

# A Taxonomy of External and Internal Attention

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## Abstract

Attention is a core property of all perceptual and cognitive operations. Given limited capacity to process competing options, attentional mechanisms select, modulate, and sustain focus on information most relevant for behavior. A significant problem, however, is that attention is so ubiquitous that it is unwieldy to study. We propose a taxonomy based on the types of information that attention operates over—the targets of attention. At the broadest level, the taxonomy distinguishes between external attention and internal attention. External attention refers to the selection and modulation of sensory information. External attention selects locations in space, points in time, or modality-specific input. Such perceptual attention can also select features defined across any of these dimensions, or object representations that integrate over space, time, and modality. Internal attention refers to the selection, modulation, and maintenance of internally generated information, such as task rules, responses, long-term memory, or working memory. Working memory, in particular, lies closest to the intersection between external and internal attention. The taxonomy provides an organizing framework that recasts classic debates, raises new issues, and frames understanding of neural mechanisms.

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## INTRODUCTION

William James famously declared that “Everyone knows what attention is,” but paradoxically, such colloquial understanding has impeded the scientific study of attention. Case in point: the extraordinary power and breadth of electronic databases have now rendered “attention” useless as a term for reference searches. Try typing “attention” into your favorite literature search engine, such as PubMed, Web of Science, or Scopus, and you will get hits in the hundreds of thousands, significantly more than other general terms such as “memory.” Or imagine

yourself as an attendee in a scientific conference wanting to learn what’s hot in attention research. How should you plan your week when “attention” yields hundreds of presentations and dozens of sessions? How can you meaningfully categorize hundreds of abstracts that claim “attention” as the primary keyword? Ironically, scientists can’t use the term “attention” to “select” relevant studies of interest.

The practical problem above happily reflects breathtaking progress in attention research. The concept of attention has now permeated most aspects of perception and cognition research. Growing consensus indicates that selection mechanisms operate throughout the brain and are involved in almost every stage from sensory processing to decision-making and consciousness. Attention has become a catch-all term for how the brain controls its own information processing, and its effects can be measured through conscious introspection, overt and implicit behaviors, electrophysiology, and brain imaging.

Attention was not always such a widely used concept. The modern birth of attention research during the cognitive revolution grappled with specific questions: Does selection occur before perception or after semantic identification? What happens to unselected information? These questions continue to guide much research, but they now apply to almost all cognitive operations beyond perception. Information processing is modulated by task goals across all stages of sensation, object recognition, memory, emotions, and decision-making. We should therefore abandon the view of attention as a unitary construct or mechanism, and consider attention as a characteristic and property of multiple perceptual and cognitive control mechanisms. And if ubiquitous, then it becomes important to understand what’s common and what’s different about these multiple forms of attention.

When a group of related concepts and ideas becomes unwieldy, a taxonomy proves useful. Organizing and categorizing large collections of findings brings clarity and understanding. The most famous Linnaean taxonomy

has advanced our understanding of the natural world, and these initial classifications based on superficial characteristics set the stage for a deeper understanding of natural taxonomies based on evolution and genetics. Within psychology, memory research has long benefitted from a taxonomy of memory systems, divided according to memory content or whether memory is consciously accessible or not (Johnson 1983, Schacter & Tulving 1994, Squire et al. 1993).

Similarly, a global taxonomy of attention can advance our understanding and stimulate further research. This review aims for a big-picture synthesis, by necessity, focusing on global issues and features at the expense of detail, pointing the readers to relevant specialized reviews where possible. The value of this taxonomy will not lie on whether it is correct in its proposed form, but rather as a starting point to sketch a big-picture framework and to develop common language and concepts. At a minimum, the taxonomy serves as a portal for the attention literature, and at its best, it can stimulate new research and more integrative theories. The review begins with core properties, followed by the taxonomy. We close with a discussion of recent progress on classic and future issues in attention research.

## **BASIC CHARACTERISTICS AND FUNCTIONS OF ATTENTION**

### **Limited Capacity**

Attention is necessary because at any given moment the environment presents far more perceptual information than can be effectively processed, one's memory contains more competing traces than can be recalled, and the available choices, tasks, or motor responses are far greater than one can handle. This constraint of limited capacity applies to all nodes of our taxonomy. Attentional mechanisms evolved out of necessity to efficiently focus limited processing capacity on the most important information relevant to ongoing goals and behaviors (Pashler et al. 2001).

### **Selection**

Limited processing capacity dictates a need for selection, and a primary goal of attention research is to understand which information is selected, how it is selected, and what happens to both selected and unselected information. Selection is a core function of all forms of attention considered in this review. Multiple stimuli or options compete for selection, and the goal of attention is to bias competition in favor of a target object or expected event (Desimone & Duncan 1995). For example, in vision, acuity is limited to the fovea requiring eye movements to targets of interest. In hearing, auditory environments typically present many competing sounds, and one must select what's most relevant, such as a conversation with a friend at a cocktail party. High-level cognitive operations require selection also. Choosing between alternatives in decision-making represents a form of selection. Selecting a memory from competing memories should be viewed as an attentional operation. The cost is that unattended information may be missed, whether it is a gorilla in a video (Simons & Chabris 1999), a traffic light while chatting on a cell phone during driving (Strayer & Johnston 2001), a boarding announcement at the airport while talking with a friend (Cherry 1953), or the name of an old acquaintance you chance to meet—only for it to pop into your mind after you part (for a review on memory failures, see Schacter 2001).

### **Modulation**

Once a target object, event, or representation is selected from competing options, attention determines how well the target information is processed, how fast and accurate a task and response are executed, and whether the event will be later remembered. Attention facilitates sensory processing throughout cortex, even changing the qualia of how attended objects are perceived (Carrasco et al. 2004). The distinction between selection and modulation is that selection entails that there are other competing items. Modulation refers to what happens to

the selected item, such that attention influences the processing of items in the absence of overt competition. Another way to think of this distinction is in terms of facilitation: As opposed to modulation, selection alone does not ensure better behavioral performance or memory (Levin & Simons 1997).

## Vigilance

Vigilance is related to the modulatory effects of attention. Here, we define modulation as the current, immediate effects of attention on processing, whereas vigilance refers to the ability to sustain this attention over extended periods of time. Perceptual and cognitive mechanisms do not always operate at peak levels, but their activation levels and efficiency ebb and flow (Berridge & Waterhouse 2003). If so, then one should be able to use noninvasive methods such as functional neuroimaging to measure the neural activity during the moments even before a stimulus is presented (Kastner et al. 1999). Remarkably, brain activity and mental state before a trial commences can be predictive of many aspects of behavior, including how well subjects remember a stimulus (Otten et al. 2002, Turk-Browne et al. 2006) and prepare for or perform a task (Leber et al. 2008, Weissman et al. 2006). The ability to sustain attention and focus over time is essential for practical domains such as tumor detection in mammography or baggage screening for airplanes (Wolfe et al. 2005), as well as for daily functioning in work, school, and social settings. Indeed, understanding how attention is sustained can inform our understanding of clinical disorders such as attention deficit disorder (Biederman & Faraone 2005).

## AGAINST A UNITARY MODEL OF ATTENTION

Is there a single mechanism that governs both visual search and selective listening? Is the selection of sensory inputs the same as selecting which item to recall from memory or which choice to make when confronted with multiple

alternatives? A strong conclusion of this review is that the answer is a resounding no.

Attention is not unitary. Rather, attention should be considered as a property of multiple, different perceptual and cognitive operations (Lavie et al. 2004, Parasuraman 1998, Pashler 1998). Hence, to the extent that these mechanisms are specialized and decentralized, attention mirrors this organization. These mechanisms are in extensive communication with each other, and executive control processes help set priorities for the system overall. However, such priority setting is still independent of the actual nuts and bolts of selection and modulation within the multiple mechanisms.

Evidence against unitary models of attention comes from behavioral studies and from cognitive neuroscience methods, including brain imaging and neuropsychology that reveal some degree of modularity in the brain. Clever tasks and manipulations have enabled researchers to carve out and map an architecture for perceptual and cognitive processing. Patterns of interference or lack of interference between tasks help to reveal which processes share capacity and which do not.

## A TAXONOMY OF EXTERNAL AND INTERNAL ATTENTION

We propose that the core characteristics of attention are shared across multiple systems: the problem, that there is too much information to process; the solution, to select and modulate information most relevant for behavior; and the challenge, to sustain vigilance. Given these general properties of all varieties of attention, our goal here is to organize them into a taxonomy.

We categorize attention according to the types of information that attention operates over—the targets of attention. From this perspective, it becomes immediately apparent that there is a distinction between selecting information coming in through the senses and information that is already represented in the mind, recalled from long-term memory or being maintained in working memory. Sitting at your desk, you can focus on the information on

the computer screen, a conversation in the hallway, or the taste of the stale coffee brew in your cup. These examples of external attention can be distinguished from how you could instead be focusing your attention on your thoughts, contemplating a talk you just heard, trying to remember the author of a paper you want to find and cite, or trying to decide where to go to lunch, all while staring at your computer screen with conversations going on in the hallway.

Thus, our taxonomy makes a primary distinction between external attention and internal attention. External attention refers to the selection and modulation of sensory information, as it initially comes into the mind, generally in a modality-specific representation and often with episodic tags for spatial locations and points in time. This sensory information can be organized by features or into objects, which can themselves be targets of external attention. Another way to think of external attention is as perceptual attention. Internal attention refers to the selection and modulation of internally generated information, such as the contents of working memory, long-term memory, task sets, or response selection. Internal attention includes cognitive control and can also be referred to as central or reflective attention (Johnson 1983, Miller & Cohen 2001).

This distinction is present in the expanded William James quote, “Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence.” William James eloquently distinguishes the possession of the mind by “objects,” which we interpret as external attention, or “trains of thought,” what we call internal attention. As empirical support, increasing the load of perceptual input has different effects than increasing the load of working memory (Lavie et al. 2004). Perceptual processing proceeds independent of demands on working memory, response selection, or task switching (Pashler 1994). More examples are reviewed below. Of course, the bound-

ary between perception and central cognition is blurry, but this distinction is the most useful and natural one.

We are certainly not the first to distinguish among different types of attention. Other classifications are prominent and are discussed here. Attention facilitates target processing while inhibiting distraction and noise. Exogenous, bottom-up, stimulus-driven attention is distinct from endogenous, top-down, goal-directed attentional control. Sustained attention operates over a longer time course than transient attention. Attention can move overtly together with eye movements or covertly with eyes fixating. These distinctions are real and useful—and hold places in our taxonomy—but individually do not provide a broad organizing principle as the external/internal axis we pursue here. A main difference is that these previous distinctions focus on differentiating specific mechanisms or properties of attention—our taxonomy is based on the targets of attention, encompassing all of its mechanisms and properties.

**Figure 1** provides a schematic overview. External and internal attention are on opposite ends of an axis. Each box within this space represents a target of attention—a class of information over which specialized selective and modulatory processes operate. Despite the implied modularity, the axis should be viewed as continuous, and the boxes are massively interactive, especially those depicted in the same or adjacent levels. Along an orthogonal dimension, goal-directed (top-down, endogenous) attention and stimulus-driven (bottom-up, exogenous) attention characterize how different levels interact (Egeth & Yantis 1997). For reasons explained below, goal-directed attention can target any of the levels in the taxonomy, whereas stimulus-driven attention is by definition a property of external attention.

The remainder of this review builds up this taxonomy with influential studies in the attention literature. An important caveat is that when studies appear in a different grouping or part of the taxonomy below, it doesn’t mean that the mechanisms involved are necessarily unique

and separate. The taxonomy simply reflects the fact that relevant studies can be grouped around a certain set of issues and questions, such that paper citations would be clustered. The goal is not to strictly segregate the different topics of attention, but rather to organize them better so that connections between areas of study will become more clear.

### External Attention

External attention to the perceptual world can be subdivided according to the focus of attention. First, attention can be directed to one or several modalities, separable from each other during initial neural processing. Second, independent of modality, attention is deployed over space and over time, with separate issues to consider for spatial versus temporal attention. In addition, attention can be allocated over space, time, and modality according to stimulus features or how they are organized into objects. These dimensions are not exclusive of each other, but they represent useful ways to organize the mechanisms of attention, and they represent lines along which studies have been conducted.

**Modality.** Sensory processing is initially separate for the five modalities of vision, hearing, touch, smell, and taste. Attention serves to select and modulate processing within each of the five modalities, and it directly impacts processing within relevant sensory cortical regions. Although the bulk of research reviewed and categorized in this taxonomy stems from the visual attention literature, these findings generalize well to the other modalities. For example, attention to visual stimuli enhances discrimination and activates relevant topographic areas in retinotopic visual cortex (Tootell et al. 1998), allowing observers to detect stimuli at lower contrast or to make finer discrimination. Attention to sounds enhances processing in auditory cortex (Woldorff et al. 1993), allowing listeners to detect fainter sounds or to discriminate finer pitch differences. Similar effects of attention operate in somatosensory cortex, olfactory

cortex, and gustatory cortex (Johansen-Berg & Lloyd 2000, Veldhuizen et al. 2007, Wager et al. 2004, Zelano et al. 2005).

One goal of research is to clarify how independent these systems are and how they interact. These different systems appear to operate separately with independent capacity—an inference that can be made by showing that multiple signals coming from the same modality interfere more with each other than do signals coming in from across different modalities (Arnell & Jolicoeur 1999, Duncan et al. 1997, Potter et al. 1998). Interference between modalities appears to occur at a more central stage of processing.

Indeed, inputs from the different modalities must converge at some stage to provide a coherent representation of the environment (Driver & Spence 1998). For example, based on a spatial representation of the environment, information from different modalities is linked according to the locations and objects in which the information arises in external space. Spatial attention to a location enhances discrimination responses across multiple modalities. For example, sudden touches not only draw tactile attention, but also visual and auditory attention toward them. Redundant signals from different modalities can enhance each other (Spence et al. 1998). Attention serves to bind simultaneously presented signals across space into multisensory objects (Busse et al. 2005).

Neural investigations are useful for understanding external attention to modality. When a touch on the hand improves vision near that hand, where do different modality signals converge and how does attention cross modalities? In the case of tactile enhancement of vision, multimodal parietal areas appear to project attentional signals to enhance unimodal visual cortex (Macaluso et al. 2000). Brain mechanisms such as the left superior temporal sulcus are sensitive to when audio-visual inputs are matched versus when they're discordant (Calvert et al. 2000). Future work should continue to clarify how information from different modalities can be integrated (Ghazanfar & Schroeder 2006).

**Spatial attention.** Spatial attention concerns how to prioritize spatial locations in the environment, and it is a prime example of the limited capacity problem. Spatial attention is central to vision, especially to deploy foveal acuity (eye movements) to prioritized locations, and hence, most of the work reviewed below involves visual tasks. But as noted above, principles of spatial attention generally apply to other modalities as well.

Spatial attention is often compared to a “spotlight” (Cave & Bichot 1999), an analogy that by definition implies a single, limited locus, although attention can be split across multiple locations (Awh & Pashler 2000, McMains & Somers 2004; c.f. Jans et al. 2010) or spread across space with reduced effectiveness (Eriksen & St James 1986). In vision, spatial attention mechanisms evolved to guide and control eye movements (Rayner 2009, Schall & Thompson 1999), so attention and eye movements are tightly interlinked (Deubel & Schneider 1996, Hoffman & Subramaniam 1995, Kowler et al. 1995). Spatial orienting and saccadic control employ overlapping neural systems (Corbetta et al. 1998). However, eye movements and attention are dissociable (Hunt & Kingstone 2003, Juan et al. 2004). That is, spatial attention can be overt, linked with the guidance of eye movements, or covert, in that a location can be attended without being foveated.

Both overt and covert spatial attention can be modulated by exogenous and endogenous cues (Corbetta & Shulman 2002, Egeth & Yantis 1997). Posner et al. (1980) popularized the distinction between exogenous cuing and endogenous cuing. Exogenous, bottom-up, stimulus-driven cuing draws attention to a location by a cue, such as a flashed stimulus, appearing in the same location as the target. Endogenous, top-down, goal-directed cuing directs attention to a location with a symbolic cue that instructs where to attend, using arrows or left/right word cues that do not appear in the same location as the target to attend (Hommel et al. 2001). The distinction between exogenous and endogenous attention is especially important for understanding attentional deployment

when there are multiple objects and events in the visual field. When attention is focused on a certain location, what are the mechanisms involved in shifting attention to a new location or a new object? Attention may be voluntarily moved to a different location in a goal-directed manner. Or attention may be “captured” by an object or event occurring in a different, unattended location in a stimulus-driven manner.

Goal-directed and stimulus-driven attention have different neural mechanisms, and it is useful to study their interactions and the relative timing of activity. Prefrontal neurons reveal target location processing first during top-down attention, whereas parietal areas are active earlier, during bottom-up attention (Corbetta et al. 2008). When oscillatory frequencies are measured, there is stronger synchrony between frontal and parietal areas in lower frequencies for top-down attention and in higher frequencies for bottom-up attention (Buschman & Miller 2007). Spatial attention increases the synchrony between posterior parietal cortex and the medial temporal area (Saalmann et al. 2007), and direct microstimulation of frontal eye fields enhances processing of sensory input in extrastriate cortex, suggesting that top-down modulation plays a causal role (Moore & Armstrong 2003).

Spatial attention facilitates processing at attended locations and inhibits neighboring locations and items. Cuing improves target detection and discrimination (Corbetta & Shulman 2002, Yantis et al. 2002), and the time course of facilitation reveals two modes of attention. Attentional facilitation is greatest when the cue precedes the target array by 70–150 ms, and this transient attentional effect is largely involuntary, benefits the simplest of tasks, and diminishes with increasing delay (Nakayama & Mackeben 1989, Weichselgartner & Sperling 1987). The transient component is distinguished from a separate, slower component that improves performance in more difficult tasks. This sustained component persists over time but takes a few hundred milliseconds to peak. Once attention is directed to a location and then reoriented to a new

location, processing at the original location is now inhibited—i.e., inhibition of return. This encourages orienting toward novel locations, playing a useful role in search and foraging behaviors (see Klein 2000 for a review).

In addition to being able to quickly reorient to a novel event, attention must also suppress distraction from task-irrelevant stimuli. Attentional sets or attentional control settings allow observers to focus on task-relevant items (Folk et al. 1992), and there is ongoing debate on what kinds of stimuli can distract people; factors include abrupt onsets, emotionally salient stimuli, or the appearance of new objects (Phelps et al. 2006, Theeuwes 2004, Yantis & Egeth 1999). Newly discovered cues that strongly demand attention include moving or looming stimuli (Abrams & Christ 2003, Franconeri & Simons 2003), especially those on a collision path with the observer (Lin et al. 2008). When a distracting stimulus matches some feature of the attentional set, it captures attention by temporarily shifting spatial attention to the distractor (Folk et al. 2002).

Different neural mechanisms mediate orienting to a cued location and reorienting to a new location. The intraparietal sulcus, superior frontal, and superior temporal cortex direct voluntary spatial shifts to task-relevant locations (Yantis et al. 2002). The parietal cortex contains representations useful for such spatial orienting based on topographic maps of attentional foci (Serenio et al. 2001, Silver et al. 2005). A different circuit, mainly the right temporoparietal junction, is active when observers need to reorient to a target appearing in an unattended location (Corbetta et al. 2008, Hopfinger et al. 2000).

Additionally, just as vision is limited by the acuity (spatial resolution) of the eye, spatial attention is limited by its own acuity (Intriligator & Cavanagh 2001, Pelli & Tillman 2008; Vickery et al. 2010). Interestingly, attentional acuity is much worse than visual acuity, and as a result, the ability to individuate (select) a target from neighboring items has a coarse grain. Resolution deteriorates dramatically moving out into the periphery (Intrili-

gator & Cavanagh 2001), affecting the ability to individuate and identify two targets appearing close to another. Surprisingly, two targets spaced close to each other are more difficult to perceive than two targets spaced far apart, even when low-level interference is controlled for (Bahcall & Kowler 1999, Kristjánsson & Nakayama 2002). The attentional limitation occurs beyond primary visual cortex, based on evidence that items can go unresolved by attention but nevertheless produce significant orientation-specific aftereffects (He et al. 1996).

**Temporal attention.** Attention can also be focused on stimuli appearing at different points in time even in the same location (Coull & Nobre 1998). Spatial and temporal attention share many properties, yet appear to arise from independent, dissociable mechanisms; they are not affected by dual-task interference (Correa & Nobre 2008), and their effects are additive (Doherty et al. 2005). Just as the number of objects that can be fully attended across space is limited, the number of objects that can be attended over time is constrained as well. That is, the rate of information processing is limited. Temporal attention selects task-relevant information to overcome these limitations in the rate of processing.

Temporal attention can be studied in its purest form by asking subjects to search for targets among distractors appearing in the same location in rapid succession. Search for single targets appearing in rapid serial visual presentation tasks helped to reveal an impressive rate of object recognition. Remarkably, viewers can detect a categorically defined target (e.g., wedding scene) at rates of around 8–10 images per second (Potter 1975), consistent with event-related potential (ERP) evidence of how quickly complex images are categorized (Thorpe et al. 1996).

However, the ability to retain and report targets presented in rapid serial visual presentation is more severely constrained. This second-stage limitation is best revealed by asking subjects to search for two or more targets instead of just one (Broadbent & Broadbent 1987,



Chun & Potter 1995, Raymond et al. 1992). Consider a simple search for letter targets among digit distractors presented at rates of 10 per second. Report for the first target (T1) is usually high, whereas the ability to see and report the second target (T2) is dramatically impaired when T2 appears within half a second of T1. This striking deficit for the second target is known as the attentional blink, and Raymond et al. (1992) showed that it is attentional because the deficit for T2 does not occur when T1 is absent or when there is a cue that allows observers to ignore T1.

The attentional blink paradigm has spawned much research focusing on questions essential to the study of attention. When T2 is missed, is its identity processed but not encoded? Or is it not identified at all? This is one incarnation of the early- versus late-selection debate (Treisman 1960). Behavioral priming and neuroimaging evidence suggests that missed targets are processed up to their semantic identity (Luck et al. 1996, Marois et al. 2004, Shapiro et al. 1997).

Understanding what limits performance in the attentional blink can inform how attention gates perceptual awareness. One idea is that encoding a target appearing amid interfering items simply takes time during which other targets cannot be encoded. In other words, a rapid identification system in the first stage of processing that can handle input rates of at least 10 items per second (and likely higher) is followed by a narrow limitation in a second stage that consolidates targets into working memory and that supports awareness (Bowman & Wyble 2007, Chun & Potter 1995, Jolicoeur 1999). This process of raising perceived items into awareness and working memory is thought to involve the fronto-parieto-temporal network (Marois et al. 2000), especially synchronization between these brain mechanisms (Dehaene et al. 2003, Gross et al. 2004), and reentrant processes (see Di Lollo et al. 2000 for related substitution masking effects).

A newly emerging view is that the attentional blink does not represent a capacity limitation, but rather inhibitory processes that delay

the re-engagement of attention to other targets or temporary loss of control (Di Lollo et al. 2005, Olivers & Meeter 2008). This is supported by evidence that attentional engagement is delayed and diffused during the attentional blink (Vul et al. 2008) and that the attentional blink can be alleviated by cuing (Nieuwenstein et al. 2005). The new view is more compatible with the fact that impairments are lessened for targets appearing in direct succession (e.g., Lag 1 sparing; Di Lollo et al. 2005), and it better links mechanisms of temporal attention and spatial attention.

**Features and objects.** Attention can be directed to spatial locations, time points, or modalities alone (as in preparatory cuing preceding a sensory event), or it can be directed to features or objects that can be selected across space, time, and modality. Features are points in modality-specific dimensions, such as color, pitch, saltiness, and temperature. One of the primary mechanisms for selection is via saliency in these feature dimensions—with saliency defined as unusual or extreme values, such as a single red item amid a field of green, a piercing baby's scream, or an unexpectedly hot faucet. Most models of visual search rely on such bottom-up (exogenous) visual features (Wolfe & Horowitz 2004), which can be described computationally (Itti & Koch 2000).

Attention to features directly modulates and enhances the processing within feature-selective cortical regions (Kanwisher 2000, Reynolds & Chelazzi 2004). Attention to orientation enhances the gain of orientation processing and the sensitivity of contrast detection in V4 (McAdams & Maunsell 1999) and modulates processing in human visual cortex (Liu et al. 2007). Feature attention can also facilitate motion processing in area MT (O'Craven et al. 1997) and heighten blood-oxygen-level-dependent activity for faces and scenes within face-selective and scene-selective cortex, respectively (Wojciulik et al. 1998). Importantly, feature attention is not spatially restricted, leading to a global enhancement of features outside the spatial focus of attention (Treue &

Martínez Trujillo 1999). Feature-based selection can be distinguished from spatial selection, and the fronto-parietal network involved in both types of selection contains subregions devoted more exclusively to spatial or feature selection (Giesbrecht et al. 2003). Going beyond demonstrations of modulation, current research is now starting to elucidate the microcircuitry, functional connectivity, and computational requirements by which attention modulates feature-specific responses. Synchronization between local neurons and more distant neuronal groups can strengthen signals and enact selection (Fries et al. 2001, Womelsdorf et al. 2007), even predicting the speed of change detection (Womelsdorf et al. 2006). Complementing such principles, recent studies suggest that attention may improve performance by reducing interneuronal correlations, effectively reducing noise as a primary mechanism beyond what is predicted from the boost in signal (firing rates) per se (Cohen et al. 2009, Mitchell et al. 2009).

Attention can be directed not just to features but also to whole objects (Scholl 2001). The distinction is that when objects are selected, all of its features are selected together with the object (O'Craven et al. 1999), including information about the identity and history of the object as it moves about or changes over space and time (Kahneman et al. 1992). Essential for individuating different objects from each other, object-based representations, known as object files, enjoy extensive empirical support (Flombaum et al. 2009, Xu & Chun 2009). It's easier to select two features coming from the same object than to direct attention to two features that span across two objects (Duncan 1984). When one part of an object is cued, then subjects are faster to respond to a target appearing within the same object at a different location than to an equally distant target appearing within a different object (Egley et al. 1994). Furthermore, shifting attention to locations within objects evokes greater retinotopic and parietal activity than do shifts of identical distances across different objects (Shomstein & Behrmann 2006). Such

object-based effects predict what patients with hemispatial neglect will perceive (Driver & Vuilleumier 2001), what information will be remembered (Yi & Chun 2005), which information dominates in binocular rivalry tasks (Mitchell et al. 2004), and how well subjects can track moving objects [Cavanagh & Alvarez 2005 (reviewed more extensively below), Scholl & Pylyshyn 1999]. Object-based attention involves cortical circuitry similar to that involved in spatial attention (Fink et al. 1997, Yantis & Serences 2003).

### Internal Attention

Whereas external attention involves selection of perceptual information coming through the senses, much of cognition involves regulating our internal mental life, such as planning what to eat for dinner on the walk or drive home from work, or trying to remember what's in the refrigerator. Just as in the case of external attention, there are severe capacity limitations in the number of items that can be maintained in working memory, the number of choices that can be selected, the number of tasks that can be executed, and the number of responses that can be generated at any given time. The primary function of cognitive (executive) control mechanisms is to select between these competing alternatives, independent of sensory modality (Miller & Cohen 2001). Given traffic ahead, one can choose to stay on one's route or decide to navigate around it. When retrieving information from memory, one must select from several competing alternatives: Did I park on the fourth or third floor of this garage? To the extent that there are limitations in the number of alternatives that can be considered at any given time—and the even broader set of responses and choices that can be made to these alternatives—cognitive control is intrinsically attentional. Thus, it would be useful to understand selective processes in executive/cognitive control, while seeing what's common and different about these processes in comparison to those in perceptual selection—external attention.

We distinguish internal attention from external attention in two different ways. The first is just based on the content of selection. Internal attention includes cognitive control processes and operates over representations in working memory, long-term memory, task rules, decisions, and responses. Because the information to be selected is internal, we define internal attention as the set of operations that are focused on such cognitive representations. External attention has more proximal, modality-specific referents to the external, perceptual world.

Second, behavioral evidence indicates that many perceptual processes, even capacity-limited ones, can proceed somewhat independently of cognitive control. This does not imply that perceptual processes are never influenced by cognitive control. Clearly, executive processes and working memory influence external selection and biasing, as we review below. However, the point is that internal attention and external attention cannot be equated and have independent capacities that can be inferred from patterns of dual-task interference and the general structure of neural systems.

Overall, a network of regions in prefrontal cortex and posterior parietal cortex sets top-down signals for biasing selection of information and competition for processing resources (Buschman & Miller 2007, Miller & Cohen 2001, Ridderinkhof et al. 2004). These attentional sets, or task rules, thereby set up perceptual filters and map perceptual features onto motor responses. Once established, these mappings can determine external selection without interference from frontal lobe dysfunction (Rossi et al. 2007). An important question is whether there is a core, central mechanism that governs all executive functions or whether there are specific mechanisms for different domains of internal attention (Badre & Wagner 2004, Duncan & Owen 2000, Rushworth et al. 2001, Wager et al. 2004, Wojciulik & Kanwisher 1999). Behavioral analyses (Miyake et al. 2000) and precise multivoxel pattern classification techniques in functional magnetic resonance imaging (fMRI) have revealed specificity for shifting visuospatial attention, switching

categorization rules, and shifting attention in working memory (Esterman et al. 2009).

We first discuss how internal attention is independent of external attention, especially for response selection, task switching, and long-term memory retrieval. Working memory is considered as a separate internal attention process (Rowe et al. 2000), but interfacing closely with external attention.

**Response and task selection.** When asked to make two simple responses or choices in succession, the ability to execute the second response is delayed when it appears within half a second of the first. This delay is known as the psychological refractory period (Pashler 1994). The precise duration of this delay, as a function of the timing between the first and second task, exquisitely reveals a central bottleneck, independent of modality and task type, although researchers debate the nature of the limitation (Logan & Gordon 2001, Meyer & Kieras 1997). Importantly, slowing down perceptual processing does not affect the response selection delay, indicating some degree of independence. Thus, response selection is categorized firmly under internal attention, distinguished from perceptual selection in external attention. Imaging studies have dissociated response selection limitations from other forms of capacity limitations (Herath et al. 2001, Jiang & Kanwisher 2003), while there is convergence for a common processing bottleneck in the lateral frontal cortex (Marois & Ivanoff 2005), especially for the psychological refractory period and the attentional blink.

In addition to the impairment associated with consecutive responses, observers are slower to switch from one kind of task to a different task, as compared to simply repeating the same task (Rogers & Monsell 1995). These task-switching costs reveal attentional limitations that can be studied separately from the response selection limitations above. The switch cost is larger as the delay between the task instruction and target appearance is shorter. Yet, even with sufficient delay, a small, residual switch cost is apparent, suggesting that the

new task must actually be executed in order to fully implement the switch. That is, there's a limit to how flexibly and effectively one can prepare for a new task before actually executing it (Monsell 2003). Functional neuroimaging is proving to be useful for identifying different internal control mechanisms in prefrontal, parietal, and basal ganglia regions (Braver et al. 2003, Dove et al. 2000, Leber et al. 2008), for revealing different roles for switching between responses versus visual features (Rushworth et al. 2002), and for demonstrating how foreknowledge and preparation may facilitate task switching (Sohn et al. 2000).

More generally, response and task selection require inhibition of competing options (Aron et al. 2004, Nee et al. 2007). This is especially true for simple behaviors such as withholding a response or saccade when a stop signal appears (Aron et al. 2003, Boucher et al. 2007) or in automated tasks such as Stroop interference, where naming the color of a word is slowed by the difficulty of suppressing the written word when it is the name of a different color. In the latter case, task representations or rules in prefrontal cortex need to prioritize color name responses over the more automatic written word responses, regulated by the detection of conflict at the response level by the anterior cingulate cortex (Botvinick et al. 2001).

Response and task selection are clearly internal processes, yet importantly they exhibit the basic characteristics of attention as defined above. They suffer from the limited-capacity problem, solve it by selecting among alternatives and modulating brain activity representing the selected item, and are challenged to sustain vigilance (Braver et al. 2003, Leber et al. 2008). Furthermore, these processes are known to be affected in disorders such as attention-deficit hyperactivity disorder (Dibbets et al. 2010, Tamm et al. 2004).

**Long-term memory.** Long-term memory can also be a target of internal attention. Attention helps determine which information is encoded into long-term memory and how it is retrieved (e.g., Chun & Turk-Browne 2007, Yi

& Chun 2005). People attend to all kinds of information every day, but they do not encode or remember all the things that they have attended. Memory researchers have long known that elaborative encoding enhances memory ( Craik & Lockhart 1972). Elaborative encoding involves actively associating new information with context and other information in the mind. Assuming this process is capacity limited such that people cannot encode an infinite amount of information, then understanding the role of attention is essential.

To study memory encoding, one can examine how neural processing is different between when an item is later remembered compared to when it is forgotten. Neuroimaging methods have relied on this subsequent memory paradigm to show higher activation in prefrontal and temporal cortices during successful memory formation of verbal and visual events (Brewer et al. 1998, Wagner et al. 1998). Pre-trial activations and patterns of neural oscillations also predict memory for both direct and indirect measures of memory (Osipova et al. 2006, Otten et al. 2002, Polyn et al. 2005, Turk-Browne et al. 2006).

In addition to these predictive effects of attention on encoding, reflecting back on a recent perceptual experience also benefits long-term memory. As opposed to working memory, which involves sustained maintenance, such reflective acts can be brief and transient. In the multiple entry, modular (MEM) memory model (Johnson 1983), this kind of reflection corresponds to a component process called refreshing. Similar to the implementation of task rules, refreshing is mediated by the dorsolateral prefrontal cortex (Johnson et al. 2005). The act of refreshing may help salvage and enhance a decaying perceptual representation or may itself be treated as a second "perceptual" experience with the refreshed concept. Correspondingly, refreshing activates visual cortical regions selective for the contents being refreshed (Johnson et al. 2007), enhancing encoding into both explicit and implicit memory (Johnson et al. 2002, Yi et al. 2008).

Once encoded, retrieval from long-term memory requires selection between specific memories competing for recall (Badre et al. 2005, Ranganath et al. 2000). Indeed, forgetting typically arises from memory retrieval failures rather than the loss of the information per se, and so it is important to understand the selection mechanisms involved in enhancing target memories from distractor memories. Accordingly, recent theories have drawn analogies between selection in the perceptual domain and selection during memory retrieval (Cabeza et al. 2008, Wagner et al. 2005). A strong version of this analogy—that the same posterior parietal mechanisms that support goal-directed attention also support episodic memory retrieval—is not well-supported (Hutchinson et al. 2009), but the general notion of functional correspondence between attention and retrieval deserves further study.

The competitive nature of memory retrieval is apparent in other ways. The act of retrieving one item increases the likelihood of later forgetting other unretrieved items that share associative links (Anderson et al. 2004). This retrieval-induced forgetting results from the strengthening of associations during retrieval combined with the weakening of associations for unretrieved items. Such competitive interactions during retrieval may be essential for learning (Norman et al. 2007) and have the adaptive benefit of ultimately facilitating retrieval and reducing conflict (Kuhl et al. 2007).

**Working memory.** Working memory enables the maintenance and manipulation of information in the absence of sensory support (D'Esposito et al. 1995, Smith & Jonides 1999). Because it operates over internal representations (of what is no longer externally available), we place it within internal attention. However, working memory is truly at the interface between internal attention and external attention. Baddeley's (2003) influential model of working memory posits a central executive mechanism coupled with separate stores for visuospatial information and phonological information. Perceptual selection serves as a filter that

determines entry into working memory for maintenance. Selection is critical because working memory is limited in capacity. In the case of vision, the capacity of working memory is about four objects. The unit of storage is important to characterize because multiple features can be chunked into objects to increase capacity (Luck & Vogel 1997). At the same time, increasing the complexity of features reduces overall capacity (Alvarez & Cavanagh 2004, Todd & Marois 2004, Xu & Chun 2006; but see Awh et al. 2007). Verbal working memory (phonological loop) has a capacity of about seven chunks (Miller 1956), and its effectiveness is dependent on phonological characteristics of acoustic input, words, and the names of pictures being rehearsed (Baddeley 1992). Internal attention includes cognitive control or central executive mechanisms that prioritize which perceptual information to encode and maintain in working memory, while suppressing distraction (Most et al. 2005). These functions reside in prefrontal cortex (Miller & Cohen 2001).

Working memory has been placed at the interface between internal and external on the basis of studies showing that maintenance of information in working memory biases attention for similar kinds of information and correspondingly guides eye movements (Hollingworth et al. 2008). For example, maintenance of spatial locations in working memory biases spatial attention to those locations (Awh & Jonides 2001, Corbetta & Shulman 2002), and these biases occur for specific shapes as well (Downing 2000, Soto et al. 2005). Working memory maintenance directly modulates processing in relevant sensory cortex (Harrison & Tong 2009, Serences et al. 2009), and suppresses irrelevant information (Gazzaley et al. 2005).

These biasing effects are capacity-limited, as revealed by specific patterns of interference. For example, concurrent visual working memory load interferes with memory-based gaze correction (Hollingworth et al. 2008). Also, when performing visual search concurrently with spatial working memory tasks, search efficiency drops, suggesting shared capacity

(Oh & Kim 2004, Woodman & Luck 2004). However, object working memory does not change search efficiency, indicating that shared mechanisms are mostly spatial (Woodman et al. 2001). Such content-specific interference effects can even reduce the distracting effects of nontargets. Verbal working memory load can reduce word interference in a Stroop task (Kim et al. 2005); likewise, holding faces in working memory can reduce interference from incongruent face stimuli but not scene stimuli, and vice versa (Park et al. 2007).

Working memory tasks can cause general interference for both internal and external attention: Encoding and manipulating information in working memory induces psychological refractoriness effects (Jolicoeur 1998), disrupts simple spatial orienting (Dell'Acqua et al. 2006), and impairs search (Han & Kim 2004). The interaction is bidirectional: Working memory contents can influence perceptual attention, but perceptual attention can also influence what gets maintained in working memory (Lepsien et al. 2005). Maintaining a location in working memory has been compared to sustaining perceptual attention on that location (Awh & Jonides 2001).

There has been a recent surge of interest in understanding the neural mechanisms of working memory and how working memory relates to other types of internal and external attention. A common thread has been that working memory shares many properties with external attention, yet it is also dissociable. Selection of items in working memory has been compared to selection of items in visual search (Asthle 2009). Overlapping brain networks for controlling attention to external and internal representations have been proposed, with a bias toward internal representations in more frontal regions and external representations in more parietal regions (Nobre et al. 2004). In a particularly insightful study, Esterman and colleagues (2009) compared brain activity associated with switching spatial attention, switching task set, and switching among memory representations. They found that a region of superior parietal cortex was involved in all types of attention

switching, but that they could train multivariate classifiers to differentiate between the patterns evoked by internal and external types of attention. Individual differences approaches have similarly demonstrated both commonalities and differences between working memory and perceptual processes (Wager & Smith 2003).

## ISSUES AND FUTURE DIRECTIONS

### Early Versus Late Selection: Lavie's Load Theory

Almost every textbook features the debate of early versus late selection as a central issue in attention research. When objects or events go unattended and even inhibited, how deeply are such ignored items processed? This question remains useful for understanding the nature of awareness and the processing architecture of the mind. And the problem seems largely tractable. Support exists for both early and late selection views, and research should focus on clarifying when unattended stimuli are processed and when they are not. As proposed in Treisman's (1960) attenuation theory, the debate should not be viewed as a dichotomy, but rather as the two ends of a continuum. Recent work has advanced our ability to determine from task to task where selection processes fall along this continuum.

Lavie's (2005) load theory is a powerful modern framework to predict the level of processing for unattended stimuli. The basic insight is that the amount of processing that unattended stimuli receive is dependent on how difficult it is to process the attended target. If the primary target task is easy, then excess attentional resources will spill over to distractors, and they will be identified, indicative of late selection (Lavie 1995). If the primary task is very difficult, then as all of attention becomes devoted to the target, distractors become less well processed, revealing patterns of early selection. A classic finding relies on the Eriksen flanker task, in which a target is flanked by distractors

that are mapped to incompatible, competing responses, slowing down responses to the target (Eriksen & Eriksen 1974). When the number of distractors is few, then the overall task is easy, so distractors will slow down the target response. Perceptual load can be increased by having more distractors on the display, exceeding the capacity of attention. Under such cases of high load, distractors are less well processed, resulting in less interference (Lavie 1995). Increased perceptual load (difficulty) of a target task attenuated neural processing of drifting gratings in V1 (Chen et al. 2008), moving dots in area MT (Rees et al. 1997) and scene stimuli in the parahippocampal place area (Yi et al. 2004).

Task difficulty itself can be broadly categorized in two different ways. Lavie's overarching theory of attention distinguishes perceptual load and central limitations, which maps onto our distinction between external and internal attention. Central (internal) load includes increasing the number of items that must be maintained in working memory or performing other executive functions such as task switching (Lavie et al. 2004). Critically, effects of central load manipulations on distractor processing are the opposite of perceptual load manipulations. Increased central load increased distractor processing because relevant executive processes lose control over focusing attention on the target task, resulting in attention spilling over to distractors. As a specific example, increased working memory load increased interference from distractors (de Fockert et al. 2001). Most manipulations of central attention will result in late selection, that is, full perceptual identification of ignored items.

## Visual Search

In natural contexts, observers typically search for a target amid many other competing stimuli (Treisman & Gelade 1980, Wolfe & Horowitz 2004), and this is a complex skill that spans across our taxonomy. Search difficulty varies along a continuum from efficient (easy) to inefficient (hard), as determined by both visual

factors and nonvisual factors such as the number of distractors and their homogeneity. Attention is most efficiently directed to target objects that are salient and dissimilar from other distractor objects (Duncan & Humphreys 1989, Itti & Koch 2000). Beyond visual factors, visual search is facilitated when targets appear in predictable locations, cued by background context and past experience (Bar et al. 2004, Chun 2000, Torralba et al. 2006).

Search strategies are maximized in a way that directs eye movements toward regions of interest based on scene statistics while minimizing demands on memory (Najemnik & Geisler 2005, Summerfield et al. 2006). How much memory is needed has been a matter of debate. On one extreme, search has been described as amnesic in the sense that searched items are not tagged to be ignored. This claim is based on the finding that search efficiency does not change whether the search display is static or whether the items move around (Horowitz & Wolfe 1998). However, most subsequent studies have provided evidence for some role for memory in search (Chun 2000, Shore & Klein 2001). At a short time scale within trials, items that were searched and rejected become momentarily tagged with inhibition to prohibit search through these items again (Klein 2000, Watson & Humphreys 1997). From trial to trial, priming of features (priming of popout: Kristjánsson et al. 2005, Maljkovic & Nakayama 1994) or learning of predictive context (contextual cueing: Chun 2000) serves to facilitate search. As direct evidence, Hollingworth & Henderson (2002) have demonstrated that people retain fairly detailed information from attended objects within scenes during search.

The visual search task has many practical applications, especially for understanding when people make mistakes, for example, missing dangerous items during baggage screening or pathological tissue while viewing radiographs. Beyond visual factors, a major source of difficulty is cognitive (Chun & Wolfe 1996). People have difficulty detecting target events that are rare in occurrence, known as the target prevalence effect (Wolfe et al. 2005). However,

giving observers the opportunity to confirm their search responses and to correct misses may reduce error (Fleck & Mitroff 2007). Understanding visual search performance requires characterizing every process, from sensation and perception, to decision-making and motivation, and motor execution.

### **Object Tracking and Perceptual Stability**

Objects and observers are frequently in motion, and thus a fundamental task for attention is to keep track of the locations of objects over time and across change (Kahneman et al. 1992). A related operation called visual indexing provides a way for attentional mechanisms to reference or point to the object files or tokens that need to be tracked (Pylyshyn 1989). Such object tracking touches on core attention themes of capacity limitation, selection, and vigilance. This ability is studied in multiple object tracking tasks that require more than one target to be monitored, often when there are no visual features distinguishing targets to be tracked from other moving distractors (Pylyshyn & Storm 1988). Accuracy in this task declines abruptly when more than about four items must be tracked and is strongly influenced by how objects maintain their integrity and spatiotemporal continuity (objecthood) as they move about (Scholl & Pylyshyn 1999). Note that tracking and working memory have comparable capacity, known as the magical number four (Cowan 2001); however, this coincidence alone does not point to a common mechanism (Fougnie & Marois 2006, Scholl & Xu 2001). Visuospatial and attentional resolution also strongly affects tracking performance (Alvarez & Franconeri 2007).

Even when objects themselves are stationary, our eyes move constantly and drastically change retinal input. Given this changing input, it is remarkable that observers can maintain a stable visual representation of the environment as the eyes move about (Cavanagh et al. 2010, Mathôt & Theeuwes 2011). This feat is intriguing because the locus of attention relative to fixation and to one's retinotopic frame of

reference necessarily changes as the eyes move around a scene. For example, one still needs to monitor a traffic light and the car ahead while driving, even while moving one's eyes about from car to car, dashboard to mirror, and so on (Lleras et al. 2005).

Historically, most work suggested that it was not possible to simultaneously make an eye movement to one location while covertly attending to another location (Deubel & Schneider 1996, Hoffman & Subramaniam 1995, Kowler et al. 1995). However, recent work has demonstrated otherwise, revealing that visuospatial attention is maintained in retinotopic coordinates and updated as necessary with each eye movement according to spatiotopic, world-centered reference frames. When subjects must maintain attention on a spatiotopic location, attention lingers at the previous retinotopic location for a brief period of time after an eye movement before updating to the correct location (Golomb et al. 2008), accompanied by corresponding fMRI and ERP facilitation in human visual cortex (Golomb et al. 2010).

### **Attention and Awareness**

The relation between attention and conscious awareness requires substantial review, available elsewhere (Block 2005, Dehaene et al. 2006, Koch & Tsuchiya 2007, Rees et al. 2002, Rensink 2000). One basic point to make here is that although attention plays a role in gating which information reaches awareness, even affecting the appearance of objects (Carrasco et al. 2004), attention and awareness are not the same (Lamme 2003). Attending to an object and becoming aware of an object are both correlated with higher activity in relevant sensory processing regions (Rees & Heeger 2003). However, to attend to an object does not ensure awareness (Levin & Simons 1997). Magnetoencephalography reveals distinct signals for consciously seen stimuli, independent of attention, while manipulations of spatial attention modulate different types of oscillatory brain activity, independent of whether



the stimuli were consciously perceived or not (Wyart & Tallon-Baudry 2008). Many demonstrations of perceptual identification without awareness involved stimuli that were spatially attended even when they weren't reportable (Dehaene et al. 2001), especially during temporal selection tasks such as the attentional blink (Luck et al. 1996, Marois et al. 2004).

Large-scale integration of neural activity may be one path toward understanding the neural correlates of consciousness (Dehaene et al. 2006). Global awareness is correlated with long-distance synchronization of gamma oscillations across widely separated brain regions (Melloni et al. 2007, Womelsdorf et al. 2007). Distinguishing aware states from unaware states remains a strong research priority for the field, and the attention taxonomy can help map out how awareness integrates processing across multiple systems.

### **Prospective Activity: Decoding and Predicting Attentional States**

Vigilance, that is, attentiveness, fluctuates over time. Behavioral methods can typically measure only the consequences of such variation, whereas functional neuroimaging methods can illuminate causal factors and the internal states that precede changes in performance. Furthermore, pattern classification methods allow researchers to decode what someone is attending to or anticipating (Haynes & Rees 2005, Kamitani & Tong 2005, Stokes et al. 2009). One only needs to examine the time periods before a trial to look at antecedent states that may explain performance fluctuations. EEG provides good temporal resolution to study how synchronous activity may predict enhanced visual perception (Hanslmayr et al. 2007). Conventional fMRI signal average measures can explain lapses of attention with reduced prestimulus activity in attentional control regions, such as anterior cingulate and right prefrontal cortex (Weissman et al. 2006), along with less deactivation of the "default-mode" network (Raichle et al. 2001). Leber et al. (2008) predicted increased cognitive flexi-

bility (smaller task switching costs) when fMRI revealed higher levels of pretrial activity in prefrontal and posterior parietal cortex, as well as the basal ganglia. Prospective activity can also predict susceptibility to attentional capture (Leber 2010). Explaining variations in attention and performance using fMRI or EEG measures will yield novel insights into the mechanisms of attention, accounting for variability in other cognitive processes that depend on attention, such as memory encoding (Otten et al. 2002, Turk-Browne et al. 2006), or performance impairments due to anxiety (choking) (Beilock & Carr 2001). Ultimately, understanding vigilance and attentiveness should open up new ways to improve attention, as discussed below.

### **Enhancing Attention With Emotion, Reward, or Training**

The notion of enhancing attention appears circular. However, attention fluctuates, so one of the most practically useful and clinically important questions to ask is how high levels of performance can be sustained. Numerous approaches can be considered here.

Emotional arousal enhances attention (Phelps et al. 2006). That is, emotionally charged stimuli capture attention (Anderson & Phelps 2001, Most et al. 2005, Ohman & Mineka 2001), facilitate visual perception (Phelps et al. 2006), and improve memory, or at least the feeling of remembering (Sharot et al. 2004). Although many of these effects may be attributed to increased arousal, the valence of mood and induced emotion can affect how attention operates. For example, positive mood widens the focus of attention (Rowe et al. 2007). As a complementary fact, attention influences emotional evaluation as well. When novel, otherwise neutral stimuli are actively ignored, they are subsequently evaluated more negatively than are previously attended or novel patterns (Raymond et al. 2003).

Not just increased arousal but also meditation or relaxation affects attentional focus. Subjects relaxed by music, pleasant pictures, or simple instructions to be less focused showed

reduced attentional blink deficits (Olivers & Nieuwenhuis 2005). Meditation and mindfulness benefit sustained attention (Bishop et al. 2004, Lutz et al. 2008). Attentional tasks, especially those related to internal attention, improve from physical exercise or even walks through nature (Berman et al. 2008, Colcombe & Kramer 2003).

Beyond explicit emotional cues, more general social cues attract attention. Faces are readily detected amid nonface stimuli (Hershler & Hochstein 2005), gaze perception triggers orienting (Driver et al. 1999), and animate objects are detected more efficiently than nonanimate objects (New et al. 2007). An especially convincing example is the way in which dynamic cues for animacy, such as perceived chasing, can draw attention in displays composed of only simple moving inanimate shapes (Gao et al. 2009).

Rewards, the outcomes of behavior (Schultz 2000), significantly shape attention and performance. When selection is reinforced with reward, processing is enhanced for rewarded items and locations and inhibited for unselected items, relative to items that are not explicitly rewarded (Libera & Chelazzi 2006, Serences 2008). The effects of reward and attention are frequently confounded in studies, so clarifying this relationship is an important area for future research (Maunsell 2004).

Finally, overt training of attention represents an exciting area for further work. Playing action video games enhances attentional skills and even perceptual acuity (Green & Bavelier 2003, 2007). Clinical settings can benefit from attention training protocols. Individual differences in pathology such as anxiety disorder predict how emotional stimuli capture attention (Bishop et al. 2004). Learning to ignore disgusted faces using a cuing task has beneficial effects for social anxiety disorder (Bar-Haim et al. 2007, Schmidt et al. 2009). Because attention controls what one perceives, and because one's mental and emotional life is fed by perceptions of one's social world (Ochsner et al. 2002), attention training protocols represent a highly promising area for interdisciplinary and

translational research, countering the effects of cognitive aging, facilitating development, and treating clinical conditions including autism and attention deficit and hyperactivity disorder.

## TOWARD A TAXONOMY OF ATTENTION

In a well-known folk story, travelers prepared a pot of boiling water containing nothing but a large stone. Curious villagers that asked how it tasted were invited to contribute ingredients to further enhance the flavor of the stone soup. Is "attention" such a theoretical soup stone, a construct with no intrinsic value but to simply draw in more substantive, concrete descriptions (Navon 1984)? If the principles of limited capacity, selection, modulation, and vigilance operate throughout most perceptual and cognitive processes, would it not be more concise just to focus on the perceptual processes and cognitive mechanisms themselves, rather than organizing them into a loose taxonomy?

Our hope is that this broad review of the literature not only highlights the utility and need for a taxonomy, but also the concept of attention itself. First, attention remains a powerful general principle. Ultimately, attention refers to what an individual is focused on, so it remains practically useful to talk about what task, object, event, or thought someone is attending to. The taxonomy is useful for understanding the details of which specific processes are at work, but it would not be productive to fractionate the mind in a way that loses sight of how the holistic individual is behaving.

Second, insights, characteristics, and principles from one part of the taxonomy generalize to other parts. Crowding effects and cuing properties are similar in both spatial and temporal selection. Modulatory and filtering effects are similar across the modalities. Hence, it remains useful to talk about issues and mechanisms of attention across different aspects of the taxonomy.

Third, the different aspects of attention interact extensively, and attention provides a common currency by which information can be

transacted between different systems and neural mechanisms. Spatial effects in working memory influence spatial mechanisms of attention. Task rules set by prefrontal executive control mechanisms influence perceptual mechanisms in posterior cortex. Attention is a useful construct for developing an understanding across these interacting systems. One of the most exciting challenges for the next era of attention research is to understand how all these different mechanisms work together. In particular, improved understanding of neural mechanisms and systems should inform the taxonomy, and vice versa.

Finally, the field and literature lack a common language to communicate and connect their work with each other. Drawing analogy

with another folk story, to abandon the term attention would cause all blind men or women to feel different parts of the elephant, not realizing that they are touching the same animal. Yet, to rely on the term attention alone has all of the practical problems we started off with. With this proposed taxonomy, we seek a way to meaningfully categorize research findings and underlying processes and mechanisms. Constructive debates about the taxonomy should yield interesting experiments and more incisive theories. Meanwhile, this taxonomy can serve as a portal to help select relevant studies in the overwhelmingly rich literature on attention.

We conclude that attention should continue to serve researchers as a useful construct—after all, everyone knows what it means.

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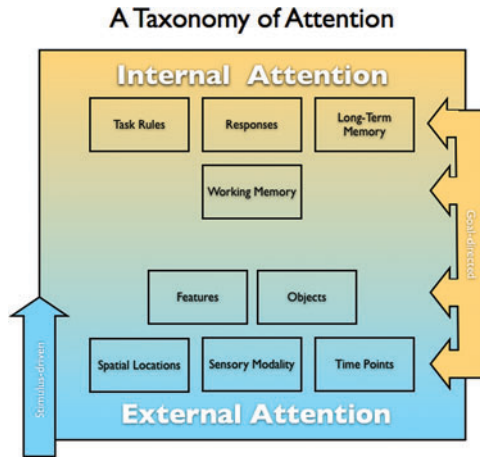
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**Figure 1**

A schematic overview of external and internal attention. Each box represents a target of attention.



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### Errata

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