CHAPTER 2

Attention

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WHAT IS ATTENTION AND WHY IS IT IMPORTANT?

A fundamental characteristic of human cognition is our *limited capacity* for processing information. We cannot see, attend to, remember, or react to everything that we encounter in our environment. Nowhere does this limited capacity play a more central role than with attention. This attentional bottleneck implies that paying attention to one source of information causes the processing of other things to suffer. For example, when a driver of a motor vehicle begins to chat on a cell phone, the driver's performance degrades as attention is withdrawn from driving and directed toward the phone conversation. Another important characteristic of attention is that it can be *flexibly allocated*, based on the task demands and goals of the operator. In the following paragraphs, we briefly describe the varieties of attention.

Selective attention refers to the ability to selectively process some sources of information while ignoring others (Johnston & Dark 1986). Given that we cannot process all the information that is constantly bombarding our sensory systems, it is important to be able to select the information that is most important to our current set of goals for further processing and exclude irrelevant sources of information from analysis. Researchers speculate that a combination of facilitatory and inhibitory processes work together to aid in the selective processing of the environment (e.g., Houghton & Tipper 1994). Facilitatory processes are assumed to amplify the processing of task-relevant information and inhibitory processes dampen the processing of irrelevant information. For the most part, the mechanisms of selection are quite effective. People are good at selectively processing task-relevant information and excluding irrelevant material, although performance is not always perfect. In the extreme, attention-related patient disorders, such as schizophrenia, provide examples where patients fail to effectively suppress the processing of irrelevant stimuli or thoughts (Beech *et al.* 1989).

Divided attention[1] refers to the ability to perform two or more concurrent tasks or activities. In this context, attention has been conceptualized as a commodity that can be flexibly allocated between different tasks, based on the *processing priority* assigned to each (Kahneman 1973; Navon & Gopher 1979). Because the capacity of attention is

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limited, it implies that there is an upper limit to how well people can perform any two tasks in combination. In many instances, when an operator attempts to concurrently perform two tasks, performance on one task prospers at the expense of the other; however, there are important exceptions (e.g., perfect time-sharing) which will be discussed below. The demands of dual-task performance are also closely associated with mental workload; as the cognitive demands increase, there is a corresponding increase in mental workload. In some instances, practice can facilitate the development of efficient automatic processing, resulting in significant improvements in dual-task performance. There are also interesting individual differences in multi-tasking ability. For example, in their review of the literature on aging and dual-task performance, Kramer and Larish (1996) noted that "one of the best exemplars of a mental activity in which large and robust age-related differences have been consistently obtained is dual-task processing" (p. 106).

Sustained attention refers to the ability to maintain the focus of attention for prolonged periods. In one variant of the sustained attention task, observers might be required to monitor a display for some task-relevant target information (e.g., a concealed weapon in airport carry-on luggage) occurring intermittently in a stream of non-target material. Not surprisingly, performance degrades when the focus of attention drifts from the monitoring task or if the observer becomes bored. As with the other variants of attention, there are important individual differences in the ability to sustain the focus of attention. For example, individuals with the predominantly inattentive type of attention deficit hyperactivity disorder (ADHD) exhibit difficulty in sustaining attention and often avoid tasks requiring sustained effort (DSM-IV 1994).

The remainder of this chapter is organized into three sections. The first provides a brief theoretical and historical overview of attention. The second gives examples of the different roles attention plays in applied settings such as aviation, medicine, surface transportation, and human–computer interaction. The final section considers future directions in basic and applied attention research.

THEORETICAL AND HISTORICAL PERSPECTIVES ON ATTENTION

William James' (1890) prescient treatment of attention is one of the earliest in the psychological literature. James observed that there are *varieties of attention* (sensory vs. intellectual, immediate vs. derived, passive vs. active), considered the effects of attention (on perceiving, conceiving, distinguishing, remembering and shortening reaction time), and the span of consciousness (i.e., how many things we can attend to at once, ranging from four to six distinct objects). According to James,

> Every one 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. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called distraction and *Zerstreutheit* in German. (pp. 403–404)

James also discussed the limits on performing two tasks at once, and the role of practice in dual-task performance. He commented on the role of attention in forming memories, noted that intense, sudden, or moving stimuli were processed reflexively, and commented on the difficulties of sustaining the focus of attention for prolonged periods of time. In short, James' characterization established the foundation for much of contemporary theorizing about attention.[2]

Attention became a central focus of research in the 1950s and 1960s, following Shannon and Weaver's (1949) work on *information theory* and the notion of a *limited capacity channel*. Broadbent (1957, 1958) applied the concept of a limited capacity channel to attention, proposing that attention acts as a filter allowing only relevant information to pass to higher levels and excluding irrelevant information from the information-processing system. Broadbent's *filter theory* operated as a gatekeeper and selection was based on the physical properties of the input. As evidence mounted that sources of "irrelevant" information, such as the listener's name, were noticed by the listener (e.g. Morray 1959; Treisman 1960), the concept of an all-or-none filter was modified so that irrelevant information was *attenuated*, but not completely blocked from access (Treisman 1960, 1969; Treisman & Geffen 1967). By contrast to these *early selection* theories, Deutsch and Deutsch (1963) proposed a *late selection* model in which all information was processed for meaning, and selection occurred at the level of the response. For several years, researchers debate the location of the filter ("early" vs. "late"). The issue was largely resolved when Johnston and Heinz (1978) demonstrated that the attentional bottleneck was flexible, based on task demands. Accordingly, selection is thought to occur so as to minimize the capacity demands on the individual.

In the 1970s and early 1980s, the predominant metaphor of attention was *resources*, based on principles borrowed from economic theory. Attention was viewed as an energetic, with performance improving as more attention (i.e., energy) was allocated to the task (Norman & Bobrow 1975). Research focused on *divided attention* tasks with performance trading off between tasks as a function of the attention allocated to each (Kahneman 1973). Later resource models considered attention to be made up of multiple pools of resources (Navon & Gopher 1979; Wickens 1980, 1984). Wickens (1984) conceptualized multiple resources as a multidimensional space formed by modalities of input (e.g., auditory vs. visual), mental codes (e.g., verbal vs. spatial), stages of processing (e.g., perceptual/cognitive vs. response), and output modalities (e.g., vocal vs. manual). According to this model, dual-task performance is predicted to be good when the resource demands of two tasks are far apart in the multidimensional resource space. When the two tasks compete for the same multidimensional space, performance will trade off as a function of processing priority. Some researchers have suggested that it may be fruitful to consider multiple resources in terms of neural structures, such as the left and right cerebral hemispheres (Kinsbourn & Hicks 1978; Friedman & Polson 1981). On the other hand, Navon (1984) has questioned the utility of the concept of resources, likening it to a theoretical *soup stone* with little explanatory power. Instead, Navon (1984; Navon & Miller 1987) suggests that dual-task interference may be due to *cross-talk* between concurrent tasks. That is, like the situation in which you can hear the "cross-talk" from another line when you are making a long-distance telephone call, the information-processing operations of the one task can contaminate the information-processing operations of a concurrent task.

Another important theme emerging in the 1970s and 1980s was the role that automatic and controlled processing play in human information-processing (e.g., Laberge & Samuels, 1974; Posner & Snyder 1975; Schneider & Shiffrin 1977; Shiffrin & Schneider 1977; Anderson 1982; Logan 1988). Novice performance is thought to rely on controlled attentional processing, which is often characterized as flexible, slow, effortful, and reliant on limited capacity attention. The transition from novice to expert involves the acquisition of automatic processing routines that have been characterized as fast, efficient, and no longer governed by limited capacity attention. Much of the theoretical work in this area has focused on the mechanisms underlying the development of automatic processing. For example, strength-based theories (e.g., Shiffrin & Schneider 1977) suggest that the associative strength of stimulus–response mappings is strengthened with consistent practice, yielding highly efficient information-processing. By contrast, memory-based theories (e.g., Logan 1988) suggest that automatic processing stems from memory retrieval processes that result in faster performance as more instances are stored in memory.

In the same period, other metaphors were developed to describe the spatial distribution of attention. Wachtel (1967; see also Posner 1980; Posner *et al.* 1980; LaBerge & Brown 1989) characterized attention as a *spotlight* that illuminated information that fell within its beam. The selective properties of spatial attention were represented by what fell within vs. outside the spotlight of attention. Posner and Cohen (1984) demonstrated that spatial attention could be directed with both *exogenous* and *endogenous cues*. In the case of exogenous cuing, a peripheral cue automatically draws (i.e., orients) attention to a spatial location. In the case of endogenous cuing, a central cue directs attention to peripheral locations in a controlled, goal-oriented fashion. Exogenous cuing is characterized as fast and effortless, whereas endogenous cuing is slow and effortful (Jonides 1981). Posner *et al.* (1984) suggest that the endogenously controlled movement of attention involves three separate mechanisms: one to *disengage* from the current focus of attention, one to *move* attention to a new location, and one to *engage* attention on a new object/location. Eriksen and St. James (1986; see also Eriksen & Yeh 1985) developed a *zoom lens* metaphor to describe other attributes of spatial attention. Like a zoom lens, the resolution of attention was hypothesized to be variable, with the magnification inversely proportional to the field of view. At low resolution, attention can be distributed over larger regions of space, with less ability to resolve fine detail. At higher resolution, attention can be distributed over a smaller region of space, but with greater ability to discriminate fine detail.

Attention also plays a critical important role in *binding features* together (Treisman & Gelade 1980; Treisman 1996). Whereas searching for a *feature singleton* (e.g., red items) can be accomplished *pre-attentively* (i.e., without capacity limitations), limited capacity attention is required to conjoin two or more features in a *conjunction search task* (e.g., searching for red squares in a field of red and blue triangles and blue squares). Metaphorically speaking, attention has been referred to as the *glue* that cements visual information together (Briand & Klein 1987), and in some instances attention can incorrectly bind features, resulting in *illusory conjunctions* (Treisman & Schmidt 1982). Treisman & Souther (1985) also observed interesting *search asymmetries*. When a task required searching for the presence of a feature (e.g., searching for a Q in a field of Os), search is easy and efficient. By contrast, when searching for the absence of a feature (searching for an O in a field of Qs), search is slow and effortful.

Meanwhile, another focus of research examined whether attention operated on *space-based* representations or on *object-based* representations. Duncan (1984; see also Kahneman & Henik 1981; Kahneman & Treisman 1984; Treisman 1988, 1992; Kahneman *et al.* 1992; Vecera & Farah 1994) suggested that attending to an object forms an *object file* and that all the attributes of the object are processed in parallel. Accordingly, it is easier to divide attention between two dimensions of a single object than to divide attention between two dimensions of different objects. However, when the task involves ignoring irrelevant or interfering material, it is often easier if the irrelevant information is on a different object than if the irrelevant information is part of the same object. Kramer and Jacobson (1991) found evidence that attention is influenced by both object-based and space-based representations, but that object-based effects often override the effects of spatial proximity.

More recently, research has focused on the role that a central processing bottleneck plays in limiting dual-task performance (e.g., Pashler 1994, 1999; Pashler *et al.* 2001; see also de Jong, 1993, 1995). Much of the evidence for this assertion comes from studies using the *psychological refractory period*, in which subjects are presented with two stimuli presented in rapid succession, each of which requires a separate discrete response. As the asynchrony in stimulus onset between the first stimulus and the second increases, reaction time to the second stimulus systematically decreases until reaching an asymptote. The delay in reaction time is often identical to the interval between the onsets of the two stimuli, indicating that processing of the second stimulus cannot begin until the first has completed. Pashler (1999) suggests that central mental operations are forced to queue while waiting to pass through the bottleneck. There has been considerable debate over whether the bottleneck is part of the cognitive architecture or whether it is strategic (e.g., Ruthruff *et al.* 2000).

Researchers have also focused on the role attention plays in executive functions and cognitive control using a variety of task-switching paradigms (Jerslid 1927; Rogers & Monsell 1995). In the task-switching paradigm, participants alternate between tasks, and the costs of switching is measured by the difference in performance from the beginning and end of a block of trials. When the two tasks use a common stimulus set (e.g., digits) with different mental operations (e.g., subtraction vs. addition), participants respond more slowly when the tasks alternate between blocks. In contrast, when the two tasks have distinct stimulus sets (e.g., digits vs. letters), there is little cost in switching between tasks (e.g., Allport *et al.* 1994). Switch costs are thought to provide an estimate of the time needed to reconfigure the cognitive network to perform a different task. Logan and Gordon (2001) suggest that the switch costs reflect an executive control process controlling subordinate automatic processes by reconfiguring their parameters in accordance with the current task demands.

Current advances in cognitive neuroscience are also beginning to shed some light on the neurobiology of attention (for a review of the neuroscience of attention, see Posner 2004). For example, evidence from fMRI studies of differential processing in the lateral geniculate nucleus (O'Connor *et al.* 2002) and single unit recordings from primary visual cortex (e.g., Reynolds *et al.* 1999) indicate that selective attention can be observed at very early stages in vision.[3] Evidence of top-down modulation of visual attention appears to come from posterior parietal and dorsal lateral prefrontal cortices (Nobre 2004). Anterior cingulated cortex also plays a major role in the selection for action and error processing (Posner *et al.* 1988; Holroyd & Coles 2002). Although our current understanding of the neurobiology of attention is far from complete and the role that this line of research will play in applied cognition is indeterminate, what is clear is that several brain regions work in tandem to regulate the flow of human information processing.

The *metaphors of attention* described in this section have been used by researchers to characterize different properties of human performance. On the one hand are theories that focus on conditions encouraging the operator to selectively process information in the environment. On the other are theories that focus on situations in which the operator engages in some form of multitasking operation. In each case, there are situations in which the mechanisms of attention operate effectively and efficiently, and situations in which capacity limitations affect the performance of the observer.

EXAMPLES FROM THE APPLIED LITERATURE

In this section, we consider selected examples of the varieties of attention and related concepts applied to real-world settings. Topics of consideration include selective attention, divided attention, sustained attention, mental workload, effects of practice, executive control, and individual differences. In each case, we have selected examples that illustrate the diverse ways in which attention influences performance.

Selective Attention

Consider the task of *selective attention*, in which the observer is overloaded with sensory stimulation and must select the most task-relevant information for further processing while excluding irrelevant sources of information. In such circumstances, it is useful to consider how successful the observer is at filtering out the irrelevant information. Simons and Chabris (1999; see also Neisser & Becklen 1975) provide a compelling example of the efficiency of selective attention in excluding irrelevant material from further analysis. Participants were asked to watch a short video clip of two teams passing a basketball back and forth and report the number of times that the team wearing white jerseys passed the ball. Midway through, a person dressed in a gorilla suit walked into the scene, stood in the middle of the basketball players, beat his chest, and then sauntered off the screen. Amazingly, 58 per cent of the people watching the video failed to see the gorilla! This *inattentional blindness* indicates that the mechanisms of selective attention are actually quite effective in filtering out highly salient, but irrelevant, information.

Attention can also be too selective, resulting in *cognitive tunnel vision*. In many cases, stress, workload, and fatigue can increase the likelihood of tunnel vision (Weltman *et al.* 1971; Baddeley 1972). In these situations, information that is critical to the observer may be ignored. For example, on December 29, 1972, Eastern Airlines Flight 401 developed problems with its landing gear on approach to Miami Airport. While the pilots focused on solving the landing gear problem, the plane was put on autopilot. Inadvertently, the autopilot was disabled and the plane began a gradual descent of 200 feet per minute. Transcripts indicate that the pilots, believing the autopilot was still engaged, focused so intently on solving the landing gear problem that they failed to respond to the ground proximity alarm until it was too late. The ensuing crash resulted in the loss of 98 lives.

Selective attention is also not perfect in filtering out irrelevant information. The Stroop color word interference task provides an excellent example of the inability of attention to exclude irrelevant information from being processed (Stroop 1935; MacLeod 1991). In the classic Stroop task, observers are presented with color word names (e.g., RED printed in blue ink). When asked to name the ink color and ignore the color word name, observers suffered considerable interference, indicating that selective attention was not successful in filtering out the irrelevant material. *Stroop-like interference* has also been observed when irrelevant information flanks critical target information (Eriksen & Eriksen 1974). Another example of a failure to suppress irrelevant or incompatible information comes when a speaker's voice is fed back with about a one second delay (as is often the case with two-way satellite communication). Speakers often find hearing the delayed audio feedback of their own voice quite disruptive to speech production (Howell & Powell 1987).

There are a number of factors that contribute to the efficiency of selective attention in searching for information in visual displays. Search is efficient if critical target information can be defined by a single feature such as color or shape (Christ 1975; Treisman & Gelade 1980; Wolfe 1994). For example, Agutter *et al.* (2003) found that anesthesiologists detected and treated myocardial ischemia more rapidly with graphical displays that changed the shape of a heart object during a heart attack. Similarly, Yeh and Wickens (2001) found color coding to be an effective attentional filtering technique for segmenting electronic battlefield maps; Fisher *et al.* (1989) reported that color coding could substantially reduce the time to search for a highlighted target in a computer menu; and Remington *et al.* (2000) found that air traffic controllers could identify traffic conflicts more rapidly when the aircraft altitude was color-coded. In each of these cases, performance was enhanced by the use of simple features making selective attention more efficient (i.e., targets seem to "pop out" of the display).

By contrast, search is slow and effortful when the observer must search for a target defined by a conjunction of features (Treisman & Gelade 1980). An entertaining example of the difficulty of conjunctive search comes from the children's cartoon book *Where's Waldo?* in which observers are given the task of finding Waldo, who is dressed in blue trousers, a red and white striped shirt, a stocking cap, and black-rimmed glasses. The task is surprisingly difficult because many of the other characters in the scene are also wearing some of the clothes from Waldo's wardrobe. Thus, observers must search for the set of features that uniquely identifies Waldo. Of course, in scenes where Waldo's wardrobe is unique, he immediately stands out in the crowd. Search is also more effective when observers are searching for the presence of an object than the absence of an object (Treisman & Souther 1985). For example, if there is a problem with the oil pressure in your automobile, it is more likely that you will notice this problem if a warning indicator comes on (presence of a feature) rather than if a status light turns off (absence of a feature).

Attention can also be captured by sudden onset stimuli (Yantis & Jonides 1990; Yantis 1993) and movement (McLeod *et al.* 1991; Franconeri & Simons 2003). If the critical target information is identified by sudden onsets (e.g., flashing) or movement, then it is more likely to be detected quickly and efficiently. In aviation, the air traffic controller's display uses flash coding to rapidly draw attention to situations requiring immediate attention (Yuditsky *et al.* 2002). Another example of using onset cues to direct attention is the blinking cursor on the computer monitor. Attention is directed to the location of the cursor which tends to pop out of the static display, making it easy for the computer user to know where they are typing. On the other hand, if irrelevant information in the display appears as an onset stimulus or with movement, then this may automatically divert attention from the task of successfully locating and identifying the target material. Sagarin *et al.* (2003, 2005) provide evidence that dynamic Internet pop-up advertisements (which often include both onset and movement stimuli) are a form of intrusive technology that "steals" consumer attention from the processing of desired content on an internet browser. New electronic billboards with bright images, flashing messages, and moving objects that are placed along the roadway can also be a potent source of driver distraction. Indeed, billboard advertisements suggest that "motorists can't miss" the new electronic signs because attention is captured by the moving display.

Expectancy also plays a major important role in selective attention. We often see what we expect to see. For example, on September 7, 2000, the pilots of a Boeing 737 airliner thought they were on final approach to runway 5 at Adelaide Airport, Australia. The pilots had expected to see the runway from the co-pilot's window, but because of strong northerly winds on final approach, the lights that they thought were from runway 5 were, in fact, lights from Anzac Highway. Fortunately, the pilot realized the error in time to abort the errant landing and later successfully landed on runway 23. Another example of expectancy bias is when an owner of a new vehicle suddenly notices many of the same vehicles on the road. Of course, the other vehicles were there prior to the purchase, but they are only noticed by the observer because *top-down processes* bias the processing of information in the environment.

Divided Attention

When attention is divided between two or more concurrent activities, this is referred to as a *divided attention* task.[4] In this context, attention has often been conceptualized as a resource that can be flexibly allocated between tasks based on processing priority (Kahneman 1973; Norman & Bobrow 1975; Navon & Gopher 1979; Wickens 1980, 1984, but see Navon 1984). Norman and Bobrow (1975) differentiated between *data-limited* and *resource-limited* regions of a theoretical function relating attentional resources and performance (i.e., the *performance–resource function*). In the data-limited region of the curve, allocating more attention to a task does not improve performance (in many cases, this is due to ceiling or floor effects in performance). For example, if a novice pilot attempted to fly a high-performance fighter aircraft, it is unlikely that allocating more attention would improve performance. In the resource-limited region of the curve, allocating more attention to a task improves performance. When an operator attempts to concurrently perform two resource-limited tasks in this "zero-sum game," performance on one task prospers at the expense of the other (but see Wickens 1980, 1984).

Dual-task combinations typically fall into one of two categories. The first includes situations in which performance of a task in dual-task conditions is similar to the performance of that task when performed in isolation. This occurs when one or both tasks are in data-limited regions of their respective performance resource functions or when the two tasks tap separate pools of resources (Wickens 1980). For example, some skills may become so automatic that they can be combined with another activity with little or no cost. In one such case, Spelke *et al.* (1976; see also Solomons and Stein 1896) trained subjects for 17 weeks so that they could take dictation while reading unrelated sentences with no decrement in reading speed or comprehension. Conditions such as this are referred to as *perfect time-sharing* (Wickens 1984).

The second category of dual-task combinations includes situations in which performance of a task in dual-task conditions varies as a function of the processing priority allocated to the two tasks. In this case, both tasks are in the resource-limited regions of their respective performance resource functions. As more attention is allocated to one task, performance on that task improves and performance on the concurrent task deteriorates.

Below, we consider examples of dual-task combinations that fall into the latter category and defer discussion of perfect time sharing to the section examining the effects of practice on attention and performance.

One dual-task activity that is commonly engaged in by over 100 million drivers in the US is the use of cell phones while driving. Studies indicate that drivers are more likely to miss critical traffic signals (e.g., traffic lights, a vehicle in front braking, etc.), slower to respond to the signals that they do detect, and are more likely to be involved in rear-end collisions when they were conversing on a cell phone (Brookhuis *et al.* 1991; McKnight & McKnight 1993; Alm & Nilsson 1995; Redelmeier & Tibshirani 1997; Strayer & Johnston 2001; Strayer *et al.* 2003). Not only does the use of a cell phone interfere with driving, but there is evidence that driving interferes with the cell phone conversation (Briem & Hedman 1995). That is, the cell-phone/driving dual-task combination is a good example of dual-task interference in which the driving and cell phone tasks compete for limited capacity attention.

Intuition might lead you to suspect that walking would be a task that is automatic and could be combined with other activities without costs. However, O'Shea *et al.* (2002) found that the stride length of patients with Parkinson's disease and control subjects was reduced when they engaged in either a motoric coin transfer secondary task or a cognitive digit subtraction secondary task. Anecdotal evidence suggests that talking on a cell phone also interferes with walking. Thus, there may be some merit to the saying that some people have difficulty walking and chewing gum at the same time (Kahneman 1973).

Finally, in considering divided attention it is worth examining how finely attention can be divided; that is, how many *independent* things can be attended to at the same time. James (1890) suggested that the range was between four and six. Interestingly, current estimates are within James' proposed 4–6 range. For example, Halford *et al.* (2005) asked participants to interpret graphically displayed statistical interactions. Task complexity increased as a function of the number of independent variables. These authors found that both the accuracy and speed of performance declined significantly between three and four variables, and performance on a five-way interaction was at chance. Similarly, Fisher (1984) suggested that the maximum number of cognitive comparison operations that can be executed simultaneously is restricted to about four, and Julez (1981) suggested that observers can subitize brief presentations of up to four objects without error. Using a different method, Pylyshyn and Storm (1988; Pylyshyn 2004) had participants monitor the location of four randomly moving targets in a field of four randomly moving distractors. The target and distractor objects were identical and were cued just before a trial began by briefly flashing the target objects. Then all eight items in the display moved randomly and independently for 10 seconds. When the motion stopped, the observers were required to locate the target objects. When initially confronted with this task, most observers had the impression that the task was too difficult and could not be done. Yet, location accuracy was about 87 per cent and observers were able to monitor the location the targets without keeping track of their identities. However, performance in the multiple-object tracking task falls rather dramatically as the number of target items increases beyond four (e.g., Oksama & Hyona 2004).

Mental Workload

> The stream of our thought is like a river. On the whole easy simple flowing predominates in it, the drift of things is with the pull of gravity, and effortless attention is the rule. But at intervals an obstruction, a set-back, a log-jam occurs, stops the current, creates an eddy, and makes things temporarily move the other way. If a real river could feel, it would feel these eddies and set-backs as places of effort. (James 1890, pp. 451–452)

Daniel Kahneman's (1973) book, entitled *Attention and Effort*, suggests that there is a relationship between attention and mental effort. Trying harder means allocating more attention to the task, often with corresponding increases in the mental workload experienced by the operator. In general, there is an inverted U-shaped function relating mental workload and performance (Yerkes & Dodson 1908). If workload is too low, then fatigue and boredom can set in and performance will deteriorate. If workload is too high, then the operator will be overloaded and performance will suffer. The "middle ground" of mental workload is a situation where the task demands are high enough to keep the operator alert and functioning at high levels of performance, but not so high as to overtax the individual.

Mental workload describes the interaction between an operator and the task (Gopher & Donchin 1986). Workload is a multifaceted construct, with no single measure completely capturing the experience. Researchers have used a variety of methods to measure workload. One measure is based on *primary task* performance, with the assumption that as performance degrades, workload must have increased. For example, as the mental workload of drivers increases, they may exhibit greater difficulty in keeping the vehicle in the center of the lane. Researchers have also added a *secondary task* while people perform the primary task, with the assumption that performance on the secondary task declines because the mental workload of the primary task increases. For example, Baddeley (1966; see also Logie *et al.* 1989) found that an operator's ability to generate a series of random numbers (as a secondary task) decreased as the primary task difficulty increased. Mental workload has also been assessed using a wide variety of *physiological measures* including electrocardiographic (ECG), electrooculographic (EOG), and electroencephalographic (EEG) recordings. Finally, workload is often assessed using *subjective* assessments of the individual performing the task. With subjective measures, the operator evaluates their phenomenological experience along several dimensions. For example, using the NASA-TLX (Task Load Index), operators are asked to rate their mental demand, physical demand, temporal demand, performance, effort, and frustration level (Hart & Staveland 1988). Primary task measures, secondary task measures, physiological measures, and subjective measures all capture important aspects of mental workload and each is associated with different strengths and weaknesses (O'Donnell & Eggemeier 1986).

Sirevaag *et al.* (1993) provide an interesting example of a comprehensive evaluation of the mental workload of military helicopter pilots in a high-fidelity flight simulation. In this study, the four methods described above for assessing mental workload were used to assess the demands on the pilot. Primary task measures included how well pilots performed each segment of their mission (e.g., to avoid anti-aircraft fire, pilots were instructed to fly 6 feet above the ground and deviations above or below this were taken to indicate higher levels of workload). Secondary task measures included presenting occasional tones over headphones, and pilots were instructed to keep a running tally of the number of tones that they had detected. In more difficult sections of the mission, the accuracy of the count tally decreased, indicating higher levels of mental workload in the primary task (i.e., flying the helicopter). Physiological measures included recording event-related brain potentials (ERPs) elicited by the secondary task tones. As the demands of flying the helicopter increased, the amplitude of the attention-sensitive components of the ERPs diminished. Finally, after each segment of the mission, pilots filled out subjective ratings of their workload. Taken together, these four methods provided converging evidence for determining the pilot's mental workload as they performed different maneuvers in the simulator.

In an example from a different operational environment, Weinger *et al.* (2004) evaluated mental workload of anesthesiologists during teaching and non-teaching anesthesia cases. Mental workload was assessed using a combination of primary task measures (i.e., observer ratings), secondary task measures (i.e., reaction to alarm lights on the patient monitor), physiological measures (i.e., heart rate), and subjective measures. Converging evidence from the four measures indicated that the workload of the clinician systematically increased from non-teaching baseline cases to situations in which when they performed their joint role as a clinician/instructor. As noted by the authors of the study, the increased workload suggests the need for caution when teaching during the delivery of patient care. As with the preceding example, the multiple measurement techniques help to provide valid and reliable estimates of the workload demands faced by the user.

With advances in computer technology and sophisticated psychophysiological techniques, it is now possible to estimate the mental workload of an operator in real time and adjust the demands of the task through computer automation when workload becomes excessive. In the case of *adaptive automation*, computer automation takes over lower priority tasks that the operator cannot perform under high workload and as the task demands and mental workload decrease, the computer automation relinquishes control to the operator (Pope *et al.* 1995). Wilson & Russell (2003) used artificial neural networks to classify in real time psychophysiological measures of mental workload while subjects performed different variations of the NASA multi-attribute task battery.[5] In this study, measures of ECG, EOG, EEG, and respiratory rate were taken while participants performed both low and high difficulty versions of the NASA task. The authors reported that classification accuracy for the artificial neural networks ranged from 82 to 86 per cent correct. Similarly, Prinzel *et al.* (2003) described a *biocybernetic* system that dynamically changed the task demands based on a combination of EEG and ERP measures, and Hillburn *et al.* (1997) used psychophysiological measures to adjust the task demands of an air traffic controller so as to maintain acceptable levels of workload.

Sustained Attention and Vigilance

Situations in which an observer must sustain attention for prolonged period of times are referred to as *vigilance tasks* (Mackworth 1948; Parasuraman, 1979, 1985; Parasuraman *et al.* 1987). In the typical vigilance task, the observer searches for target signals (e.g., enemy planes on a radar display, tumors in a radiograph, hidden weapons in a luggage x-ray, etc.) that are unpredictable and infrequent. Vigilance tasks are often quite taxing, performed under time pressure, associated with high levels of mental workload, and have levels of performance that are less than desirable (Hitchcock *et al.* 1999; Temple *et al.*

2000). The task of airport baggage screening provides an excellent example of a vigilance task in which the screener must monitor x-ray images for prolonged periods of time searching for prohibited items (e.g., guns, knives, bombs, etc.). McCarley *et al.* (2004) used an eye-tracker to measure fixation patterns in x-ray images of luggage and found that airport baggage screeners missed 15 per cent of the hunting knives that were fixated upon and 44 per cent of knives that appeared in locations that were not fixated on by the screener. This performance is clearly less than desirable.

Moreover, in sustained attention tasks there is a characteristic decrement in vigilance performance over a work shift that occurs in conditions where observers must hold information in active memory and use it to make decisions (i.e., the *vigilance decrement*).[6] For example, Parasuraman (1979) found decrements in detection sensitivity when the task required that target templates be held in working memory and observers to make *successive discriminations* (i.e., by comparing the item in question to an internal template in working memory). This vigilance decrement appears to stem in large part from the capacity drain brought about by prolonged effortful attention (Grier *et al.* 2003). By contrast, the decrements in detection sensitivity are less prevalent in *simultaneous discrimination* conditions in which the task does not overload working memory. In the latter case, an external template may be provided for comparison purposes to ease the burden on working memory.

Airport baggage screening provides a good example of successive discrimination. Because the list of prohibited items is quite large and there is considerable variation in the features within each category, the screening task places a considerable load on working memory. Thus, it is not surprising that McCarley *et al.* (2004) found poor detection rates, even when the screeners looked at the prohibited items in the x-ray. However, in cases where a template can be provided (e.g., in a production assembly-line) and the task does not overburden working memory, vigilance decrements should not be as pronounced.

Several methods have been proposed to improve vigilance performance (Davies & Parasuraman 1982). One suggestion is to provide consistent practice to make critical target information automatically capture attention (Shiffrin & Schneider 1977; see below for more details). If the potential set of target items is well defined, then consistent practice is likely to improve performance by increasing the *detection sensitivity* of the observer. However, as in the case of baggage screeners, if the critical target information varies based on viewing angle and from instance to instance, then it will be difficult to develop automatic detection of the targets (McCarley *et al.* 2004). Another option is to provide incentives to increase the motivation of the observer. For example, a baggage screener could get a bonus for detecting prohibited weapons. Incentives that increase the payoff for target detection are likely to decrease the observer's *response criterion*, resulting in an increase in *hits* (i.e., correctly indicating that a target is present) and *false alarms* (i.e., erroneously indicating that a target is present) and a decrease in *misses* (i.e., erroneously indicating that a target is absent), and *correct rejections* (i.e., correctly indicating that a target is absent) (see Green & Swets 1966). A final possibility considered here is the introduction of "false" signals that increase the probability of an event. In the case of airport baggage screening, prohibited items have been introduced into the screening process by transportation security officials. The introduction of false signals is also likely to result in a decrease in the response criterion (and lead to an increase in hits and false alarms and a decrease in misses).

Effects of Training

The old adage *practice makes perfect* implies that performance improves when people perform a task routinely. Indeed, one of the most important characteristics of human cognition is the ability to acquire new skills and expertise (Posner & Snyder 1975; Shiffrin & Schneider 1977; Anderson 1982, 1987, 1992; Logan 1985, 1988). Novice performance is typically characterized as slow, effortful, and reliant on limited capacity attention. At the other end of the continuum, an expert's performance is often characterized as fast, effortless, and automatic. In their classic studies of controlled and automatic human information-processing, Shiffrin and Schneider (1977) demonstrated that performance improves with certain types of practice, whereas other types of practice do not improve performance (even with tens of thousands of trials of practice). When there is a *consistent mapping* of stimulus to response over trials, performance will improve with practice and may eventually be characterized as automatic (e.g., free of capacity limitations, autonomous, ballistic). By contrast, when the mapping of stimulus to response varies across blocks of trials (i.e., *varied mapping*), performance does not improve with practice and remains subject to the capacity limitations of attention. For example, people who drive different vehicles can become frustrated because the process of activating the windshield wipers, headlights, and other devices varies from vehicle to vehicle (i.e., variable mapping). Other aspects of operating a motor vehicle, such as controlling the gas pedal or steering wheel, are consistent from vehicle to vehicle, making transfer from one vehicle to another relatively easy (i.e., consistent mapping). One implication of these findings is that benefits of practice are only to be had with parts of a task where there is consistency in the input–output mappings.[7]

An important characteristic of tasks as they become more automatic is that they place fewer demands on limited capacity attention. Anyone who watches an expert in action cannot help but be amazed at the mastery of his/her skill. Experts can make a seemingly impossible task for a novice look routine and effortless. At high levels of automatization, attention can be withdrawn from the task (Schneider & Fisk 1982) and the skills can be performed autonomously (i.e., without attentional control). In fact, there is evidence to show that paying too much attention to the automatic components of a task can interfere with the performance of an expert. Beilock *et al.* (2002, 2004) found that experienced golfers benefited from dual-task conditions that limited, rather than encouraged, attention to the execution of their swing.

Consequently, tasks that are processed automatically can be combined in dual-task situations with little change in performance from single-task levels (i.e., perfect time-sharing). For example, Schneider and Fisk (1982) found that subjects can sometimes perform two visual search tasks without noticeable deficit when one of the search tasks is automatic. In their dual-task study, subjects searched for a target letter in a series of 12 rapidly presented frames. Subjects searched for a consistently mapped target on one diagonal of a 2×2 character array and searched for a variably mapped target on the other diagonal of the array. When subjects performed the dual-task condition with a strong emphasis on the variably mapped search task, target detection sensitivity on the consistently mapped search task did not differ from single-task baseline levels. These data indicate that subjects were able to perform automatic visual search without allocating attention to the task.[8] Another example of perfect time-sharing comes from the dual-task studies described earlier requiring participants to take dictation and read unrelated passages (Spelke *et al.*

1976; see also Solomons & Stein 1896). After extensive practice, two hearty souls were able to take dictation with no decrement in reading speed or comprehension. Moreover, with additional encouragement, these subjects were able to detect relations among the dictated words and categorize the dictated words for meaning without interference on the reading task. Likewise, Allport *et al.* (1972) reported that a skilled pianist could shadow a series of aurally presented words without decrements in concurrent sight-reading performance. Similar evidence of perfect time-sharing has been reported with experienced ice hockey players (Leavitt 1979) and soccer players (Smith & Chamberlin 1992).

Given that consistent practice improves performance, an effective strategy for training is to provide extensive practice on the parts of the task that are amenable to improvement (Schneider 1985). With *part-task training*, a task analysis is used to identify the consistent components of a task. These sub-tasks are practiced in isolation until performance is proficient, before being integrated into the whole task. Wightman and Lintern (1985) differentiated between two forms of part-task training. *Segmentation* refers to situations in which practice is provided on segments of the whole task. In the case of segmentation, the components of the part and whole task are identical and transfer is expected to be good. A good example of segmentation is when a musician practices a particularly difficult part of a score several times before performing the entire piece. *Fractionation* refers to situations in which practice is provided on the individual components of two or more tasks that must eventually be performed together in the whole task. In the case of fractionation, the time-sharing demands of the part and whole task are likely to differ and part-task training is not likely to be effective. Indeed, researchers have found that part-task training has varying degrees of success. For example, using a space fortress videogame, Fabiani *et al.* (1988) found that participants who received part-task training performed better than participants trained for the same amount of time on the whole task. Likewise, Drews *et al.* (2005) found that part-task training improved resident anesthesiologists' ability to detect and diagnose critical events during simulated surgeries. However, when the demands of integrating task components are high, practicing each task in isolation may not be any more effective than practicing the whole task, and in some instances may result in negative transfer if the integrative dual-task components go unpracticed.

A variation on part-task training designed to avoid the limitations associated with fractionation is *variable priority training* (Gopher *et al.* 1989, 1994). With variable priority training, participants always perform the whole task, but they are systematically instructed to emphasize some components of the whole task while deemphasizing the other parts of the whole task. Note that with variable priority training the integrality of the dual task is maintained while trainees flexibly allocate attention to the different components of the task. Kramer *et al.* (1995) compared the effectiveness of variable priority training with a fixed priority training strategy. Subjects were initially trained to concurrently perform a monitoring task and an alphabet-arithmetic task, and then were transferred to a scheduling and a running memory dual task combination. Not only did variable priority training better facilitate the rate of learning and the level of mastery during the initial training period, but subjects trained under variable priority showed better transfer to the scheduling and running memory tasks. Thus, variable priority training appears to be an effective technique for training the flexible allocation of attention in dual-task conditions.

Executive Control

Working memory capacity, as measured by counting, operation, and reading span tasks, is thought to play a critical role in helping to keep task-relevant information active and accessible during the execution of complex tasks (e.g., Daneman & Carpenter 1983; Kane *et al.* 2001; Conway *et al.* 2005; Cowan *et al.* 2005). From this perspective, Engle *et al.* (1999) have suggested that working memory capacity reflects an executive attentional system[9] reliant upon prefrontal cortical brain regions in which "the memory representations are maintained in a highly active state in the face of interference, and these representations may reflect the action plans, goal states, or task-relevant stimuli in the environment" (Kane & Engle 2002, p. 638). As an illustrative example, consider the operation span task originally developed by Turner and Engle (1989) and recently used by Watson *et al.* (2005, Exp. 1) to study how individuals with low and high operation span differ in the susceptibility for creating false memories. In the first phase of the study, participants were asked to read and solve aloud a math problem followed by a to-be-remembered word (e.g., $2 \times 5 - 3 = 6$? cow). The number of math problem-word items was randomly varied from 2 to 6 and at the end of each list participants were prompted to recall the words from the list in order they were presented. Participants were subsequently classified as having low operation span if they correctly recalled between 0 and 9 words in the correct order, whereas participants were classified as having a high operation span if they correctly recalled more than 20 words in the correct order. In the second phase of the study, Watson *et al.* (2005) compared low- and high-span individuals' susceptibility for false memories by creating lists of words to be memorized where the list items are strong associates of a critical missing word (e.g., the critical missing word might be "sleep" and the presented list items are bed, rest, awake, dream, blanket, etc.). Participants were given explicit task instructions warning them how the lists were designed to induce false memories. Nevertheless, low-span individuals were more susceptible to false memories than were high-span individuals, and this was interpreted as reflecting differences in the ability of low- and high-span individuals to actively maintain the task goal of not falsely recalling items that were not on the list.

There are a number of important individual differences in the executive control of attention that have been reported in the literature (see below for additional discussion of individual differences). For example, working memory span tasks have been found to be predictive of reading comprehension and verbal SAT scores (Friedman & Miyake 2004), differences in the spatial distribution of attention (Bleckley *et al.* 2004), performance on dichotic listening tasks (Conway *et al.* 2001), ability to perform the anti-saccade task (Kane *et al.* 2001), and the degree of interference in a Stroop color naming task (Kane & Engle 2003). Working memory span tasks have also been shown to decline with senescence (Balota *et al.* 1999; Watson *et al.* 2004) and to be reduced for patients with Alzheimer's dementia (Balota *et al.* 1999; Watson *et al.* 2001). Thus, the executive attentional system appears to be a critical component in people's ability to successfully perform a task when confronted with distraction or interruption.

In a similar vein, Altmann and Trafton (2002) developed an activation-based model for memory for goals which has been successfully applied to understand the ability to recover from an interruption in an ongoing activity. Indeed, in the workplace we are often interrupted by ringing phones, beeping emails, queries from colleagues, alarms, etc., and it is often a challenge to resume the interrupted task at the appropriate place in the sequence. These interruptions can have harmful consequences if the task is resumed in such way that an important item is omitted. For example, a National Transportation Safety Board (1988) investigation of the crash of Northwest Airlines Flight 255 determined that the first officer was distracted by several intervening events which diverted his attention from the task of adjusting the flaps and slats. Consequently, the flaps and slats were not fully extended and the airliner crashed immediately after takeoff, killing 148 passengers, six crew, and two people on the ground. In fact, Dismukes *et al.* (1998) concluded that nearly half of the NTSB reported aviation accidents attributed to crew error involved lapses of attention associated with interruptions, distractions, or preoccupation with one task to the exclusion of another. Similarly, interruptions have been shown to negatively interfere with operating a motor vehicle (e.g., Strayer & Johnston 2001; Monk *et al.* 2002; Strayer *et al.* 2003), the delivery of patient care in the emergency room (e.g., Chisholm *et al.* 2000, 2001) and in the intensive care unit (e.g., Drews 2006). Given the potential adverse consequences of interruptions, it may prove fruitful to include working memory span tasks in the battery of selection instruments used during the initial screening of employees in operational environments where task-item omission is of concern.

Individual Differences

As with all aspects of human cognition, there are important individual differences in the diverse varieties of attention and, in the extreme, deficits in attentional processing are important defining characteristics for several psychopathologies (e.g., schizophrenia, attention deficit hyperactivity disorder, etc.; for details, see DSM-IV 1994). Here we consider non-pathological differences in attention and performance.

Ackerman (1987, 1988) demonstrated that *between-subject* variability in performance decreases with consistent practice on a task such that individual differences tend to be greater early in training than they are later in training. To better understand the role skill acquisition plays on individual differences, Ackerman (1988) developed a theoretical framework incorporating differences in general ability, perceptual speed ability, and psychomotor ability. As the consistency of a task increases, the role that these ability differences play in skill acquisition grows. Ackerman's framework builds on the three phases of skill acquisition developed by Anderson (1982, 1987, 1992). The first phase of skill acquisition is the *declarative stage* and is dependent upon the general processing abilities of the individual. The second phase is the *knowledge compilation phase* and is dependent on an individual's perceptual speed ability. The third phase is the *procedural stage* and is dependent on psychomotor ability.

In applied settings, an important goal is to select the right people for the right job. Individuals differ in their abilities and each job has unique requirements. For example, the requirements for an anesthesiologist differ from those of a fighter aircraft pilot and from an NFL lineman. In considering the task of selecting the right person for the right job, it is important to identify the goal of selection. Using Ackerman's (1988) framework, if the goal of selection is to identify those individuals who will do well during the early stages of training, then general abilities are likely to be good predictors of success. By contrast, if the goal of selection is to identify those who will do well in the later stages of training, then at least in some cases psychomotor abilities may be good predictors of success.

Of course, as illustrated in the preceding section, not all ability differences can be practiced away and differences in attention can have important consequences for performance in applied settings. Surprisingly, this area has not been a major focus of research for non-pathological populations. However, several investigators have demonstrated that individual differences in attention are predictive of real-world performance. For example, Gopher (1982) found that individual differences in a selective attention dichotic listening task were correlated with individual differences in performance in flight training. Jones and Martin (2003) suggest that an individual's ability to distribute attention is a predictor of successfully avoiding the accidental loss of computing work. Finally, Schweizer *et al.* (2000) found that performance on a sustained attention task was correlated with measured intelligence and that the correlation grew in strength as the cognitive demands of the sustained attention task increased.

CONCLUSIONS AND FUTURE DIRECTIONS

Looking back over the years since James (1890) published his chapter on attention in *The Principles of Psychology*, it is clear that his original framework is still with us. Attention is Balkanized into subcategories (e.g., selective attention, divided attention, etc.) and we still have no unified theory of attention. Although a number of paradigms have been developed to study attention and many of the details have fallen into place, advancement toward a coherent theoretical picture has been unsatisfactory. This has led some to lament the progress in the field (e.g., Johnston & Dark 1986). Pashler (1999) suggests that "no one knows what attention is, and that there may not even be an 'it' to be known about" (p. 1). Pashler argues for "the inadequacy of the term attention" (p. 317), suggesting that our folk psychological use of the term may be getting in the way of understanding the phenomenon. By contrast, Logan (2004) paints an optimistic picture of cumulative progress in theories of attention.

Our brief survey of the theoretical literature indicates that researchers have used a number of metaphors to describe attention, including: filter, gatekeeper, spotlight, zoom lens, resources, object file, glue, and bottleneck. Each metaphor describes important characteristics of attention, but each falls short of helping to explain the underlying mechanisms. Gentner and Jeziorski (1993; Gentner 1998) suggest that metaphors (and analogies) exploit partial similarities between different systems which can be misleading as well as helpful. From a scientific perspective, a useful metaphor maps the knowledge from one *well-understood* domain onto another, such that a system of relationships that holds for the former also holds for the latter. In some cases, metaphor can lead to new insight into a phenomenon. However, it is important not to be misled by superficial similarity of a metaphorical relation.

From an applied perspective, it is useful to consider whether it is *necessary* to have a general unified theory of attention in order to apply the principles derived from basic research on attention to the real world. Clearly, as outlined in the preceding section, the properties of human performance associated with selective processing of the environment have important consequences in applied settings. Likewise, capacity limitations play a fundamental role in human performance in real-world multitasking situations. Moreover, related concepts, such as workload, practice, executive control, and individual differences, are undeniably important in applied contexts. We suggest that even an inchoate theory of attention can be useful in helping to understanding human performance in the real world.

From our viewpoint, the distinction between basic and applied research is somewhat arbitrary. Good applied research has often provided important insights into the basic mechanisms of human cognition, and basic research can lead to new directions in applied research. What should be the role of applied attention research given the theoretical ambiguity of the term attention? Among other things, we suggest that applying our current understanding of the mechanisms of attention to applied issues provides useful information for how well a theory scales from the laboratory to the real world. The ultimate arbitrator on the utility of a theory of attention is how well it explains human behavior in everyday life.

NOTES

1 We use the terms divided attention and dual task interchangeably throughout this chapter.
2 A notable exception is James' concept of an *effect theory of attention*, which has largely been ignored by contemporary researchers (but see Johnston & Dark 1986). With effect theory, attention is the *effect* of differential processing, rather than the *cause* of differential processing.
3 Note, however, that evidence of the effects of selective attention in lower visual areas may be indicative of feed-forward "early selection" or "late selection" feedback from higher cortical levels.
4 It often proves difficult to determine if dual-task performance is the result of sharing attention between tasks or rapidly switching attention between the two tasks. However, estimates of the time to switch attention between to sources of input range from 80 ms (Peterson & Juola 2000; Logan 2005) to 300 ms (Weichselgartner & Sperling 1987), which would seem to preclude rapid shifts of attention in many dynamic dual-task configurations.
5 The NASA multi-attribute task battery subtasks include light and dial monitoring, manual tracking, resource management, and auditory communication.
6 However, Adams (1987) suggests that typical laboratory paradigms may overestimate the real-world decrements in vigilance performance.
7 It is interesting to note that in commercial aviation, pilots are certified to fly specific types of aircraft so as to avoid the inconsistency (i.e., varied mapping) that would result from switching from one model of aircraft to another. By contrast, in healthcare the configuration of equipment (e.g., in the different operating rooms of a hospital) often varies as a function of equipment manufacture and purchasing policies, thereby requiring physicians to operate in an environment with higher levels of inconsistency that is optimal.
8 Although single-task and dual-task *detection sensitivity* did not differ in Schneider and Fisk's (1982) study, the overall accuracy of detection dropped by 17 per cent from single- to dual-task conditions. This suggests that even in ideal settings, perfect time-sharing may not be truly "perfect."
9 The executive attention system has also been referred to as a central executive (e.g., Baddeley & Hitch 1974; Baddeley 1993), controlled processing (e.g., Posner & Snyder 1975; Shiffrin & Schneider 1977), and the supervisory attentional system (e.g., Norman & Shallice 1986; Shallice 1988).

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