**Attention:** **A Two and a Half Millennia Guide to its Sources**

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FOUR VOLUME COMPENDIUM OF IMPORTANT DOCUMENTS IN THE HISTORY OF RESEARCH ON ATTENTION

Attention is a central link in understanding how the complex activity of our environment leads to the more limited world of which we are aware. Attention mechanisms are also central to the generation and inhibition of voluntary behavior. Attention represents our sensory and motor interface with the world and with our own feelings and thoughts. As a consequence of its importance the study of attention has a long history both within and outside of psychology.

In these four volumes we seek to tell the developing story of the human effort to define and understand the mechanisms of attention. To students of attention this may provide some perspective for their current studies. To others it might allow a better understanding of how the mechanisms of attention and studied and how attention relates to understanding problems our world.

In developing a set of volumes to summarize the history of work on attention,

one can try either to select those pieces that are most important for current researchers, or attempt to find the earliest treatment of enduring issues in the field. Citation counts emphasize the first goal, while historians would most likely subscribe to the second one. In this selection I have tried to implement both strategies.

To solicit help from experts in the field of attention a questionnaire was sent out to 40 researchers with an attempt to represent diversity of gender, nationality, approach to the field etc. They were asked to list five papers that had most influenced paper their work and to suggest their own papers they thought most important. Using these questionnaires as a basis, particularly for volumes 2 and 3, I have worked to select the papers to be included in these books. These papers and books from which excerpts were taken are all available in English directly or in the case of some books, in translation. I have organized the four volumes so that volume 1 summarizes the 2,500 year history of thinking about attention from antiquity until roughly World War II. The second volume concerns empirical studies following the war until as recently as 2012. Since the number of studies meeting these criteria was enormous, I relied heavily on the questionnaire, highly cited papers and my own instincts in choosing those in the volume. The empirical studies provide a context for Volume 3 that includes the same time period as Volume 2, but involves theory. Theories, particularly those involving strictly behavioral levels of analysis are often in principle computational, but some involve mainly systematic verbal descriptions. I also include theories largely based on imaging and those involving cellular or molecular mechanisms. Volume 4 summarizes the application of attention to human use of language and thought, including consciousness, human development, human performance at work and play, training the brain to improve attention and studies of neurological and psychiatric patients

These volumes raise one overriding issue. Is there a cumulative development of work on attention? Can we argue that recent work answers issues raised earlier, even in the distant past? Based on my reading I think the answer is yes, despite many changes in language and method. I have tried to illustrate the reasons for this conclusion for each of the volumes below.

**VOLUME 1: HISTORICAL BACKGROUND**

*Ancient Origins*

One of the most basic issues of attention involves control. On the one hand, this refers to how to control ones attention and thus keep the mind from wandering; on the other, how attention controls behavior. These issues have origins in eastern traditions at least 2,500 years old, as is pointed out in the first two selections of volume 1 from the Hindu classic *Baghavad Gita* and the sayings of the Chinese sage *Lao Tsu.* Although essential to religious thought, these concepts rest on philosophical issues that made them difficult to address until in the modern era when we began to have methods for examining brain mechanisms that might underlie them. Thus although the concepts are ancient, the means to address them by detailed empirical studies are new. Attentional control raises the issues of will and volition. Despite the long tradition of methods to achieve control through meditation, self denial, or physical training, only in the early 21st century were these issues addressed by the powerful scientific methods open to psychology (see *Smallwood & Schooler vol 2*; *Tang & Posner vol 4*). In the next section philosophers addressed such conceptual issues as how to localize the mind and how the mind was related to the body and brain.

*Conceptual Foundations*

The first reading in this section is taken from *Descartes (vol 1 first published 1649)*. Aristotle had placed the study of the soul (psychology) within the natural sciences. He also regarded the organ of the mind as the heart*. Descartes*, however, recognized the brain as the target of the senses. Because mental processes lacked extension in time or space *Descartes* believed that the mind, unlike the physical world, could not be described in mathematical terms (Burt, 1932) . *Descartes* placed the soul (mind) within all parts of the body, but especially in the pineal gland. This gland was chosen principally because unlike other parts of the brain, it was a single and not a dual organ. The distinction *Descartes* made between the physical and the mental led to a dualism in which physical properties of the world were subject to precise measurement, but mind, was not. Over 200 years later Fechner, in his Elements of Psychophysics, originally published (1860) did attempt precise measurement of mental experience. Although not directly applied to work on attention by Fechner, the issue of precise measurement of attenton is discussed by many of the papers in volume 1 and 2.

*George Lewes vol 1* 1859 distinguished between attention and sensation. Attention was a direction of the mind toward a sensory event. Attention led to a perception, distinct from the sensations which remained present regardless of our awareness of them.

*William James vol 1 1890* provided the most frequently cited definition of attention.

*“Every one knows what attention is: It is the presence in the taking possession by the mind in clear and vivid form, of one out of what seem several simultaneous possible objects or trains of thought….*

Although the close identification of attention with consciousness found in James has been a matter of dispute (*Koch & Tsuchiya volume 4*), James’ separation between objects and trains of thought fits well with models of different brain networks (*Dossenbach vol 2, Fan vol 2*). In this reading, James warns that studies using reaction time carried out by Wundt and others with seemingly precise measurement, often miss the essence of mental phenomena.

The James chapter should be read in conjunction with the chapter from Titchener, who is a strong representative of the approach favored by Wundt and his associates. In this chapter *Titchener* claims that attention was discovered in Leipzig laboratory and is the centerpiece of the psychological enterprise. He discusses the experimental approach advocated by Wundt*. James and Tichener’s* differences seem to presage the desire for ecological validity (i.e. application to real world phenomenon as opposed to the possibly vacuous precision of experimental paradigms (see, Neisser, 1968 vs Neisser, 1976).

*Ribot* points out that voluntary sustained attention such as that required to write a textbook is a rare feature of humanity. More frequently consciousness is more diffuse and driven by habitual patterns of thought. In this selection from his volume The Psychology of Attention, *Ribo*t (1898, this volume) seeks to understand both attention and non attentive states of mind. This topic of non-attentive mental state has more recently involved the study of the default state of brain activity in alternation with brain activity underlying attention (Raichle, 2009).

After the outpouring of writing on attention at the start of the 20th century discussed in this section, in the following decades the dominance of behaviorism resulted in relatively little conceptual writing on the topic. However, a number of important methods were developed in this period that are represented in the paper in the final section of this volume.

*Neuropsychology*

Our modern understanding of attention is shaped by publications that came immediately after World War II. The war produced many unique events. Brain injuries during wartime allowed better understanding of reduced cognition with injuries to different parts of the brain. Advances in technology in cryptology and radar, for example, led scientists to think more about human information processing. The displacement of many scientists from academia to war related activities brought them into contact with people from many disciplines. These factors may have been instrumental in providing the environment for conceptions of neuropsychology and information technology that have guided thinking following the war.

*Moruzzi and Magoun this volume 1949* found that activation of the midbrain reticular system gave rise to the desynchronized EEG characteristic of the alert state that underlies attentin. In a subsequent paper they showed that lesions of the reticular system resulted in a comatose state. This work led to studies showing how chemical modulators in these areas tune the cortex and form the basis of the alert state (Iversen et al 2009).

*Donald O. Hebb* *this volume 1949* provided much of the background for our modern conception of learning via synaptic change (cells active together, wire together) and for the idea that distributed groups of cells (cell assemblies) might operate in concert (phase sequences) to form brain networks underlying attention and other aspects of cognition. The cell assembly formed a guide for the network concepts that much later arose from neuroimaging. Hebb built upon previous work to argue that each event in addition to stimulating the sensory pathways also worked via the reticular system to keep the state of the cortex tuned.

*Grey Walter* *this volume 1964* traced the time course of cortical preparation for a target following a warning signal. The negative shift in the baseline EEG appeared to originate in frontal areas and sweep to the posterior brain to activate the sensory system relevant to the target. The warning signal paradigm and its neural signs became key to later thinking about the role of the alert state in attention (Coull et al vol 2).

During this period the Russian psychologist *Luria* worked with patients to discover the neural basis of attention. He was the first to distinguish between a posterior largely automatic biological network related to sensory orienting and a later developing largely voluntary system heavily under environmental influence. These observations were critical to more recent brain network ideas (*Dosenbach et al Vol 2; Fan et al Vol 2*) related to various functions of attention. This work is summarized in the selection from his book The Working Brain published in English in 1973

*Information Processing*

The technological advances during World War II include work by Alan Turing and Claude Shannon providing technological changes that greatly influenced a generation of psychologists in thinking about the human brain.

In their 1949 volume *Shannon and Weaver this volume* developed a mathematic theory of communication that included a way of measuring information capacity of a channel of input. The introduction to this work outlines diagrams a communication system and measures information in terms of binary digits (bits). This work was quickly applied to psychological issues.

*Kenneth Craik 1947 this volume* followed Sir. Frederick Bartlett as the leader of the Applied Psychology Unit at Cambridge University during the war. This Unit was a central place for the new views of the human as an information processing system*. Craik* was a leader in using the idea of communication to view the human as an element within a control system and to develop a theory of the human operator. He built upon findings of Telford’s work (see next section) concerning delays introduced by central attention systems.

The measure of information developed by Shannon allowed *Hick 1948, this volume* and then *Hyman 1953, this volume* to test human channel capacity by relating the information transmitted to the reaction time required to perform a task. This brought back methods developed by *Donders* (1868 see the next section) of measuring human reaction time, but now in relation to the amount of information contained in the stimulus. *Paul Fitts* applied the measure of information developed by *Shannon* to the motor system, showing that the speed and accuracy of a voluntary movement to a target was proportional to the distance of the movement and the accuracy of its termination measured as the amount of information needed to reach the target. Although the notion of a fixed finite human channel capacity was shown to be incorrect in subsequent work by

Neisser, (1968), studies using information theory (Attneave, 1958) have allowed attention researchers to summarize such important variables as the number and probability of a stimulus, the complexity of the transformation between stimulus and response and the accuracy of responding by the information transmitted measure. Work on information theory still plays a role in biological (Gleick, 2011) and psychological studies (Fan et al 2014).

In 1958 *Broadbent* summarized the accumulating literature of the information processing approach in his book Perception and Communication. This work suggested that people are influenced not only by the stimulus itself, but also by the possibilities out of which the stimulus was selected. He viewed attention as a limited capacity channel that formed an important bottleneck between stimulus and response. Broadbent’s book is frequently viewed as the major stimulus to modern efforts to study attention.

*Methods*

The founding of experimental psychology is usually dated from 1879 when the laboratory of Wilhelm Wundt was created in Leipzig. But as Hatfield (1980) points out, this is mostly an academic fiction created to locate an appropriate institutional starting place for the field. Experimental methods as applied to attention had an older beginning, and accumulated for well over a century before the formal founding of experimental psychology by Wundt and after the elimination of consciousness from psychology’s agenda due to the behaviorist doctrine of Watson.

This story unfolds with the development by Sir William Hamilton’s (this volume, 1859) of a method to measure of the span of attention. He proposed that one throws a handful of objects and determines how many objects can be accurately reported from a single glance. A dozen years later *Jevons* (this vol., 1871) reported in *Nature* his conclusion that 4.5 items could be perceived with accuracy in a single glance. Given his sample of one, his data have proven surprisingly accurate for his method.

With the advent of the use of backward masking it was possible to define a glance more precisely by limiting the time for processing the items (Averbach; 1963; Oyama, Kikuchi & Ichihara, 1981). With appropriate masking, it took approximately 10 millisec to go from one item to two and the linear increase held until about 6-7 (often called the subitizing amount),after which the addition of items proceeded much more slowly. Related issues are still subject to careful refinement, for example, in understanding the mechanisms leading to individual differences in attention span (Vogel & Machizawa, 2004 )

Prior to the founding of Wundt’s laboratory the Dutch Physiologist F.C. *Donder*s *this volume 1869* developed a subtractive method to measure the time for internal mental operations of discrimination and choice. Because different tasks were used to introduce each internal mental operation, *Donders’* method was criticized by the possibility that each task was treated in a different manner, so that subtraction of the reaction times could not lead to consistent results. One hundred years later S. Sternberg (1969) showed that stages of processing could be separated within a single task, showing that measurement of mental operations by the time for each operation required was possible. Sternberg (2004) also showed that it was possible to measure operations that occurred in parallel by an appropriate adjustment of his method allowing it to be used in conjunction with brain imaging. Mental chronometry as first outlined by *Donders vol 1* is still yielding results in the era of cognitive neuroscience **(see also *Goebel; volume 3*).**

In 1896 Helmholtz argued that visual attention could be preset without an eye movement to improve perception in the attended part of the field. Studies of orienting of attention within an empty visual field has since led to an understanding of a network of brain areas in the parietal and frontal lobes that carry out the computation needed to orient to a location (see *Corbetta & Shulman Vol 2, Posner, Vol 2, Hillyard vol 2*). It has been argued that oscillatory activity is involved in carrying these computations to the visual areas (*Wolmsdorf Vol 2*). The role of parietal areas and frontal eye field continues to be areas of active research. This is perhaps the field of attention research for which there is the largest amount of agreement and the most convergence across behavioral, electrical, imaging and cellular methods.

Another active area of research began with the investigation of shifts between tasks *Jersild vol 1*, 1927. The methods introduced by *Jersild* have led to a much more detailed understanding of shifting between pairs of tasks ( Monsell, 2002) and in the role of such shifts in allowing the implementation of a hierarchy of during real life behavior (Farooqui et al 2012). In 1941 *Gibson this volume*  reviewed Jersilid’s study along with others that have investigated various aspects of the more general concept of set in psychology.

*Arthur Bills this volume 1931* observed that in a serial reaction time task occasional long response times occurred. These time seemed to be the result of the person tuning out for brief periods. This finding became a major part of the Broadbent filter theory described in Volume 2.

*Telford( this volume, 1931)*  and separately *Welford (this volume 1952)* examined delays in carrying out a second task when it occurs while actively processing a first task. The so-called psychological refractory period remains a central way of examining bottlenecks that might be caused by current processing. This topic is examined in detail by current studies (*Pashler, vol 2*) and various theoretic perspectives (see M*eyer and Kieras* vol 3 ).

The Stroop effect (*Stroop vol 1*) is probably the best known experimental test in all of psychology. The person is asked to respond to the ink color of a word which can be the same as the word (congruent; red in red ink) or incongruent (blue in red ink). It takes longer for incongruent trials. The time to resolve conflict has become the hallmark of a brain network that involves the anterior cingulate and other frontal midline brain areas (e.g. insula, striatum etc) (*Botwinick et al* vol 2). Results of many hundreds of Stroop studies were summarized by McLeod (1991) and they are the subject of an important model (*Cohen et al* Vol 3.). More recently we have learned more about the neural systems that might underlie conflict related tasks (Fjell et al 2012).

The invention of radar during World War II led directly to tests of how well people can maintain vigilance over long periods of time when targets are difficult to discriminate and occur infrequently (*Mackworth vol 1* 1948) summarized the decrement in performance in tasks of vigilance. The study of vigilance remains an important basic and applied topic in psychology and neuroscience. Much of the current literature distinguishes between long term vigilance e.g. found over a few hours by Mackworth(1948) and more phasic changes that follow stimuli that serve as warning signals *(Coull et al vol 2, Sturm et al vol 2).*

An important method for the study of attention in modulating perception was a task where information was presented separately and simultaneously to the two ears. This task was first used by *Cherry (1953 vol 1)* and was an important part of the Broadbent summary of the role of attention in audition. Dichotic listening tasks have been a prominent part of the attention literature ever since.

*Leonard (this volume 1958)* at the time a researcher in Cambridge, sought to discover the length of time needed to assimilate one bit of information. He wanted to separate the time to absorb one bit of knowledge from the time to perceive the stimulus or produce the response. To do this he presented subjects with six lights; the participants were to respond as quickly as possible when one light was turned off. In some conditions,

prior to extinguishing the target light he turned off three of the lights, thus reducing the possible stimulus– response (S– R) combinations by one bit (from six to three alternatives). The time require to reduce reaction time from that obtained with six alternatives to that obtained with only three alternatives was the time for assimilating one bit of information. This cuing method has been widely applied to understand aspects of attention by separating the shift of attention from the motor task necessary to make the response (*Corbetta & Shulman vol 2 Posner vol 2*).

Twenty five hundred years ago Hindu and Chinese sages wondered how to control attention. In subsequent centuries other important functions of attention were developed by Descartes, James and others. Helmholtz measurement of the time required for neural conduction in 1850 was likely the key to the development of many empirical methods for the exploration of attention. These methods were key to the conceptual advances related to the discovery of information theory and to explorations of the human brain during and after World War II. In my summary above I have stressed how these slowly developing methods have been incorporated in the modern studies and in the theories presented in Volumes 2 and 3.

**VOLUME 2 EMPIRICAL STUDIES**

This volume includes empirical studies from 1970 until 2012 which I believe capture advances in ideas and methods that were applied to attention during these important years. These year encompass the development of cognitive science, with its emphasis on the measurement of mental operation, and the start of cognitive neuroimaging. In addition cellular recording from alert behavior animals and the use of large number of implanted or scalp electrodes were among the methods applied to attention during this period. In 1985 Prof. Oscar Marin and I hosted a meeting of Attention and Performance at which many of the major researchers using different levels of analysis (eg cellular recording and scalp electrodes) met and discussed common issues in attention research. Since that time, there has been more integration between levels as highlighted in this volume.

**Processing Stages and Effort**

In 1973 *Daniel Kahneman* *(this volume*) summarized the work on attention in his volume *Attention and Effort*. While the title and theory emphasized the subjective nature of attention as a limited resource, the chapters skillfully blended physiological measure, including heart rate and pupil size with well designed cognitive paradigms. This book, along with Broadbent cited above, helped to return the area attention to a central position within psychology that it had not occupied since *Titchener (vol 1).*

The effort to understand the consequences of attending continues to be an area of active research. *Ostry et al* (1976 this volume)using auditory input channels demonstrated central interference effects for both semantic and non semantic targets, but show they can be greatly reduced with ten hours of practice.  *Pashler (1984)*  updated the work on the psychological refractory period, by isolating its components and showing refractoriness involves a central bottleneck in performance.

**Orienting of Attention**

Orienting to sensory events is the most studied of all aspects of attention, particularly in animal studies. These studies provide an excellent vehicle for illustrating the possible integration of behavioral, imaging and cellular studies around common questions a major goal of this historical effort. Accordingly, orienting is given an extensive treatment in this volume.

*Behavioral methods*

The section on orienting begins with purely behavioral treatments of the topic. In 1960

*Sperling vol 2* demonstrated that a brief glance at an array of multiple visual items could lead to an visual trace that could then be sampled for some period of time. He used a cue to indicate which row had to be reported and found that although the person could report only about four items. However, the high percentage correct indicated that many more items were available from which the person could sample the cued row. This method of partial report became crucial for many subsequent studies.

In 1970 *Bouma* found that the acuity of a letter is diminished by distractor letter particularly those between the fovea and the target. Some twenty five years later *Desimone and Duncan ( 1995, vol 3)* placed the idea of competitive interactions within a receptive field at the basis of their cellular theory of biased competition.

A major puzzle in the study of orienting concerns whether there is a limit to the number of items one can monitor. The psychological refractory period had shown that only one target could be processed at a time. On the other hand, a study by Shiffrin et al 1976 found that one could monitor a 7X7 matrix of items for a target just as well as a single item. If both tasks were about attention, how could this be? In 1980 *Duncan vol 2* took a major step in understanding this issue by showing that people could monitor for multiple targets simultaneously with little or no deficit, but once they detected a target they were likely to miss any additional targets. Thus monitoring had little limit but once a target was found the limit was drastic. That same year using reaction time *Posner Vol 2* showed that the benefits of knowing where a target would occur were small, but once a target was found the costs of shifting to a new target location were large. A further clarification was in a study by *Rensink et al 1997 vol 2.*  They reported that in complex visual scenes a powerful semantic change (e.g. ubstituting a horse head for a human head) was not seen if it was away from the focus of attention, unless there were low level luminance or motion cues to produce orienting toward the change. This finding, called attentional blindness, illustrated the important cues required for efficient orienting and the drastic consequences when such cues were not present.

What are the consequences of orienting to a visual stimulus? *Posner* *(this volume, 1980)* suggested that the main consequence was improved priority of that signal to further processing mechanism, but *Yesuhrun & Cerasco* *(1998, this volume)* showed an actual improvement in sensitivity to targets requiring high acuity.

*Orienting Imaging Studies*

The orienting reflex was an important development within Russian psychology to explore the earliest responses to sensory input (Sokolov, 1958 see also *Luria, Vol 1*). Behavioral studies using reaction time and other chronometric measures provided the methods and theoretical issues for imaging studies that started with positron emission tomography (PET) and later functional magnetic resonance imaging fMRI). While purely behavioral work continues to investigate limits of attention, the larger part of work in psychology since the early 1990s has been examining the brain mechanisms related to attention with neuroimaging.

Behavior and imaging methods have pointed to several networks involved in different functions of attention. In a behavioral study (Fan et al 2002) used the Attention Network Test to measure individual differences in the ability to orient to sensory input, the ability to resolve conflict between the target and the surrounding flankers when incongruent and the ability to obtain the alert state. *Fan et al 2005 this volume* subtracted images from fMRI to show the neural systems involved alerting, orienting and resolving conflict. They found that the brain areas involved were mostly separate for the three functions.

It is also possible to look at brain activity when at rest. Among the brain networks active during rest are two that are involved in attention control (*Dosenbach, et al* *2007 this volume )*. The fronto-parietal network is involved in control over short time periods and overlaps many of the brain areas that *Fan et al 2005* identified as related to orienting toward external stimuli. Another network reported by *Dosenbach* involves the anterior cingulate and insula and is called the cingulo-opercular network. It is involved in long lasting strategic control and includes some of the same brain areas as named by *Fan et al 2005* as the Executive network.

In *2002 Corbetta and Shulman* summarized work on a fronto-parietal network of brain areas related to attention. This network has been studied, in purely behavior studies, with with lesioned patients, with fMRI and with various cellular recordings in alert monkeys. The studies used the arrow version of the spatial orienting task introduced by *Posner, this volume 1980.* It employed varying temporal separation between the cue target ( see *Leonard Vol 1 1954)* to separate brain areas related to orienting cues from those related to target detection. The network consisted of dorsal areas including the frontal eye fields and interparietal sulcus which were thought to be related to voluntary use of the cue to align attention to the cued location and dorsal areas including the temporal parietal junction which were active when the person had to break attention and reorient to a target that occurred in a non cued location.

By examining correlations between fMRI signals in remote areas *Crotaz Herbette & Menon vol 2, 2006)* were able to show cases in which the anterior cingulate was coupled to the selected sensory areas during selection of visual or auditory targets, thus providing a mechanism by which sensory information could be voluntarily selected based on instructions.

While fMRI has become increasingly precise spatially and temporally it is clear that electrical or magnetic recording from the outside the skull or with depth recordings can provide better temporal information about when a stimulus occurs and when it is related to events at remote sites. When it became common to use a large number of scalp electrodes, algorithms were developed allowing the calculation of a putative scalp distribution from a known generator (Scherg & Berg, 1993 ). These equations could be used to relate EEG signals to PET and fMRI data (*Heinze et al vol 2* 1994 ). A number of studies showed encouraging results (Heinze et al Vol2 1994) in relating EEG signs of attention in sensory systems ( *Hillyard et al 1973 vol2*) to generators developed from imaging studies (*Heinze et al 1994, vol 2*). It was then possible to use recordings of electrical signal from the brain to explore transfer of information between sites related to attention and those coming from sensory areas (*Salamann et al vol2 2007; Wolmsdorf et al2007 vol2*).

*Cellular Studies*

Electrodes that would allow recording of neurons in alert and freely moving animals were developed by Jasper et al (1960) and used by Evarts (1966 ) to study motor behavior. *Mountcastle* (*1978 this volume* ) and *Wurtz , Goldberg & Robinson* (*1980 this volume*) adapted the microelectrode to study brain areas involved in visual orienting. Two prominent brain areas in this research were the posterior parietal lobe and the superior colliculus.

Cellular recording methods could be applied to problems of orienting that had previously been addressed by behavioral and imaging methods. Among these was the problem of how eye movements and covert orienting of attention might be related.

*Thompson et al (2005, volume 2)* found two populations of neurons intermixed in the frontal eye fields. One population was active before eye movements, an entirely different set of neurons was before covert shifts of attention. The independence of these neural populations was disputed in a paper by *Shafer & Moore, 2007 volume 2*, however. They argued that covert attention mechanism might by primary in some situations, thus supporting the likely separation of attention from movement mechanisms. Another reason for asserting the independence of attention is the literature supporting an entirely different frontal network for the some aspects of attention which is presented in the next section.

**Executive Network**

Early studies of imaging using positron emission tomography (PET) found that during generation of word associations there was activation of the frontal midline in the anterior cingulate gyrus (Petersen et al 1989). It was proposed that this activation might be related to aspects of attention. The proposition was first tested by having people perform the Stroop task (see vol 1) while undergoing imaging *(Pardo et al 1990 this volume).*

Activation was increased during incongruent trials. Botvinick et al 2001 volume 3

argued that the anterior cingulate was a crucial part of a brain network related to the monitoring of conflict. They developed a theoretical argument that the detection of error and the monitoring of conflict were central operations of this network.

*Corbetta et al 1991 vol 2* showed activity in frontal structures including the anterior cingulate and dorsolateral prefrontal cortex when attention had to be divided between dimensions such as color and form that were processed by different prestriate visual areas.

*John Duncan et al 2000 volume 2* used PET imagingto show that areas of the lateral and medial frontal lobe were related to the general (g) factor of intelligence tests. This greatly extended the range of cognition that might be related to frontal areas. In another paper Duncan & Owen ( 2000) argued that these general purpose frontal areas might be related to problem solving regardless of the content of the problem

Smallwood & Schooler (2006) focused interest to the control of mind wandering which had been raised by the Bagavad Gita (volume 1) and in the works of Lao Tsu (volume 1).*,Christof et al 2009 volume 2*  showed that the executive attention system was critical to the return to the default state following mind wandering.

**Alerting**

There is a long history of studies using warning signals to improve reaction time. *Kahneman 1973 volume 2)* pointed out the important changes in the brain that occurred following a warning signal, which included inhibition of ongoing activity, the restriction of changes in pupil size and the slowing of heart rate. *Grey Walter* volume 1 had shown that a slow negative electric potential (contingent negative variation) followed a signal that warned of a coming target. *Coull et al 2000 volume* 2 used fMRI to show a full range of brain areas that became active following warning signals. These areas were distinct from brain regions related to spatial orienting, but the two overlapped in time. Later studies have argued that orienting in time involves the brain norepinephrine systems.

*Sturm & Willmes 2001 volume 2)* used fMRI to highlight brain networks related to phasic alertness (following warning signals) and tonic (sustained alertness). They show a thalamic and right cortical network related to sustained alertness, with additional left hemisphere areas related to warning signals.

In this volume we have used alerting, orienting and executive networks as the organizing principles for grouping studies. Although this is one common taxonomy that is used for studies of attention, many others have also been used. The studies in this volume may also be cited using other frameworks to organize them. The next volume highlights the many levels of theory that draw upon these and other empirical studies.

**VOLUME 3 THEORIES OF ATTENTION**

This volume considers theories of attention following World War II. The theories are roughly grouped into four categories. The first group of theories is based primarily on behavioral data and may or may not include a specific computational model. The second group relies on the behavior of individual neurons and most often relies on evidence based on cellular recording. The third group deals specifically with large scale neural systems and much of the data is from imaging studies. The fourth group are studies involving a form of computation called connectionism arising from the method introduced by Rumelhart and McClelland (1986). These studies feature computations that inspired by the brain but do not usually consider the detailed mechanisms involved.

Behavioral-Computational Models

*Visual Search*

*Triesman & Galade (1980, this volume)* developed a feature integration theory (FIT)make a distinction between feature search which occurs without attention in parallel across the visual field and conjunction search in which reaction time to find a target is linearly related to the number of targets. Targets that differ from the background by a single feature are detected without attention, although attention is needed to generate the response. However, when targets differ by a conjunction of features a slow attention demanding search is needed.

*Jeremy Wolfe (1994, this volume*)built partly on the *Treisman this volume* FIT model applies to visual search. The model features a massively parallel preattentive stage (detection of features) and a later resource limited stage that carries out more complex functions such as face recognition, reading and object identification. The orienting network is guided by the parallel stage. A computer model is used to fit numerous set of data.

During the the 1990s visual search models were updated by many new findings from the neurophysiological literature, *Itti & Koch (200 (this volume)* proposed a search model in which Inhibition of return (Posner & Cohen, 1984, Sapir, Soroker, Berger & Henik, 1999) and covert and overt orienting play key roles in producing a biologically plausible computational model.

*Executive Attention*

*Treisman ( 1969 volume 2 )* built her analysis upon the filter theory developed by Broadbent (1958, see volume 1). Basing her studies on selective listening. She modified the all or none filter theory to consider attention as a reduction of input strength when there were multiple channels of input, multiple dimensions of input or multiple features of input. Her work raised the issue of the fate of unattended information and the level at which selection occurred. Both of these issues were pursued over the decades since the publication of this influential analysis.

About ten years after Treisman, *Navon and Gopher (1979 volume 3)*  published a theory based in *Kahneman’s* resource limit analysis of attention (*see Kahneman 1973 vol 2*). The authors employed the mathematics of economics to develop a computational model based on the assumption of limited resources within the brain. Even though one of the authors rejected resources limitation as a strong theory (Navon, 1984) resource limitation remains an influential theoretical tool.

In 1997 *Meyer and Kieras this volume)* developed a symbolic computational model of executive attention in multitasking called Executive Processes and Interactive Control (EPIC). This paper explicitly modeled the reaction times obtained in tasks that related to the work of *Telford and Welford, volume 1,* on the psychological refractory period. EPIC involved the execution of simultaneous production rules to handle multiple tasks, but included limits on sensory and motor mechanisms. This model has been cited more than 500 times and applied to many issues involving cognitive control.

A currently important theoretical perspective emerging from work on visual attention in the 1980s was a model developed by B*undesen (1990 volume 3)*. The paper provides a computational model for single stimulus recognition and for multi target arrays related to the empirical work of *Duncan 1980 discussed in Volume 2.* Bundesen’s theory has had a continuing influence on studies of attention. It has been applied to classifying brain injury in patients, relating functions of attention to aging and cellular recording and to many other important issues in the field.

*Dehaene et al (2003 this volume)* present a model that seeks to link conscious subjective reports of all kinds to neuronal networks. Dehaene et al argue that a global brain state, first proposed by Baars, is implemented by a computation model involving simple neurons linked through reciprocal loops connecting frontal, thalamic and sensory systems. They tested the model with new experimental data from the attentional blink (Raymond et al 1992). The global workspace has been elaborated and extended to form a general view of consciousness by Dehaene (2014).

*Neuronal Models*

Work with microelectrodes, (*see Mountcastle & Wurtz volume 2* ), provided a basis for modeling that was based upon the known properties of neurons. *Anderson et al this volume* proposed such a model in 2005 based upon dynamic control of connectivity. They proposed a hierarchy of areas in the visual system and a dynamic routing circuit that controlled the transit of information. They posited control neurons as a basic unit in control of the efficiency of connectivity.

Cohen & Maunsell *(this volume 2009)*showed that attention may work both to increase signal to noise level for individual neurons and to reduce the correlations between neurons. These data point toward the interaction between neurons as a key to understanding the population response of a set of cells.

Astin-Jones and Cohen reviewed data suggesting nor-epinephrine (NE) input from the locus coeruleus (lc) modulated the gain of cortical cell which show increased both greater excitation and greater inhibition. Modulation by NE involves both parietal and collicular cells involved in orienting of attention. The lc has both a phasic and a tonic mode of operation. This view fits well with the alerting functions (see Coull et al vol 2), but the lc may also modulate orienting, even though there is data that orienting depends more on modulation from the cholinergic system (Marrocco & Davidson, 1998).

*Neural System Models*

In an important theoretical review, *Desimone & Duncan this volume,* draw upon behavioral and neural data to propose a model that contrasts with what they regard as the standard view in which attention orients to a location as described in *Posner, Vol 2.* The Desimone and Duncan model stresses competitive interactions within each of the many maps in which objects and locations are processed. While the model also recognizes top down influences it does not specify their mechanisms. In later publications (Duncan & Owen 2000; Duncan, 2013) a set of “general purpose” frontal and parietal brain areas are identified with attention. Thus the idea of competitive interaction with top down control and accounts of the neural systems of orienting (see *Corbetta & Shulman, vol 2*) become much closer.

*Formisano & Goebel ( 2003, this volume)* adapt event related MRI to the task of tracing the time course of mental operations during cognitive tasks. The authors adopt a f complex cognitive task involving mental imagery and show how MRI can be adapted to discovering the order of the many activation present in the several seconds required by the task.

*Rizzolatti et al (1987, this volume)* lay out a theory of how attention depends upon premotor mechanisms. This has been one of the most popular theoretical accounts of the relation of eye movements to attention. A covert shift is thought to be the motor program for an eye movement even though the movement does not occur. The evidence reviewed in this theoretical paper is largely behavioral, but the theory also relates to the evidence presented in *Volume 2 by Posner; Thomson et al and Schafer & Moore*

*Connectionist Models*

In he 1980s a new form of approaching theory in psychology and neuroscience was developed by a team in the University of California at San Diego. The connectionist or parallel distributed processing model has had vast influence on theory in every aspect of psychology including attention. In this volume *Rumelhart & McClelland (1982)* use interactive activation models to explain why every letter of a word can be more visible than the letter in isolation (Reicher, 1969). According to their view each letter of a word contacts a representation of the word and feeds back to influence the visibility of each of the individual letters. This lowers the threshold for reporting each of the letter over what it would be true of the letter by itself.

In the next paper by *Cohen, Dunbar and McClelland (1990 this volume)* parallel distributed processing theory is applied to the Stroop effect (*see Stroop, vol 1 and Pardo et a,l Vol 2).* The interference of the word in processing the ink color found in the Stroop effect has often been taken to mean automatic processing of the word. However, in Cohen et al attentional control is graded and even the word is subject to its influence. Automaticity increases with practice of the Stroop task through the gradual strengthening of connections. The resultant model is used to account for various Stroop phenomena. This paper has a close relation to the prior paper by *Rumelhart & McClelland* and to others in this section of the volume.

A traditional question in attention is how responses to one task are delayed when they occur during the reaction time to a previous task, often labeled the psychological refractory period (see *Telford, Welford, volume 1*). Sigman & Dehaene present a tone close in time to the task of deciding whether a visually presented number is above or below 45. They find the numerical distance from 45 cannot occur in parallel with the tone task, but all other operations performed on the number are processed in parallel with the tone. This provides one answer to the question about stages of the task can be carried in parallel stage with processing the tone.

*Bovinick et al, this volume* examine conflict related reaction time tasks in order to determine how the conflict is detected. They use anterior cingulate activation during conflict tasks (see Pardo, et al, volume 2) using a model that assumes the cingulate activity monitors the presence of conflict, which is then resolved by other brain regions. Using the connectionist methodology (*Rumelhart & McClelland, and Cohen, Dunbar & McClelland, this volume* they show how their model fits various aspects of brain activation data.

**Volume 4 Applications**

In Volume 4 we examine how ides of attention are applied in other areas of psychology and neuroscience. Attention is an important topic within many areas of psychology we have chosen human development, human performance studies, conscious thought, training of attention and psychopathology to highlight its role in important psychological topics. Human development is a large field of research that has been illuminated to a significant degree by understanding the development of attention. Human performance is a subject that relates to industrial and military issued with the use of human operators in conjunction with machines. Attention is central to the issues of what is consciousness, but there are also reservations about whether the brain mechanisms of consciousness are closely related to attention networks. A major development has been the ability to train attention by exercises including video games and meditation. Finally many neurological and psychiatric disorders involve deficits in aspects of attending. Before our understanding of some of the brain networks related to attention this information was not particularly useful. Now it may be possible to use the specific deficit of attention to better understand the impairment in terms of brain processes. The papers in this volume provide perspective on these applications of attention research.

*Development*

*Columbo’s review this volume* summarizes behavioral studies examining alertness, orienting, and endogenous attention during infancy. Colombo notes the progress of voluntary control over orienting in infancy might suggest the start of executive attention. However, subsequent work has shown that orienting may serve as an important control system of special importance during infancy, and while executive networks do show a presence in infancy they only slowly exert control over behavior (Posner et al 2014).

Infants of a few months old can learn to orient to stimuli that occur in a fixed order prior to their presentation. *Haith et al this volume* first found this form of anticipatory looking at 3.5 months of age. Individual differences in this skill at 7 months is related during infancy is related both to the ability to regulate emotion and to the later development of the orienting network as measured by the ANT (Sheese et al 2008; Posner, et al, 2014). During 6-12 months of age as early language develops infants shown faces direct their gaze primarily to the mouth, but before and after this age they look more at the eyes (Lewkowicz & Hansen-Tift, 2011)

*Fjell et al this volume* uses fMRI to image brain areas while participants from 4 to 21 years carry out a conflict related task. At ages 4-7 the best predictor of the ability to resolve conflict is the size of the anterior cingulate, after that age overall task performance is best related to efficiency of white matter connectivity.

A major new method for examining brain networks in infancy and later is resting state

MRI (rsMRI) introduced by *Fair et al this volume*. Fair shows increased long term connections of ACC and midfrontal cortex between 9 years of age and adulthood (see also *Dosenbach et al vol 2*). These findings have now been brought down into infancy (Gao et al 2014).

*Consciousness*

The study of consciousness has again become prominent in the field of cognition and neuroscience. It is obvious that attention has an important role to play in understanding consciousness, but there is a lot of dispute about how similar the two concepts are to one another. Posner (1994) argued that understanding attention was as critical to consciousness as DNA was to life. However, there are important dissociations as pointed out by *Koch and Tsuchiya 2006* this volume in this influential piece outlining some of the differences between the two concepts.

*Posner & Snyder 1975 this volume* argued that stimuli which were unconscious could prime other items, but when processed consciously they also created costs for unrelated stimuli. *Neely (1977) this volume* produced strong evidence for an inhibition less spreading activation and a limited capacity attention process in a lexical decision task.

Neely

The use of backward masking to render a stimulus unavailable for conscious report has been critical both in the study of attention and in the study of consciousness was pioneered *by Marcel 1983 this volume*. In recent years this method has been greatly expanded to allow masking of segments larger than single words and applied by

Dehaene (2014) to the study of consciousness.

*Roca et al this volume* explore the links between attention, executive functions and intelligence with frontal lobe patients.

*Human Performance*

Application of attention to many areas such as accidents, health and the design of machines has used many names including ergonomics, human factors and applied industrial psychology (see Posner 2012 for a brief history). A smaller subset of these have involved applications of attention.

*Donald Broadbent et al 1982* developed the cognitive failures questionnaire that included questions about lapses of attention that he thought might be useful in understanding accidents in the workplace. It has long been known that attention play an important role in many accidents (Flannagan, 1954). Critical incident analysis highlighted issues of the design of equipment. Broadent’s questionnaire suggested that some aspects of industrial accidents might be related to individual differences in ability to deal with stressful situations in work and other environments.

Further evidence for the role of individual differences in attention matter is examined in a classic paper by *North and Gopher 1976* this volume. They applied reaction time and tracking tasks as measures of attention to prediction of performance of students in flight school. Similar tests had previously been useful in prediction of road accidents ( Kahneman, Ben-Ishi & Lotan, 1973).

In recent years it has become possible to study individual differences in attention by examining their relation to genetic polymorphisms in orienting of attention. In one such study Parasur*aman et al 2005* this volume show that differences in performing a spatial orienting task related to polymorphisms in s gene related to the cholinergic and dopaminergic transmission.

*Training*

Can brain networks underlying attention be trained? Studies of children with ADHD showed that working memory training could improve performance in that task and also improved attention (Klingberg et al 2002). Training with video games also shows improvement in some aspects of attention (*Green & Bavelier, 2002, this volume*). The largest effect of action video games appears to be on the orienting network, but some training of executive function might also occur (Green et al 2012).

*LaBerge and Samuels 1974 this volume* develop a theory in which long continued practice on a single task, such as occurs with reading, greatly reduces or eliminates the need to pay attention to lower levels of analysis such as deriving the word name or lexical meaning, thus allowing concentration on comprehension of the passage.

*Tang & Posner, 2009, this volume* argue for two fundamental ways to training attention. Training attention through practice on the trained network is one of these ways. However, physical exercise, meditation and other such methods may produce a brain state during which attention is improved in efficiency.

*Pathologies of Attention*

It has long been known that many neurological and psychiatric pathologies involve attention as a feature. However, when attention was primarily a resource or filter on external information the connection of pathology with attention was not particular helpful in diagnosis or treatment. If we regard attention as a set of brain networks (see *Corbetta & Shulman, vol 2*) attention may be an important feature is diagnosis and given the training section above in treatment as well.

*Corbetta & Shulman, 2011, this volume* view lesions of the right ventral parietal cortex as central to the loss of information from the contralateral space. They regard neglect primarily as a deficit of attention network, but argue effectively that this includes both spatial and non spatial elements. The impairment of orienting of attention with specific lesions complements the networks discovered in brain imaging and provides a clear demonstration of how attentional disruption can impair specific aspects of behavior.

A specific example of was carried out by *Posner, Walker Friedrich &Rafal 1984 this volume.*

A rather different appearing disorder autism also appears to have an orienting deficit

*(Courchesne et al 1994 this volume)*. In this paper *Courchesne et al* identify the cerebellum as one likely brain area involved in this deficit. Although there has been some dispute about the specific lesion involved, the presence of orienting deficit even in tasks with no social involvement has been confirmed by more recent studies (Landry & Bryson, 2004 ). Whether an early orienting deficit is central to autism remain uncertain but it has been a persistent feature in studies of the disorder.

Perhaps the disorder most closely identified with attention is Attention Deficit/Hyperactivity Disorder (ADHD). Symptoms of this disorder include difficulty in concentration particular in school setting in some patients it includes an inability to be still (hyperactivity). *Halperin & Schultz 2006, this volume* identify an early problem in the alerting network often followed with a deficit in the executive control. This supports the connection between the locus coeruleus and ACC discussed by *Astin-Jones & Cohen, vol 3*. *Halperin and Schultz* suggest specific therapies upon the neurobiology of the disorder.

ADHD is the pathology most identified with a specific genetic variant the 7 repeat allele of the dopamine 4 receptor gene (DRD4). In their paper *Swanson et al 2000 this volume* show that children with ADHD have a slowing of RT while those children with the 7 repeat allele show no deficit in RT. They suggest that the genetic version of the disorder is not due to attention, but the non genetic version may involve some specific brain damage. Their have been efforts to improved the symptoms of ADHD by working memory training, *Olsen Westerberg & Klingberg 2003 this volume* use fMRI to show in normal persons that working memory training can alter frontal and parietal activity.

The most commonly report attention deficit in pathology involves the executive network including the anterior cingulate, anterior insula and striate brain areas. Schizophenia has often been characterized as an attention deficit and *Nuerchterlein 1977 this volume* reviewed the literature at that time. Since his review many papers have found deficits in Stroop, flanker and other tasks designed to measure executive attention (Wang et al 2005). Most of this work has involved chronic schizophrenic patients. First break schizophrenics show a focal abnormality in left globus pallidus (Early et al 1989) which is closely connected to the anterior cingulate.

Borderline personality disorder is a severe developmental disorder that feature dysregulation of emotion and behavior. Patients with this disorder show a specific deficit in executive attention (Posner et al 2003). In this paper *Silbersweig et al 2007 this volume* use fMRI with patients. In comparison with controls the patients show over activity in the amygdala when challenged with negative affect and underactivity in the anterior cingulate. This fits very well with the symptom of dysregulation of emotion due to the problems in the executive attention network.

Psychopathy is another disorder that seems to depends in part upon abnormalities of executive attention *(Zeier et al 2009 this volume*). This paper shows an abnormality in the executive attention of psychopaths as measured by the flanker task. They speculate that this results in a failure to use inhibitory cues to regulate behavior. The finding fits with earlier imaging studies showing the role of the mid frontal cortex in control of antisocial behavior (Blair, 2004).

This volume illustrate many applications of attention to daily life. This brings attention research into close contact with many areas of psychology and with other disciplines including computer science, engineering, neurology, psychiatry and child development.

Hopefully these interactions will serve both to illuminate many problems of daily life as well as sharpen and improve future empirical studies and theories related to attention.

10

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