forgiven for scanning the list and moving on.

On top of the fundamentally serial process, search for faces or facial emotion can be modulated by many factors, including the political stance of the searcher (Mills, Smith, Hibbing, & Dodd, 2014) or the searcher's race (Sun, Song, Bentin, Yang, & Zhao, 2013). Whereas some would argue for an ability of facial emotion to guide search (Dickins & Lipp, 2013), others argue that this, too, reflects the operation of more basic features (Savage, Lipp, Craig, Becker, & Horstmann, 2013). The more common finding is that emotion modulates relatively inefficient search tasks (Skinner & Benton, 2012; Shirama, 2012; Sato & Yoshikawa, 2010). This can probably be attributed to differences in the time that observers are engaged with attended distractors. If an

Table 13.2 Probable and Possible Guiding Attributes. These Items can Make a Reasonable Case for Their Status As Guiding Attributes. However, More Data Would Be Needed to Address Dissenting Opinions or the Possibility of Alternative Explanations

Probable and Possible Guiding Attributes		
Luminance onset (flicker)	(Spalek, Kawahara, & Di Lollo, 2009; Theeuwes, 1995; Yantis & Jonides, 1990)	5
Luminance polarity	(Gilchrist, Humphreys, & Riddoch, 1996; Theeuwes & Kooi, 1994)	
Vernier offset	(Fahle, 1991a, 1991b)	6
Stereoscopic depth and tilt	(He & Nakayama, 1992; Holliday & Braddick, 1991; McSorley & Findlay, 2001; Moore, Elsinger, & Lleras, 2000; Nakayama & Silverman, 1986; O'Toole & Walker, 1997; Sousa, Brenner, & Smeets, 2009)	7
Pictorial depth cues	(Aks & Enns, 1993; Enns & Rensink, 1990, 1993; Enns, Rensink, & Douglas, 1990; Epstein, Babler, & Bownds, 1992; Johannesson, Sigurdardottir, & Kristjansson, 2013; Sun & Perona, 1996a; Von Grünau & Dubé, 1994)	7
Shape	(Bergen & Julesz, 1983b; Cheal & Lyon, 1992; Chen, 1982, 1990; Huang, 2015b; Kristjansson & Tse, 2001; Orsten-Hooge, Portillo, & Pomerantz, 2015; Pilon & Friedman, 1998; Pomerantz & Pristach, 1989; Treisman & Gormican, 1988; Tsal, Meiran, & Lamy, 1995; Wolfe & Bennett, 1997)	8
Line termination	(Donnelly, Humphreys, & Riddoch, 1991; Julesz & Bergen, 1983; Taylor & Badcock, 1988)	8
Closure	(Chen, 1982; Elder & Zucker, 1994, 1998; Enns, 1986; Kanbe, 2009; Kovacs & Julesz, 1993; Treisman & Souther, 1985; Williams & Julesz, 1992)	8
Topological status	(Chen, 1982, 1990, 2005; Rubin & Kanwisher, 1985)	8
Curvature	(Fahle, 1991b; Foster & Savage, 2002; Gurnsey, Humphrey, & Kapitan, 1992; Sakai, Morishita, & Matsumoto, 2007; Treisman & Gormican, 1988; Wolfe, Yee, & Friedman-Hill, 1992)	8
Lighting direction (shading)	(Adams, 2008; Aks & Enns, 1992; Braun, 1993; Kleffner & Ramachandran, 1992; Ostrovsky, Cavanagh, & Sinha, 2005; Ramachandran, 1988; Sun & Perona, 1996a, 1996b; Symons, Cuddy, & Humphrey, 2000; Zhang, Huang, Yigit-Elliott, & Rosenholtz, 2015)	9
Glossiness (luster)	(Wolfe & Franzel, 1988)	10

NOTES:

[5] At first, it seemed that onsets were the ultimate attention-capturing feature (Yantis, 1993), but the picture subsequently became more complicated (Kunar & Watson, 2014). Still, in an otherwise static display, an abrupt onset is very like to pop out.

[6] Vernier as a guiding property suffers from a lack of follow-up research since Fahle's work. Moreover, it might be a version of an orientation cue (Findlay, 1973).

[7] A sufficiently salient bump on a smooth background will attract attention (Kleffner & Ramachandran, 1992), but there are lots of depth cues that will indicate the presence of that bump, and it is not clear if they should be treated as separate guiding attributes or as different ways to produce a change in the 3D structure of the scene. Here, again, there is room for a host of experiments. Moreover, not every bump will pop out (Johannesson et al., 2013).

[8] It is clear that something about the shape of objects guides attention, and it is decidedly unclear what that something is. Probably there are multiple aspects of shape that have the status of guiding attributes. For instance, line termination, closure, curvature, and some topological properties all support efficient search. The issue is complicated by our failure to settle on a set of shape features (Kourtzi & Connor, 2011; Yamane, Carlson, Bowman, Wang, & Connor, 2008). The advent of deep convolutional neural networks (Krizhevsky, Sutskever, & Hinton, 2012; Szegedy, Toshev, & Erhan, 2013) that can perform impressive feats of object recognition and detection may provide new insights into human shape processing, but, at this writing, that is in the future.

[9] Some early work suggested a guiding role for shading and lighting direction (e.g., Ramachandran, 1988). This was undercut by some later work (Cavanagh, 1999; Ostrovsky et al., 2005). The most recent work on the pop-out of cubes lit from different directions may support the idea that shading information should be grouped with other cues like stereopsis into one omnibus 3D depth property (Zhang et al., 2015).

[10] The evidence for shininess or gloss comes from one paper on binocular luster (Wolfe & Franzel, 1988). There have been subsequent conference talks supporting (Formankiewicz & Mollon, 2006) and questioning (Birnkrant, Wolfe, Kunar, & Sng, 2004) that finding. We have recently replicated the 1988 finding, but we find that luster is not a strong guiding feature (Zou, Utochkin, & Wolfe, 2016).

Table 13.2 (*Continued*)

Probable and Possible Guiding Attributes		
Expansion/looming	(Braddick & Holliday, 1991; Franconeri & Simons, 2003; Skarratt et al., 2009; Takeuchi, 1997)	11
Number	(Reijnen, Wolfe, & Krummenacher, 2013; Taylor & Badcock, 1988; Treisman & Gormican, 1988)	12
Aspect ratio	(Treisman & Gormican, 1988)	

NOTES:

[11] "Expansion" and/or "looming" cues are somewhat problematic because they might be decomposed into a depth cue, a size cue, a motion cue, or some combination of these. There is some evidence that looming has a special role as a stimulus that requires a response: the behavioral urgency hypothesis (Franconeri & Simons, 2003; Lin, Franconeri, & Enns, 2008).

[12] Recent evidence shows that numerosity (Does this cluster contain more dots than the other clusters?) is, at best, a rather weak feature, requiring large (>3:1) ratios between target and distractor numerosities.

angry face, for example, holds attention longer, search for a happy face will be less efficient than search for an angry face because searchers are taking more time to get through each of the angry distractors than the happy distractors.

Mechanics of Feature Guidance

The ability of an attribute to support an efficient visual search is governed by an extensive set of rules. Some of these are quite basic. For instance, the more similar the target is to the distractors, the less efficient the search will be (TD similarity) and the more heterogeneous the distractors are, the less efficient a search will be (DD heterogeneity). While these are good general principles, the details need to be worked out for each attribute. For example, TD similarity functions have been worked out for at least some of the color space by Nagy et al. (Nagy & Sanchez, 1990; Nagy, Sanchez, & Hughes, 1990).

TD and DD relationships are not independent. In color, for example, search for one color among two others will be quite efficient if a line can be drawn in color space that puts the target on one side of the line and the distractors on the other side. Search will be quite inefficient if the target lies on a line in color space at a point between the two distractors. This is known as the principle of linear separability (Bauer et al., 1996, 1998; D'Zmura, 1991). The principle works for other features as well. Thus, it is easy to find a vertical line among lines tilted 20 and 60 degrees to the left of vertical, but it would be hard to find the target if the distractors were 20 degrees to the left and 20 degrees to the right of vertical. The average DD heterogeneity is the same, but in the first case a line can be drawn in orientation space putting the target on one side and the distractors on the other. In the second case, targets and distractors are not linearly separable, and search will be inefficient (Wolfe, Friedman-Hill, et al., 1992).

Utochkin and Yurevich (2016) describe another important interaction of TD and DD similarity. Search for a 45 degree tilted target among 0 and −45 degree tilted distractors will be quite efficient. It will be more efficient if the distractors are distributed between 0 and −45 (0, −9, −18, −27, −36, −45). Utochkin and Yurevich describe this more continuous set of distractors as "segmentable." Another way to think about it focuses on the local DD and TD differences. It is the difference between an item and its near neighbors that makes it salient and allows it to attract attention. When there are only 0 and −45 degree

Table 13.3 Doubtful Cases and Probable Non-Guiding Attributes. Probably Not: Candidates for Guiding Attribute Status Where the Data Is Weak or Negative. In Some of These Cases, More Data Might Change the Conclusion

Doubtful Cases and Probable Non-Guiding Attributes		
Novelty	(Flowers & Lohr, 1985; Frith, 1974; Johnston, Hawley, & Farnham, 1993; Q. Wang, Cavanagh, & Green, 1994; Wolfe, 2001; Zhaoping & Frith, 2011)	13
Learned features (e.g., letters)	(Atkinson, Holmgren, & Juola, 1969; Golcu & Gilbert, 2009; Grice & Canham, 1990; Kinchla, 1974; Kinchla & Collyer, 1974; Shiffrin & Gardner, 1972)	14
Alphanumeric category	(Brand, 1971; Duncan, 1983; Jonides & Gleitman, 1972; Krueger, 1984)	15
Intersection	(Bergen & Adelson, 1988; Bergen & Julesz, 1983a, 1983b; Julesz, 1981, 1984; Julesz & Bergen, 1983; Julesz & Krose, 1988; Nothdurft, 1991; Wolfe & DiMase, 2003)	16
Optic flow	(Braddick & Holliday, 1991; Bravo, 1998; Royden, Wolfe, & Klempen, 2001) (but see Rushton, Bradshaw, & Warren, 2007)	17
Color change	(Theeuwes, 1995)	
3D volumes (e.g., geons)	(Brown, Weisstein, & May, 1992; Pilon & Friedman, 1998)	
Luminosity (i.e., light sources)	(Correani, Scot-Samuel, & Leonards, 2006; Vincent, Baddeley, Correani, Troscianko, & Leonards, 2009)	18
Material type	(Wolfe & Myers, 2010)	
Scene category	(Greene & Wolfe, 2011)	
Duration	(Morgan, Giora, & Solomon, 2008)	
Stare-in-crowd	(Doi & Ueda, 2007; Palanica & Itier, 2011; von Grunau & Anston, 1995; Williams, Moss, & Bradshaw, 2002)	

NOTES:

[13] Accepting novelty as a guiding feature requires evidence that there is not some other, more basic feature guiding attention. Thus, for example, it is easier to find a novel, mirror-reversed, letter N among normal Ns than it is to find an N among mirror-reversed Ns. This is curious because the orientation of the central diagonal should be adequate to do the task. It is interesting that this advantage for mirror-N targets is not found for bilingual Russian–German readers for whom neither Ns nor mirror-Ns are novel (Malinowski & Hübner, 2001). Wolfe (2001) found that mirror-Ns produced stronger effects than mirror-reversed versions of the letters P, K, f, or y, even though all those letters also produced asymmetries favoring the unfamiliar target. A version that controls well for low-level visual features is the report by Q. Wang et al. (1994), showing that search for mirror-N or mirror-Z among normal Ns or Zs is very efficient. The reverse is not efficient. It would be worth replicating that result. In the same vein, it would be worth understanding why Wolfe (2001) found that an inverted elephant was easy to find among upright elephants but an inverted swan was not so easy to find (an odd finding).

[14] If a mirror-N is easy to find among Ns, this must be the product of learning. We were not born with a bias toward one of those two stimuli. Any asymmetry must be learned. But what is learned when an item becomes very familiar? Do new, preattentive features emerge, or are observers simply learning to use features like line termination or closure more effectively? Is it possible to learn a new preattentive feature? This is a long-standing question in visual search. Work with overlearned alphanumeric characters certainly shows that this learning can influence search (Caerwinski, Lightfoot, & Shiffrin, 1992; Malinowski & Hübner, 2001; Sigman & Gilbert, 2000; Sireteanu & Rettenbach, 1995), but it remains unclear whether this overlearning results in the creation of new features.

[15] It was once thought that a letter might “pop out” among numbers and vice versa, but these effects (e.g., the “zero-oh” effect; Jonides & Gleitman, 1972) have been hard to replicate (Krueger, 1984).

[16] Intersection once seemed to be a good candidate for guiding attribute status, but subsequent experiments show that it is unlikely to be such an attribute (Wolfe & DiMase, 2003).

[17] Optic flow might be a reasonable candidate for a guiding attribute status, but the data indicate that flow itself is not a feature. Instead, attention is guided by the motion of objects in the world. This involves an ability to disregard the optic flow motions due to observer motion (Rushton et al., 2007).

[18] Correani et al. (2006) found that luminosity did appear to support efficient search, but this was attributable to local luminance effects and not to luminosity itself. Using eye tracking while observers viewed scenes containing light sources like streetlights, Vincent et al. (2009) found that these self-luminous stimuli did not preferentially attract attention.

Table 13.3 (*Continued*)

Doubtful Cases and Probable Non-Guiding Attributes		
Eye of origin/ binocular rivalry	(Paffen, Hooge, Benjamins, & Hogendoorn, 2011; Shneor & Hochstein, 2006; Wolfe & Franzel, 1988; Zhaoping, 2008)	19
Your name	(Bundesen, Kyllingsbaek, Houmann, & Jensen, 1997)	
Threat	(Batty, Cave, & Pauli, 2005; Lipp, 2006; Notebaert, Crombez, Van Damme, De Houwer, & Theeuwes, 2011; Öhman, Flykt, & Esteves, 2001; Soares, Esteves, Lundqvist, & Ohman, 2009; Tipples, Young, Quinlan, Broks, & Ellis, 2002)	20
Biological motion	(Pratt, Radulescu, Guo, & Abrams, 2010; L. Wang, Zhang, He, & Jiang, 2010)	21

NOTES:

[19] Wolfe and Franzel (1988) had argued that binocular rivalry did not guide attention, but some newer results suggest otherwise (Paffen et al., 2011; Paffen, Hessels, & Van der Stigchel, 2012). The same could be said about "utrocular," eye-of-origin information. Our recent results suggest that rivalry might guide search if noise from other dimensions (like orientation) is eliminated (Zou et al., 2016).

[20] Clearly, threatening stimuli elicit threat-specific responses (e.g., the responses of phobics to snakes or spiders; LoBue & DeLoache, 2008; Rakison & Derringer, 2008; Reinecke, Rinck, & Becker, 2006). However, threat does not appear to guide search if other basic features are controlled for. Thus, a snake may *hold* attention once it is found, but if attention is guided to a snake, it is because attention can be guided by attributes like line termination.

[21] Biological motion is one of those stimuli that seems like it should be found efficiently because of its obvious importance (Blake, 1993; Blake & Shiffrar, 2007; Johansson, 1973). However, such stimuli do not seem to support efficient visual search. The related property of animacy may have feature status (Gao, McCarthy, & Scholl, 2010; Gao, Newman, & Scholl, 2009; Gao & Scholl, 2011).

Table 13.4 Complicated Cases

Complicated		
Faces (presence of, familiarity of, upright, angry, real, schematic, etc.)	(D. V. Becker, Anderson, Mortensen, Neufield, & Neel, 2011; S. I. Becker, Horstmann, & Remington, 2011; Devue, Van der Stigchel, Brèdart, & Theeuwes, 2009; Doi & Ueda, 2007; Eastwood, Smilek, & Merikle, 2001; Frischen, Eastwood, & Smilek, 2008; Hansen & Hansen, 1988; Hershler, Golan, Bentin, & Hochstein, 2010; Hershler & Hochstein, 2005, 2006; Horstmann, Bergmann, Burghaus, & Becker, 2010; Langton, Law, Burton, & Schweinberger, 2008; Nothdurft, 1993b; Purcell, Stewart, & Skov, 1996; Suzuki & Cavanagh, 1995; Tong & Nakayama, 1999; Vanrullen, 2006; von Grunau & Anston, 1995)	22
Other semantic categories (e.g., "animal")	(Levin, Takarae, Miner, & Keil, 2001)	

NOTES:

[22] Perhaps no candidate attribute has been the subject of more research and controversy than the face. Obviously, faces are very important. We even have brain areas that seem especially devoted to them (Grill-Spector, Knouf, & Kanwisher, 2004; Kanwisher & Wojciulik, 2000). Moreover, it sometimes feels like a familiar face pops out of a crowd or that facelike configurations of stimuli grab attention. However, as with other complex stimuli, debate has raged about whether efficient search for faces, when found, can be explained by other, simpler features (see, e.g., Hershler & Hochstein, 2005, 2006; Vanrullen, 2006). One piece of evidence for guidance by faces seems to inspire a subsequent study that shows that another visual feature is at work. Others will conclude differently, but our conclusion is that faces are processed one at a time.

Table 13.5 Modulators

Modulators		
Cast shadows	(Rensink & Cavanagh, 2004)	23
Amodal completion	(Rensink & Enns, 1998; Wolfe et al., 2011)	
Apparent depth	(Aks & Enns, 1996; Champion & Warren, 2008; Wheatley, Cook, & Vidyasagar, 2004)	

NOTES:

[23] Some stimulus properties seem to modulate search even if they are not guiding attributes in the classic sense. It seems as if these properties are computed before attention selects the object, and the results of that computation can have an influence on other basic features. For example, apparent depth changes apparent size, and the apparent size of an item, rather than its extent on the retina, is what is critical in search. Similarly, amodal completion of an item behind an occluder can make a small line segment in the image appear to be part of a long line that continues under the occluder. Rensink and Enns (1998) show that, in a search task, this line will behave like the long line and not like the physically present small segment.

distractors, there are a lot of salient Δ45 degree DD differences. With the larger set of distractors, though the average distractor orientation remains −22.5, there are fewer large DD differences to distract attention from the TD differences.

Orientation search has been more extensively studied than, perhaps, any other guiding attribute. We can use these findings to illustrate a set of rules that probably apply to other attributes, as well. Guidance is based on a coarse representation of an attribute. In orientation, observers can easily discriminate between lines whose orientations are only a few degrees apart if they are attending to the stimuli. However, efficient search requires a much greater TD separation of 10–15 degrees (Foster & Ward, 1991a). Moreover, this coarseness is not just a scale factor. Efficient search does not simply appear when the TD distance is some multiple of the just noticeable difference (JND) for that attribute. Thus, for color, the JNDs around a specific color form an ellipse in a 2D color plane (MacAdam, 1942). When Nagy and Sanchez (1990) produced a similar contour for efficient color search, they found that the critical TD differences did not form a bigger ellipse of the same shape. Instead, they found a different, more quadrilateral shape. In orientation, the coarse processing appears to have a categorical nature. It is easier to find a target if it is the only steep or shallow item in the display (Hodsoll & Humphreys, 2005; Wolfe, Friedman-Hill, et al., 1992). It is easier to find a target if the distractors are symmetrical about a vertical axis and harder if the target is symmetrical with distractors (Wolfe & Friedman-Hill, 1992a). It is easier to find a target if it forms a unique implicit angle with distractors than if it does not (Wolfe & Friedman-Hill, 1992b). It is likely that similarly specific rules apply to other attributes as well, but the research has not been done. It is important to remember that the properties that guide attention are not the same as the properties that we see, a point made in an interesting taxonomy of features by Huang (2015b).

A recurring theme in our understanding of the ability of features to guide attention is that the TD and DD *relationships* are critical. What angle is formed by two distractor orientations? What is the just noticeable difference between two colors, and so forth? A series of studies by Stephanie Becker and her colleagues has made this point especially clear (Becker, 2010, 2013; Becker, Harris, Venini, & Retell, 2014). For example, one search trial can speed a subsequent search trial if they are similar searches. Thus, if you search for red among green on one trial, you will be faster to respond to a second red among green trial than to a green among red trial, even though both trials are trivially easy (Maljkovic & Nakayama, 1994). Becker showed that if you find an orange target among yellow on one trial, you are faster to find red among orange than orange among red on the next trial. This appears to happen because orange among yellow was the search for the target that was relatively more red. In the second search, you are faster to find another target when it is the relatively more red even though the absolute colors have shifted.

Bottom-Up and Top-Down Guidance

A feature can guide attention in one of two ways. As discussed earlier, if an item differs from its neighbors by more than a preattentive just noticeable difference, it will attract attention in a *bottom-up*, stimulus-driven manner. The intentions of the observer are not critical. The extent to which such bottom-up guidance is mandatory is the root question behind the extensive literature on attention capture (e.g., Carmel & Lamy, 2015; Franconeri et al., 2005; Harris, Becker, & Remington, 2015; Hillstrom & Yantis, 1994; Pratt, Radulescu, Guo, & Abrams, 2010; Rauschenberger, 2003). Work on stimulus salience and on "salience maps" in the brain is (for the most part) work describing this bottom-up component (Koch & Ullman, 1985; Z. Li, 2002; Parkhurst, Law, & Niebur, 2002; Thompson & Bichot, 2004). Under the right circumstances, observers can usually manage to ignore or largely ignore bottom-up signals if they are pulling attention in the wrong direction (Yantis & Egeth, 1999). However, if the bottom-up signal is strong enough, it will attract attention even if those effects may be hidden under some circumstances (Gaspelin, Ruthruff, & Lien, 2016). Or, in the words of the 19th-century author Sully, "One would like to know the fortunate (or unfortunate) man who could receive a box on the ear and not attend to it" (Sully, 1892, p. 146).

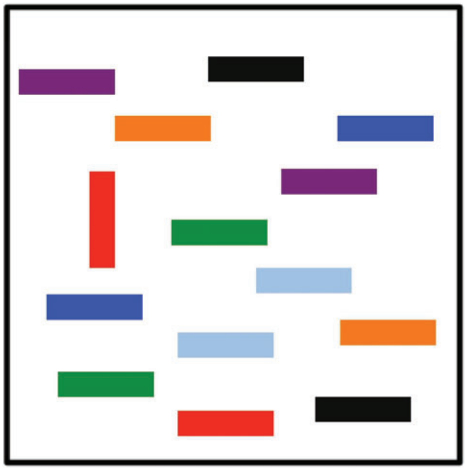

Figure 13.8 Even if the vertical line "pops out," it is not hard to search for green (in the full-color, on-line version).

Bottom-up signals can be largely ignored if the observer is guiding attention in a *top-down* fashion. Thus, in Figure 13.8, on first glance the vertical line would attract attention in a bottom-up manner. However, if you were told to find green stimuli, you would have no problem doing that (in the on-line version). If you were doing a series of such searches, you would be minimally inconvenienced by the vertical line (Snowden, 1998; Yantis & Egeth, 1999) (but see Becker, 2007). Top-down guidance is guidance of attention by the user's goals. Attentional deployments in the real world will be a combination of top-down and bottom-up factors. What is here called top-down guidance seems to be what is discussed as "feature attention" in the physiology literature (e.g., Bichot, Heard, DeGennaro, & Desimone, 2015; Martinez-Trujillo, 2011; Schoenfeld et al., 2007). The basic physiological observation is that training a monkey to search for red, for example, gives a boost in activity to all red items in the field. This is as distinguished from spatial attention, where the monkey would be trained to direct attention to a specific location. Spatial attention tasks change the size and position of receptive fields (e.g., J. Moran & Desimone, 1985; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006).

The distinction between top-down and bottom-up processing is not as clear is it might seem at first glance. Consider the effects of priming and of value. In priming studies, it is found that the appearance of a target on previous trials (or as a preview to the current trial) makes observers faster and/or more likely to find the same target again (Hillstrom, 2000; Huang, Holcombe, & Pashler, 2004; Maljkovic & Nakayama, 1994; Wolfe, Butcher, Lee, & Hyle, 2003). Some hold that large swaths of the search literature can be explained by such bottom-up priming (Theeuwes, 2013). Alternatively, priming could be described as top-down since attention is being guided by the user, albeit in an implicit, automatic manner (Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). The lack of volition should not be seen as critical. When you look for an apple, you do not (usually) explicitly ask yourself to find “red” and “round.” That top-down guidance is also essentially implicit. There is no answer to the question of whether priming is top-down or bottom-up. It is a matter of the precise definitions one cares to apply to those terms.

The same can be said about the effect of value. Attention is attracted to more valuable items in a manner resembling attentional capture by salient items (Anderson, Laurent, & Yantis, 2011; Anderson & Yantis, 2013; Kristjansson, Sigurjonsdottir, & Driver, 2010). Items are made more valuable by associating them or their features with rewards. The effects of this training are often considered to modify bottom-up, stimulus-driven attention (Munneke, Hoppenbrouwers, & Theeuwes, 2015), but, as with priming, one could consider value to be a type of top-down set—again, outside of clear conscious control.

Guided Search to Conjunctions of Features

Regardless of the precise definitions of top-down and bottom-up guidance, it is clear that attention can be guided by features of the target. When an observer looks for a specific type of target, the effectiveness of this feature guidance is an important component in determining the efficiency of the search. Returning to Figure 13.7, if you are told to search for the dark green L, your attention will be guided to the dark green items, making the search more efficient. Your attention will not be preferentially directed to Ls over Ts, because no guiding attribute distinguishes L from T. You will attend to dark green items until you discover that one of those is an L.

As was discussed earlier, conjunctions of two or more basic features have been a subject of particular theoretical interest since Treisman and Gelade (1980) declared that they required inefficient, serial search. As noted, it subsequently became clear that conjunction search could be very efficient if the stimulus conditions were correct. In the context of the discussion of guidance, we can see that conjunction search could be efficient if observers could make effective use of guidance. Consider Figure 13.9. If you can guide attention to red and vertical and oval, you should rapidly find the one red, vertical oval. Now switch to blue, horizontal, and rectangle, and, again, you rapidly find your target. Indeed, if top-down feature guidance were perfect, such searches could be independent of set size. In practice, however, it appears that bottom-up contrasts between the items in a display like Figure 13.9 exact some cost. The resulting search, while efficient, is

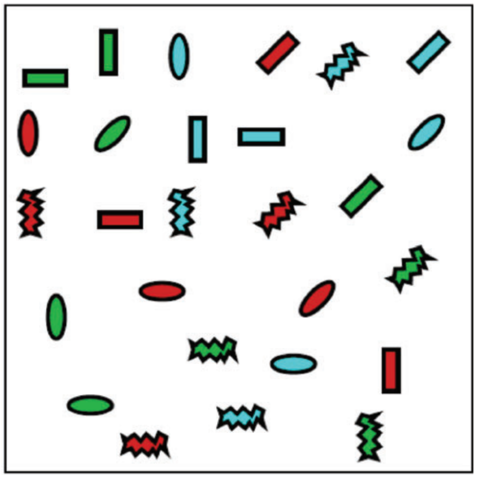

Figure 13.9 Triple conjunctions of color, shape, and orientation.

not perfectly efficient (Nordfang & Wolfe, 2014).

Intuition seems to suggest that guidance to multiple features is nested. In the previous example, people might feel as if they first segregate out all the red items, then the vertical members of that subset, and then the ovals. In fact, it appears that observers can guide simultaneously to multiple features. If the task is structured so that observers *must* search a subset (e.g., find the odd item in the red subset), search times are much slower (Friedman-Hill & Wolfe, 1995). Moreover, search for triple conjunctions is *more* efficient than search for standard two-way conjunctions (Wolfe et al., 1989), again suggesting that more simultaneous sources of guidance are better. It is possible that different features, even if invoked at the same time, take different times to become fully active (Olds, Cowan, & Jolicoeur, 2000a, 2000b).

Models of search propose that guidance to particular features is accomplished by adjusting the weight given to different sources of information. This can be seen in physiological studies. For example, if a monkey is trained to look for a target that is a red crescent, responses to red color and crescent shape are boosted across the visual field (Bichot, Rossi, & Desimone, 2005) (see also Treue & Trujillo, 1999). Guidance has a hierarchical structure to it. It is possible to guide attention to a specific color, like red, but it is also possible to guide attention preferentially to the entire attribute of color (Found & Muller, 1996), suggesting that weights can be set at multiple levels in the system (Rangelov, Muller, & Zehetleitner, 2011, 2012). The observer can be induced to attend specifically to singleton items, regardless of their dimensions (the so-called singleton mode; Bacon & Egeth, 1994; Egeth, Leonard, & Leber, 2010). Treisman's original feature integration model had a set of feature maps within each dimension, all of these feeding a master map (Treisman, 1986a). Successor models like guided search (Wolfe, 1994) allow for weights to be set at each of these levels, with attention guided by a priority map (Fecteau & Munoz, 2006; Serences & Yantis, 2006). The priority map combines inputs from multiple features and attributes into a single representation, though it is possible to find situations where a stimulus seems to produce an attentional deployment and a response without the need for a map that combines signals from multiple dimensions (Chan & Hayward, 2009, 2012) (but see Zehetleitner, Proulx, & Müller, 2009).

Search Asymmetries

If we have two stimuli, A and B, it is sometimes easier to find an A among Bs than a B among As. This is known as a *search asymmetry*. Early on, Treisman et al. (Treisman & Gormican, 1988; Treisman & Souther, 1985) proposed that asymmetries could be useful in determining what properties counted as basic features in visual search. The core idea is that it is easier to find the presence of a feature than its absence. For example, search for a moving item among stationary items is easier than a search for a stationary item among moving distractors. This would be taken as evidence that motion was a basic feature. Rosenholtz (2001) offers an important caution. To continue with the motion example, in a search for a moving item among stationary distractors, the distractors are homogeneous; they are all stationary. In the reverse situation, the moving distractors could be heterogeneous if distractors are allowed to move in multiple directions. In fact, the asymmetry does persist if distractors all move in one direction, but it is weaker (Royden et al., 2001). Many interesting nuggets of information can be derived from this sort of analysis of search asymmetries. It is easier to find a tilted line among verticals than vice versa. This could be taken as evidence that tilt is the feature and that the main axes of vertical and horizontal are defined by the absence of that feature (Wolfe, Friedman-Hill, et al., 1992). It is easier to find orange among yellow than vice versa, suggesting that redness might be the critical feature in the orange target, whereas both yellow targets and orange distractors contain yellowness.

In the asymmetries just described, the more efficient of the two searches is typically very efficient, with a slope near zero. In contrast, there are many tasks in which there is an asymmetry but where both searches are inefficient. Such asymmetries should *not* be held to be diagnostic of the presence of a basic feature. Rather, in Treisman and Souther's words, they seem to reflect "the speed at which distractors can be serially checked to determine if they meet the target specification" (Treisman & Souther, 1985, p. 292). Thus, Treisman and Souther offer the case of letters and mirror-reversed letters. Mirror-reversed targets are found more efficiently among normal letter distractors than normal letters are found among mirror-reversed distractors (Frith, 1974; Ostrovsky et al., 2005; Reicher, Snyder, & Richards, 1976; Richards & Reicher, 1978). However, both searches are relatively inefficient, and the difference probably reflects the speed with which the distractors can be rejected. Normal letters are more familiar and can be dismissed more quickly.

Searching for Two Features Within a Dimension

In Figure 13.9, we saw that it was easy to find a target defined by a triple conjunction of features. In Figure 13.10, we see, in the online color figure, that this is not the case when all the features are drawn from the same dimension—in this case, color. The target is the item that is red, blue, and yellow. It is not hard to identify once it is attended. However, it will need to be searched for in an inefficient manner. This would be true even if only two colors defined the target (Wolfe et al., 1990). Interestingly, guidance seems to be limited to one feature per dimension or, perhaps more precisely, attempting to guide to the item that is, say, red and green, turns out to guide to any item that is either red *or*

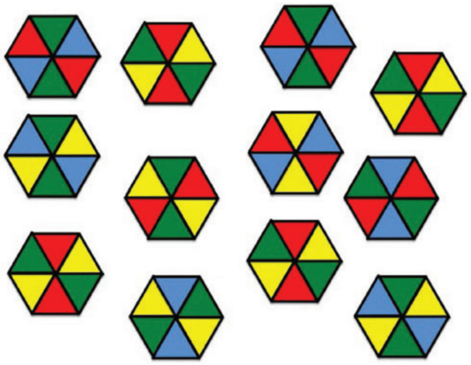

Figure 13.10 A triple color × color × color conjunction. Find the item that is red, blue, and yellow. It is not hard to identify, but the search will be inefficient.

green, at least initially (Berggren & Eimer, 2016).

This is not just an oddity of color. Search is inefficient if observers look for two sizes or orientations as well: For example, search will be inefficient for a vertical and oblique "X" among a mix of distractors that formed from oblique and horizontal components or from vertical and horizontal components (Wolfe et al., 1990).

There is an exception to the one-value-per-dimension rule. It is possible to search for an object of one color with a part of another color. So a red house with yellow windows can be found among blue houses with yellow windows and red houses with blue windows, though this is still a color × color conjunction (Wolfe, Friedman-Hill, & Bilsky, 1994). Apparently, guidance is sensitive to the part–whole structure of objects. The same result is found for size but, curiously, not for orientation (Bilsky & Wolfe, 1995). As a possible explanation, Bilsky and Wolfe noted that a red thing with a yellow part was still a red thing with a yellow part, even if that object was rotated in the image plane. The same would be true of a big thing with a small part but not of a vertical thing with an oblique part.

Multisensory Guidance to Objects

We live in a multisensory perceptual world (Stein, 2012), and many objects of our search are not purely visual. If you are walking though the woods looking for a bird, your search is, self-evidently, a combination of visual and auditory search. You may orient to a snatch of birdsong and, searching for the source, you will restrict your visual search to items that could plausibly be birds. What is the nature of that multisensory guidance? It is not easy to simply transfer the logic of something like a color × orientation search to a color × auditory search. Imagine a search for the buzzing red item among buzzing green and clicking red items. If the visual stimuli are presented on the normal computer screen, the auditory stimuli will be hard to localize and, worse, they will tend to merge together. If the stimuli are sparser and more spread out, eye and head movements will be required, and the efficiency of search will be harder to establish (Sanders & Houtmans, 1985). However, there is evidence for multisensory guidance of attention (Dalton & Spence, 2007; Ngo & Spence, 2010). Some of the most successful work has involved benefits from the presence of a single sound as in the "pip and pop" work of Van der Burg, Olivers, Bronkhorst, and Theeuwes (2008). They found that a "pip" sound, synchronized with the temporal properties of the visual target, made an otherwise hard-to-find time-varying visual stimulus "pop" out of the display even though the sound was otherwise uninformative. Fujisaki, Koene, Arnold, Johnston, and Nishid (2006) reported that search for such targets defined by audiovisual conjunctions was quite inefficient. However, Van der Burg, Cass, Olivers, Theeuwes, and Alais (2010) went on to show that the "pip and pop" effect did produce efficient search when transient, square-wave auditory stimuli were used. Similarly synchronized but gradual, sinusoidal variation did not work.

If we accept that there is some form of multisensory guidance, how early in sensory processing is this guidance made manifest? One possibility is that multisensory objects are created early in processing and that attention is directed to those objects (Matusz & Eimer, 2011). Others argue that the interactions are late, involving more cognitive processes (Orchard-Mills, Alais, & Van der Burg, 2013). Probably there are interactions at both levels (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). The bird example with which we started this section seems likely to be a relatively late phenomenon where, perhaps, an auditory signal cues attention, as well as the head and eyes, to a region, and then visual attention is guided to birdlike objects.

The Role of Objects

In the online version of Figure 13.11, look for green vertical targets.

After a bit of inspection, you will probably conclude that there are no such targets. If you now switch your search to green horizontal targets, you will probably decide that there is one, partially occluded in the lower left quadrant. In fact, there are clearly visible green vertical *contours* in the upper left and lower right quadrants, but these do not seem to count as green vertical targets. For those reading this in black and white, the two squares in the upper left are green. These green objects in the figure are not vertical, even though they might have vertical edges or might be occluded by a vertical edge. Apparently, when asked to search for green vertical, you were searching for a green vertical *object*. Moreover, the green horizontal object in the lower left is green horizontal only if it is amodally completed behind the pink and yellow occluders. This is more than a matter of fooling the observer with ambiguous instructions (green vertical target). Visual search and visual selective attention appear to be preferentially directed to objects and not to raw image features.

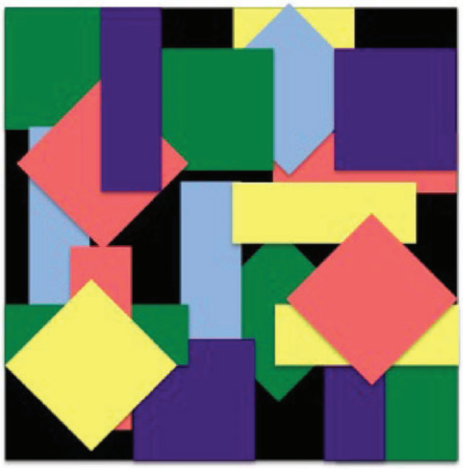

Figure 13.11 Targets are green vertical.

There is considerable evidence for a preferential role of objects in visual selective attention and search. Duncan (1984) found that confirming the presence of two features on one object was easier than confirming one feature on each of two objects even when the objects overlapped in space. Egly, Driver, and Rafal (1994) found that attention to one part of a simple object seemed to spread to other parts of the same object but not to equidistant parts of another object. New objects seem to preferentially capture attention (Yantis, 1993). Kahneman and Treisman proposed that attention operated on object files (Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992) that collected all the basic features of an object into one entity in the mind, and Treisman had shown that search for two features was difficult when those features were not present on the same object (disjunctive search; Treisman & Gelade, 1980). Subsequent work has made clear that, even when spatial factors are controlled, conjunctions of two features on one object are easier to find than disjunctions (Goldsmith, 1998). Wolfe and Bennett (1997) argued that, when discussing the status of the stimulus before selective attention was deployed, it might be best to talk about "preattentive object files" that they conceived of as "shapeless bundles of basic features" waiting to be bound by an act of attention. The pluses of Figure 13.2 were introduced by Wolfe and Bennett (1997), who argued that, prior to being selected by attention, each of these was represented as a preattentive object file having light purple and dark green and vertical and horizontal features. Only with attention did the color get bound to the orientation.

As illustrated by the green horizontal object in the lower left of Figure 13.11, the objects of attention are sophisticated enough to account for occlusion. Rensink and Enns (1998) found that it was very hard to search for a distinctive piece of an occluded object if that piece could be interpreted as part of a larger item. For example, you may find it hard to locate the triangular regions in Figure 13.11. Online, one will be green. All of them are the results of occlusion forming a triangular region in the image. None are triangular objects (see also Wolfe, Reijnen, et al., 2011). This sophistication points to a problem. If attention is directed to objects, it follows that there are preattentive objects available to be attended. That, in turn, implies that the scene is segmented into objects in parallel. That is hard to do. Part of the problem is that the definition of "object" in search is very task dependent. Consider a social media photograph of a group of people. You could search for people or you might search for eyes. In the second search the objects are part of the objects of the first search. What, then, is computed in the initial segmentation into "objects"? To hedge our bets and, in part, to acknowledge that we do not have a clear answer, researchers speak of an initial partition of the scene into "proto-objects" (Rensink, 2000; Russell, Mihalas, von der Heydt, Niebur, & Etienne-Cummings, 2013; Yanulevskaya, Uijlings, Geusebroek, Sebe, & Smeulders, 2013; Yu, Samaras, & Zelinsky, 2014) or preattentive object files. The exact nature of the "objects of attention" remains to be uncovered.

SCENE GUIDANCE

In Figure 13.12, look for traffic lights. Since you know something about what traffic lights look like, you can probably guide your attention to things that might have traffic light features. However, it should be clear that feature guidance is not the only force that is shaping the deployment of your selective attention. You know enough about urban intersections to know where traffic lights are

Figure 13.12 Look for traffic lights at this Shanghai intersection.

and are not likely to appear. This guidance is not based on properties of the target but on the structure and content of the rest of the scene. We can call this "scene guidance." Scene guidance is not a factor in tasks like the one illustrated in Figure 13.11, because those scenes have no meaningful structure. However, it is a major factor in real-world searches, embedded as they are in the real world.

Part of becoming an expert searcher in a specific domain is learning how to let the scene guide attention. When radiologists' eye movements are examined, it is found that experts look at less of the image than do novices (Kundel & La Follette, 1972). Just as you know where to look for traffic lights, a radiologist knows where to look for lung cancer in a chest X-ray. Similarly, a chess player can find specific pieces on a real game board more quickly than on a board where the pieces have been placed at random (Brockmole, Hambrick, Windisch, & Henderson, 2008). The features of the target remain the same, but the structure of the scene tells the expert where to look.

In thinking about scene understanding, Biederman (1977) suggested that "something roughly analogous to what may be needed to account for the comprehension of sentences is required to account for the speed and accuracy of the comprehension of scenes never experienced before." He went on to propose that one could talk about scene syntax and scene semantics. *Syntax* refers to the structure of the scene. A coffee mug floating in midair would be a syntactic violation of the grammar of a scene, because coffee mugs don't float. *Semantics* refers to the meaning of a scene. Knowing where an object would be meaningful in a scene helps guide your attention when you are looking for that object (Castelhano & Witherspoon, 2016). A coffee mug sitting in a bathtub would be a semantic violation because, although a coffee mug can be placed in the tub, it does not normally make sense in that location (Biederman, Mezzanotte, & Rabinowitz, 1982). Vo and Wolfe (2013) found that syntactic and semantic anomalies produced different electrophysiological signals.

It has been clear for a long time that search in a scene is guided by the content of that scene (Enoch, 1959b; Kingsley, 1932; Matusz & Eimer, 2011). That said, it is difficult to quantify the efficiency of search in scenes because it is essentially impossible to establish the set size of a scene. Returning to Figure 13.12, in a search for traffic lights, is each person an "item"? How about each shoe or the black diamonds on the wall in the distance? However one tries to measure the set size of a scene, the data indicate that search for meaningful objects in meaningful scenes is very efficient (Wolfe, Alvarez, Rosenholtz, Kuzmova, & Sherman, 2011). Search for less meaningful targets can be very laborious (Pomplun, 2006). Neider and Zelinsky (2008) introduce the useful idea of the "effective set size," the subset of items in a scene that compete for attention in a search for a particular target. Thus, in Figure 13.12, the effective set size would be different in a search for shoes and a search for women. We may not be able to precisely quantify the effective set size in a natural scene, but it is clear that the effective set size is almost always far smaller than any count of the objects in a scene for any realistic search.

Thus, visual searches in scenes are strongly guided by the observer's understanding of the scene. One way to see this is to ask observers to search after a very brief glimpse or preview of a scene. Castelhano and Henderson (2007) pioneered a method where observers could view only a small part of a scene around the point of fixation. Under these conditions, search is akin to sweeping a flashlight around a darkened room. The brief preview is enough to give the observer considerable guidance as to where to direct the aperture of visibility. The information available in a flash is both syntactic and semantic. Showing a preview of one kitchen does not help very much in a search through another kitchen. It is important to get a quick impression of the layout of the space (Greene & Oliva, 2008), as well as to gather some information about the scene's contents (de Groot, Huettig, & Olivers, 2016). The scene information can be thought of as providing a Bayesian prior that tells the searcher that a target is more or less likely in each location (Torralba, Oliva, Castelhano, & Henderson, 2006). Using measures of eye movements (Ehinger, Hidalgo-Sotelo, Torralba, & Oliva, 2009) or measurements of the deployment of a magnifier (Ehinger & Wolfe, 2015), one can see this guidance at work in tasks as varied as search for humans in natural scenes (Ehinger et al., 2009) or for gas stations in overhead satellite imagery (Ehinger & Wolfe, 2016).

Scene guidance poses a problem for simple search architectures, described earlier in this chapter. If object recognition requires attention and involves a severe bottleneck in processing, how can a scene guide attention? Wouldn't you need to attend to the objects before you could guide attention based on an understanding of the scene containing those objects? There are two important components of an answer to that question. First, significant information about a scene can be extracted in a very brief glimpse (Biederman, Rabinowitz, Glass, & Stacy, 1974). This gist includes a spatial structure that can be extracted without processing individual items (Oliva & Torralba, 2001). This information, based on the raw (unbound) image statistics, is adequate to very rapidly categorize scenes (mountain, beach, etc.) (Greene & Oliva, 2008, 2009) and can be used to detect the presence of some classes of objects (e.g., animals: F. F. Li, VanRullen, Koch, & Perona, 2002; Thorpe, Gegenfurtner, Fabre-Thorpe, & Bulthoff, 2001; or vehicles: Peelen, Fei-Fei, & Kastner, 2009). The timing of this gist effect makes it very unlikely that the gist is the result of repeated acts of selective attention, binding, and recognition. Instead, it has been proposed that there is visual experience that arises from both a selective pathway and a nonselective pathway (Wolfe, Vo, Evans, & Greene, 2011). The selective pathway is required for most standard object recognition. The nonselective pathway fills in the visual experience at currently unattended locations. It is useful for gist and other statistical analyses of the image (Alvarez, 2011), and its outputs can guide attention.

In addition, some aspects of scene guidance can be quite slow (de Groot et al., 2016; Kunar, Flusberg, & Wolfe, 2008b). As one processes the details of a scene, multiple objects will be attended. These will inform subsequent deployments of attention. Thus, it may require attention to identify the fork on the dining room table. However, once identified, the fork can help to guide attention to the spoon.

Scene structure can speed search even if the scene is meaningless. Chun and Jiang (1999) developed the *contextual cueing* paradigm in which observers might search a series of seemingly meaningless arrays for a specific letter. Unbeknownst to the observer, some of the arrays repeat. Over time, RTs for repeated displays become shorter than those for unrepeated displays. The leading account of contextual cueing would be that the implicitly recognized scene guides attention toward the target (e.g., Geyer, Zehetleitner, & Muller, 2010; Olson, Chun, & Allison, 2001), though there is data to support the alternate view that the context serves to speed response once the target has been attended (Kunar, Flusberg, Horowitz, & Wolfe, 2007).

THE ROLE OF MEMORY IN VISUAL SEARCH

The contextual cuing phenomenon shows a role for memory in visual search. Observers show clear evidence that they remember previously viewed displays, even if that memory is implicit. Interestingly, there are a variety of situations where memory seems to have less of an effect than one might expect. For example, suppose an observer is viewing a display of six letters. On each trial, he is asked if a specific target letter is present (Is there an "E"? Is there a "Q"?). The display remains unchanged across trials. If this search task is repeated for a display of three letters, the difference between RTs for the two set sizes can be used to derive the slope of an RT × set size function for the first trial or for the *n*th trial. The first trial resembles a standard inefficient letter search with a slope around 35 ms/item. The surprise is that this slope remains essentially unchanged over several hundred trials (Wolfe et al., 2000). Even though the observer learns the display perfectly, it appears that this memory is not useful in search. Results are about the same as if all the letters are changed on each trial. An explanation can be seen if the visual display is removed and the observers perform the task from memory. They can do it, but the slope for the memory search is steeper than that for the visual search (Kunar, Flusberg, & Wolfe, 2008a), suggesting that in repeated search observers do the visual search over again de novo each time simply because vision wins a race with memory search. On most trials, vision finds the target first.

Memory appears to have a similarly limited role within a search. Many standard models of search assumed that inefficient searches involved sampling from the visual display "without replacement." That is, attention might select one item after another but, once selected and rejected as a distractor, those items would not be selected again. "Inhibition of return" (Posner & Cohen, 1984) was proposed as a mechanism by which rejected distractors were tagged during search (Klein, 1988). Horowitz and Wolfe (1998) called this into question with an experiment in which observers looked for a T among Ls in a display where all items were randomly replotted every 100 ms, making inhibitory tagging impossible. This had surprisingly little effect on search slopes. Their claim that "visual search has no memory" (Horowitz & Wolfe, 1998) was controversial (Horowitz & Wolfe, 2003, 2005; Hulleman, 2010; Korner & Gilchrist, 2008; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; Shore & Klein, 2000). Most likely, there is some limited memory for rejected distractors, enough to act as a "foraging facilitator" that prevents perseveration on one salient distractor (Klein & MacInnes, 1999; Z. Wang & Klein, 2010).

These failures of memory tend to be seen with simple searches that take a fraction of a second. It is intuitively obvious that memory serves a more substantial role in more extended search. If you are ransacking the house for your car keys, there is a role for memory of where you have already searched, but even in these cases you may find yourself revisiting previously examined locations. In laboratory tasks, there is a significant role for memory when observers search repeatedly through real scenes (Vo & Wolfe, 2012; Wolfe, Alvarez, et al., 2011).

SEARCH TERMINATION

A role for memory in visual search was a part of standard models of search, in part because it provided an account of how observers knew when it was time to abandon an unsuccessful search. If you were marking each rejected distractor, you could stop searching when all the distractors were marked. In guided search, you could stop searching when all *plausible* distractors had been checked. However, if memory for rejected distractors is too impoverished to support this sort of search termination rule, a different rule must be at work. Various approaches have been tried (Chun & Wolfe, 1996; Cousineau & Shiffrin, 2004; Zenger & Fahle, 1997). As a general rule, they involve attempting to set a quitting threshold based on time (How long have I been searching?) and some estimate of the probability that there is a target present. For example, a version with some clever features is found in the "competitive guided search" model of R. Moran, Zehetleitner, Mueller, & Usher (2013). In that model, the probability of quitting is calculated after each deployment of attention. P(quit) is defined as QuitWeight/(sum(AllSalienceWeights) + QuitWeight). The QuitWeight is a parameter that changes by increments after each deployment of attention, and the sum(All SalienceWeights) is a measure of how target-like the stimuli appear to be. That sum is likely to be higher for a target-present trial, making it less likely that the trial will end, even if the target has not yet been found. The QuitWeight parameter will be set to grow faster for simple feature searches than for harder tasks, so those trials can end more quickly when no target is present. Quitting models can have a more explicitly Bayesian flavor in which there is an explicit estimate of the likelihood that a given stimulus contains a target (Ehinger & Wolfe, 2016). Such models can incorporate scene-based priors ("This is the sort of scene where I might find a turkey.").

TARGET PREVALENCE

In the lab, targets are typically presented on 50% of trials. This target prevalence might go to 100% in tasks where observers are asked to localize the target. Target prevalence varies widely in real-world search tasks. In the search for your car keys, the target is almost undoubtedly present, even if that presence is not obvious. At the other extreme, targets are very rare in search for threats at the airport checkpoint or search for breast cancer in a screening program (about 0.3% in North America; Lee, Bhargavan-Chatfield, Burnside, Nagy, & Sickles, 2016). Target prevalence has a substantial effect on search behavior. Rare targets are missed simply because they are rare (Mitroff & Biggs, 2014; Wolfe, Horowitz, & Kenner, 2005). In mammography, for example, radiologists may miss twice as many cancers when prevalence is low (Evans, Birdwell, & Wolfe, 2013). Similar effects occur in other medical screening situations (Evans, Tambouret, Wilbur, Evered, & Wolfe, 2011) and with airport screeners (Wolfe, Brunelli, Rubinstein, & Horowitz, 2013). Prevalence does not generally have a major effect on the *detectability* of stimuli (e.g., in radiology; Gur et al., 2003, 2008; Reed, Ryan, McEntee, Evanoff, & Brennan, 2011). Rather, the main effect appears to be on decision criteria (Wolfe & VanWert, 2010). At low prevalence, observers make more miss errors, but few false alarm errors. At high prevalence, this pattern reverses. Low prevalence also induces observers to terminate search more quickly (Wolfe et al., 2007). This can have an effect on overall accuracy when observers simply quit before doing an adequate search or when they make a motor error, responding "absent" out of habit (Fleck & Mitroff, 2007).

FORAGING TASKS

The classic search literature has mostly dealt with search for the presence or absence of a single target item. Real-world search tasks often involve search for multiple targets: for example, pulling all the pennies out of the coin bowl or picking ripe berries off a bush. These are foraging tasks and have been much studied in the animal literature (Stephens, Brown, & Ydenberg, 2007; Stephens & Krebs, 1986). For present purposes, these tasks are of most interest for the search termination problems they pose. When do you abandon foraging, given an unknown number of targets? When targets are plentiful, Charnov's marginal value theorem (MVT; Charnov, 1976) provides a good account. It holds that the forager will leave the current patch or bush for the next one when the instantaneous yield from the current patch falls below the average rate for the task as a whole. Developed to account for animal behavior, this does a good job describing human performance in simple simulated berry picking (Wolfe, 2013). If targets are more sparse (as in many medical imaging tasks), MVT does not work well and other, more Bayesian theories better describe the data (Cain, Vul, Clark, & Mitroff, 2012; Ehinger & Wolfe, 2016).

HYBRID SEARCH AND HYBRID FORAGING

In other real-world search tasks, there may be more than one target type. Think of a shopping list held in memory. These combinations of visual search with memory search have been called "hybrid search" tasks (Schneider & Shiffrin, 1977). Older research used a relatively small number of alphanumeric targets (Neisser, Novick, & Lazar, 1963). However, if one uses specific photographs of objects as targets, it is possible to have observers search for literally hundreds of different target types at the same time. When visual set size and memory set size are varied orthogonally, it is found that RTs increase linearly with the visual set size but logarithmically with the memory set size (Wolfe, 2012). This log compression of the memory search makes it possible to search for any of 100 possible targets in seconds rather than the many minutes that might be required if RT increased linearly with memory set size. The log function is very robust, being found when multiple categories are used as targets (find all animals, socks, and coins: Cunningham & Wolfe, 2014) or when word lists are used (Boettcher & Wolfe, 2015). The ability to search for 100 target types at the same time argues against the idea that the target templates for search reside in visual working memory (VWM), since VWM is held to have a capacity of three or four items (Drew, Boettcher, & Wolfe, 2015). Still, it is clear that VWM plays a role in guiding search (Olivers, Peters, Houtkamp, & Roelfsema, 2011). The precise nature of that role in hybrid search remains to be worked out.

If observers are asked to search for multiple instances of multiple targets, they are engaged in a "hybrid foraging" task. Here a somewhat different set of questions come to the fore. Suppose you are sorting the US pennies, nickels, dimes, and quarters out of your bowl of coins from around the world. If the last coin that you selected was a dime, with four targets in the memory set, we can ask if all four target types are equally likely to be selected next. The answer is "no." Even if the underlying probabilities are the same, you are biased to pick what you have just picked. Selections tend to go in runs of multiple instances of the same type (Jóhannesson, Thornton, Smith, Chetverikov, & Kristjánsson, 2016; Kristjansson, Johannesson, & Thornton, 2014). Switching from one type to another can be seen as a variety of search termination decision, and, as in foraging more generally, the marginal value theorem predicts average behavior quite well, though predicting the foraging behavior on a finer grain requires modeling of the interaction of vision, attention, and memory in ways that are just beginning to be considered.

MODELING APPROACHES

Space does not permit a comprehensive survey of models of visual search (for recent surveys see Nobre & Kastner, 2014). The classic debate has been between serial and parallel models. Serial accounts are typically two-stage accounts with intellectual roots in Triesman and Gelade's feature integration theory (1980). Following Neisser (1967), they proposed an initial parallel stage of processing that could handle processing of basic features across the entire visual field followed by a serial stage in which attentional resources were deployed from item to item to bind features, allowing stimuli defined by conjunctions of features to be found, but only one at a time. Models like the early versions of guided search (Wolfe et al., 1989) and later versions of feature integration theory (Treisman & Sato, 1990) proposed that information from the first stage could be used to guide deployment of attention in the second stage (see also Cave, 1999; R. Moran et al., 2013).

Parallel models dispense with the bottleneck following the first stage. Often, these models see search as a signal-detection problem with uncertainty about the location of the signal (the target). Early versions accounted for letter search tasks (Kinchla, 1974). These models have their greatest success in accounting for detection of fairly simple targets (e.g., Gabor targets) in relatively small arrays of distractors (McElree & Carrasco, 1999; Palmer, 1995; Palmer, Verghese, & Pavel, 2000; Verghese, 2001). In Bundesen's theory of visual attention (TVA), multiple items race in parallel to occupy visual working memory. TVA can be placed in the family of parallel models (Bundesen, 1990; Bundesen, Vangkilde, & Petersen, 2015).

As noted earlier, simple RT × set size functions are not adequate to distinguish between standard serial and parallel architectures (Townsend, 1971, 1976, 1990; Townsend & Wenger, 2004). One approach to this problem has been to move beyond just looking at average or mean RTs and to look at the whole RT distribution (R. Moran et al., 2015; E. M. Palmer, Horowitz, & Wolfe, 2009; Sung, 2008; Wolfe, Palmer, et al., 2010). Others have developed sophisticated new RT and/or accuracy methods to distinguish between classes of models (e.g., Baldassi & Verghese, 2002; Dosher et al., 2004; Thornton & Gilden, 2007), though proponents of the losing model can usually tweak the model to accommodate the new data. Many models attempt to ground themselves in the neurophysiological data rather than in behavioral RT data (for reviews see Nobre & Kastner, 2014; Reynolds & Chelazzi, 2004). The most influential of these is biased competition (Desimone & Duncan, 1995), based on work showing that items in the visual field compete for control of visual cortical neurons (J. Moran & Desimone, 1985).

More recent modeling has tended to blur the distinction between serial and parallel models. For instance, when essentially parallel accounts include eye movements, they are incorporating a necessarily serial aspect of the process (Najemnik & Geisler, 2005; Pomplun, Reingold, & Shen, 2003; Zelinsky, 2008). Similarly, models that place a major focus on the role of peripheral crowding (Rosenholtz et al., 2012) need to worry about the serial deployment of the fovea even if the model does not see a need for serial deployments of attention. Turning to the two-stage models, estimates for the rate of deployment of covert attention in search are in the vicinity of 20 Hz, but accounts of object recognition typically assume that processing takes several hundred milliseconds. One way to accommodate these two temporal parameters into a single model is to assume that object recognition in search is a pipeline. Items are selected, say, every 50 ms, but they may take 300 ms to be recognized. This means that multiple items will be in the process of recognition at the same time—in parallel—even if individual items are selected in series. If it is possible to select more than one item at a time, the distinctions between parallel and serial models are further blurred. In retrospect, this is not surprising. The neural substrate of the human search engine is neither strictly serial nor parallel, so an effective model is likely to reflect that fact. In the end, the mark of a successful model will be its ability to capture the richness of the human search behavior that we have been describing in this chapter.

LOOKING BACK AND LOOKING FORWARD

Three or four decades of work on visual search support a number of conclusions (though, to be fair, good scientists could be found who might argue with each of these):

- We search because some aspects of visual processing are severely capacity limited. In particular, object recognition appears to be limited to one item or a very small number of items at a time.
- Interpretations may differ, but there is a reliable body of empirical results on search. This is especially true for oft-repeated searches for targets like feature singletons or color × orientation conjunctions in random arrays of distractors. These are highly replicable findings.
- In order to be useful, most searches are strongly guided. Attention is guided toward items and/or locations displaying target features and away from parts of scenes—especially structured, meaningful scenes—that are unlikely to contain a target.
- The list of guiding features is limited relative to the set of all possible visual properties that could potentially guide attention. Membership on the list needs to be empirically established, as there does not appear to be a clear principle that mandates membership.
- Features that can guide attention must, by definition, be available preattentively, but it does not follow that some pieces of the visual system are exclusively preattentive while others are attentive. A preattentive representation of, say, color in one neural location may become attentive later in the sequence of processing.
- Strict dichotomies between serial and parallel processing are probably unwise. Search processes are probably a mixture of both. For instance, if items are selected every 50 ms or so and then processed for recognition for 200–300 ms, then serial selection and parallel processing of items would be occurring simultaneously.

Looking forward, there are a many topics that would benefit from more research. Our goal is to understand the ways that humans search in the world. For practical reasons, most of the work in this field has involved search of single images on computer screens. Even the efforts to apply visual search results have typically involved imaged-based search tasks in the real world (e.g., medical image perception or airport baggage screening). More typical real-world search has qualities quite different from most laboratory search tasks. The searches are extended in time. The bulk of lab searches take on the order of 0.2 to perhaps 10 seconds. Your search for the cat takes longer. Moreover, that cat search takes place in a 3D space with a mobile observer. In the lab, you might search for the T among Ls for hundreds of trials. If you are putting that cat in the basement for the night, you search for the cat. You then search for the basement (guided, one presumes, by memory). You search for the cat food to give the beast an evening snack. There is very little work on this sort of concatenated series of searches, spread out over significant time. Perhaps with the advent of commercially available virtual reality systems, researchers will begin to study tasks of this sort. If so, the next *Stevens' Handbook* might feature quite a different chapter on visual search.

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