CHAPTER 8

A Century of Human Information-Processing Theory

Vision, Attention, and Memory

Barbara Anne Dosher
George Sperling

I. THE EVOLUTION OF PSYCHOLOGICAL THEORY

A. Overview

Both theories and the types of data that are considered appropriate for theories underwent major changes during the 20th century. There were some outstanding examples of careful theorizing in perception and other areas of psychology in the late 19th century, but few theories were what we would, at the end of the 20th century, call *process theories.* At the end of the 19th century, such process theories as there were, were mentalistic, speculative, and unsuccessful. At the end of the 20th century, theories have become process oriented, detailed, and accurate in their account of experimental data. Concurrently, there has been a continuing trend in the style of data collection: In the late 19th century, it was the norm to use a small range of relatively simple stimuli and to encourage the observer to make complex—frequently introspective—responses. In the domain of perception, particularly, there has been a trend toward using increasingly simple responses (e.g., merely selecting one of two intervals in a two-interval forced choice procedure), with the complexity being displaced from the response to the stimuli. The advent of computer-generated displays has accentuated this trend. In this chapter, we illustrate the development of theories with examples from the areas of visual perception, attention, and memory.

Perception and Cognition at Century's End

B. Why and Whither Theories? Utility and Expected Lifetime

Some theories have immediate practical utility, for example, Newton's laws. Newton's theory enables us to calculate the time of occurrence of eclipses, satellite orbits, and many other useful properties of objects in motion. On the other hand, a theory that relates the origin of the universe to a big bang 17 or so billion years ago has little immediate utility. Such a theory can be regarded as having infinitely deferred practical utility but some immediate aesthetic value.

Theories achieve longevity by being the best theory at a given level of complexity (Sperling, 1997). For example, Newton's laws are not valid at extremely high speeds, but they are the most accurate theory at their level of complexity and therefore seem destined for immortality. Moreover, they have both practical and aesthetic value, something which few psychological theories have achieved.

C. Theories

1. Accomplishments at the End of the Nineteenth Century

The nineteenth century produced some outstanding researchers in psychology, including the following:

1. Weber offered a simple and quite reasonable theory about the discrimination of differences (Weber's Law). A just noticeable increment or decrement was proposed to be a constant percentage (the Weber constant) of the value of the stimulus that was being incremented or decremented (Weber, 1846).
2. Fechner further developed a psychophysics of sensory discrimination and scaling, including much of what we now call signal detection theory (Fechner, 1860; see also Nakayama, chap. 7, this volume).
3. Pavlov proposed the theory of conditioning, now called Pavlovian or classical conditioning (Pavlov, 1927).
4. Helmholtz (1866/1924) elaborated Ohm's (1843) theory of acoustic perception based on Fourier analysis of sounds. He also proposed a quite detailed theory of the coordinated movements of the eyes and of corresponding points on the retinas, a comprehensive color theory based on Thomas Young's (1802) observations, and many other fine-grained theories (Helmholtz, 1924).
5. At the turn of the century, Binet developed an IQ test (Binet & Henri, 1896; Boring, 1942), and it was followed by many useful developments in test theory and statistical hypothesis testing.
6. Ebbinghaus made numerous observations about memory, including the effects of repetition, of interference, and of the consistency of measures of memory strength as indexed, for example, by recall, recognition, or savings on relearning (Ebbinghaus, 1885; 1964).

With such solid, hard-earned progress, one might have thought that psychology would be regarded as off to a marvelous start in the 19th century. Unfortunately, these theories addressed specific phenomena. Except for Pavlovian conditioning and IQ, the developments were too scientific—too technical—to be of general interest. They did not begin to address global psychological questions to which a larger public sought answers, such as "How does the mind operate?" and "What is the nature of consciousness?"

2. Mentalism

The void was eagerly filled by an entirely different kind of theorist, the mentalists. Foremost among these were Wundt and James; later, Freud and the Gestaltists worked within a similar framework. Wundt proposed that consciousness could be understood in terms of a succession of mental states or "ideas." Perceptionists of the 19th century generally took "ideas" for granted in their explanations of various phenomena of perception, but Wundt made the idea itself the central object of study. The succession from one idea to the next was determined by three kinds of influences: the current idea, the internal state of the organism, and the external stimuli. Ideas had various sensory properties that could be determined by introspection. Our graphical interpretation of the mentalists' basic model is illustrated in Figure 1.

The mentalists' theory was a departure from the formal quantitative work of their predecessors mainly in the data that were considered appropriate for modeling. In a formal sense, we would say today that their theory dealt with a particular kind of (typically verbal) behavior, introspection, which was intended to describe the subject's mental state. That is, the data that mentalism addressed were statements about the contents of consciousness, rather than actions that were directly related to solving an environmental problem.

Another characteristic of the introspectionists is that they tended to present very simple stimuli and to record very complex responses. For example, a simple patch

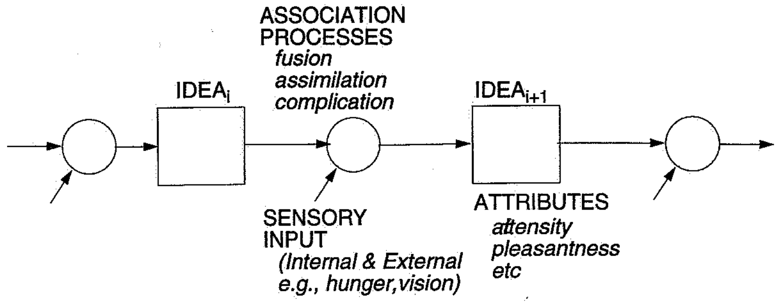

FIGURE 1 The mentalists' model. The content of consciousness is assumed to be an "idea." The succession from the current idea (designated IDEA$_i$) to the next idea (IDEA$_j$) is determined by internal and external stimuli, the IDEA$_i$ and by various, incompletely specified processes of association. An idea is defined by its attributes; some of which (such as attensity and pleasantness) received considerable attention at the time but today seem quite obscure. (Reproduced with permission of G. Sperling.)

of red might be presented, and a long response would be made concerning the uniformity of the perceived hue, its vividness, attensity, and other attributes.

Among the problems of mentalism recognized almost immediately was that not all thought processes are available to introspection. Some better known examples are the so-called "imageless thought" of Külpe's Würzburg School (Boring, 1950), and Freud's unconscious drives and suppressed ideas.

At the beginning of the 20th century, no adequate theoretical apparatus for dealing with long, complex responses (sentences or paragraphs) was available. For the remainder of the 20th century, a different approach would be much more successful. The complexity was placed in the stimulus, and the response was kept as simple and as constant as possible (the principle adhered to by the successful experimentalists cited earlier). Thus, one might vary the properties of a patch of light, its wavelength composition, exposure duration, the background, the configuration, and so on, while the only response recorded was "yes" if it was discriminable from nothing (i.e., from a null stimulus)—or "no" when it was not.

Yet another problem with the mentalists' approach was that consciousness is perhaps an incidental by-product of adaptive behavior. Suppose only evolutionarily adaptive behavior matters, and adaptive behavior occurs with or without consciousness. Many important mental operations simply precede consciousness and are therefore automatic and inaccessible; others are related to the mechanisms of introspection itself and therefore inaccessible (i.e., a camera cannot photograph its internal parts), and other mental operations are inaccessible for a myriad of other reasons.

For all these reasons, the mentalists' efforts were a dismal failure in the sense that, although the phenomena they investigated remain of interest even today, essentially nothing of value remains of their theoretical efforts.

3. Behaviorism

The mentalist approach incited two early 20th-century counter movements: the behaviorists, who initially wanted to discard verbal behavior entirely, and the "dust-bowl" empiricists, who eschewed theory and hoped to solve the problems of psychology by cataloging all the useful empirical relations that might be of psychological interest.

The behaviorist era was initiated by John B. Watson and was carried through the 1950s by B. F. Skinner (Skinner, 1938; Watson, 1919). In fact, the behavioral and empirical approaches were quite similar, and are schematically represented in Figure 2. The description of psychological phenomena is represented by a collection of S_i–R_i relations, that relate a particular presented stimulus S_i to a particular observed response R_i. The behaviorists' concentrated on the observation that "reinforcement," the delivery of a favorable outcome for a particular S_i–R_i combination tended to make R_i a more likely response to future occurrences of stimulus S_i.

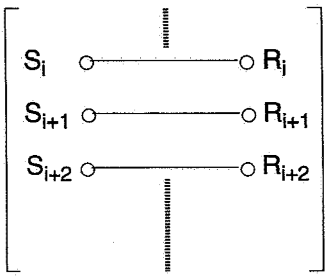

FIGURE 2 A basket of empirically observed stimulus–response (S-R) associations. Only a few associations are shown. The behaviorists, from Watson to Skinner, attempted to understand behavior by determining all the S-R associations of importance. Reinforcement (reward) following the occurrence of a particular S-R sequence was assumed to make the association of the R with S more likely when S reoccurred. The empiricists, psychologists of the first half of the 20th century, were concerned less with learning processes than with sensory and cognitive issues; they attempted to collect all the useful relationships under the formula: S-O-R (stimulus-organism-response). (Reproduced with permission of G. Sperling.)

To avoid state dependence—an S–O–R theory in which the response depended on the state (e.g., hunger) of the organism, O, the behaviorists sought to incorporate the state into the stimulus. Thus, the organism works for food not because of an internal state (hunger), but because the complete description of the stimulus incorporates not only, say, the current visual stimulus, but also the description of the recent history of food deprivation. This is incredibly cumbersome, and it is not surprising that the behaviorists left us with a cornucopia of observations but no surviving theory.

The problem with trying to create a psychology without theory but with merely an exhaustive enumeration of all the interesting and useful S–R relationships, or S–O–R relationships, is illustrated by a simple example. Consider a primitive computer screen. It has only 16 × 16 pixels and each pixel displays only one of two possible gray levels. Suppose we wish to make a list of the stimuli produced by this incredibly impoverished display screen and to record some simple responses that might be made to each possible stimulus. These are 2^{256} different displays. We cannot record even one response to each display because the number of different stimuli (2^{256}) is larger than the number of atoms in the universe. If the brute force approach of cataloging behavior is hopeless even in this contrived trivial environment, consider how much more futile it would be in complex natural environments.

4. The Cognitive Revolution

What has emerged in the second half of the 20th century, the post-World War II era, is a cognitive revolution in which descriptive and process theories are integrated with empirical work. Typically, process theories are represented as flow chart diagrams

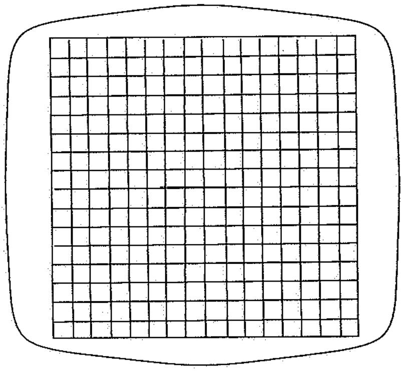

FIGURE 3 A computer display screen with 16 × 16 pixel resolution. If each pixel can display two different gray-scale values, there are 2^{256} different possible displays. (Reproduced with permission of G. Sperling.)

with boxes, which represent processes, connected by arrows, which represent the flow of information. Initially, a box represents a process that is perhaps too complex to be described precisely; subsequently the box is expanded into component boxes and arrows that define it more precisely. For example, a component that in an early theory is called simply "motion detection" and left undefined can now be expanded into three distinct motion-direction systems and five seperate motion energy computations, each of which can be further expanded into numerous subcomponents. Ideally, these more highly specified components are more closely related to biological substrates and to neural computations than the more abstract branch from which they sprang. This sequence of successive refinements in the second half of the twentieth century is strongly reminiscent of the history of atomic and nuclear physics during the earlier part of the century. Initially there were atoms, then they were divided into protons, electrons, and neutrons; then these components were described in more detail and further subdivided.

In the next sections, we illustrate the evolution of theory in the second half of the 20th century with several examples with which we have special familiarity: computational models of vision (motion perception in particular), visual attention, and serial versus parallel models of short-term recognition memory.

II. VISUAL PERCEPTION

A. Progress in Models of Perception

The straightforward formulations of perceptual relationships of Weber, Fechner, Mach, and Helmholtz at the end of the 19th century were superceded by the introspective descriptions of the mentalists. The introspective approach to perception was continued by the Gestalt school, in the sense that gestaltists were concerned with the appearance of objects (i.e., whether they exhibited "good form", or whether they grouped into one configuration or another), rather than with skilled or adaptive behavior.

A useful indicator of whether or not experiments concern adaptive behavior is whether the experiments use corrective feedback or, at least, could profitably use it. Feedback and adaptation are inextricably linked. Experiments with feedback measure capacity—the asymptotic level of performance reached with training. Experiments without feedback assess achievement—skills the subject has already acquired before entering the experiment and proclivities—how the subject prefers to respond (Sperling, Dosher, & Landy, 1990).

In the United States, the first half of the 20th century was a period marked on the whole (with a few notable exceptions) by an intense counterreaction to mentalism that discarded not only the subject matter and style of the mentalists but the also discarded any use of theory, and blindly embraced atheoretical, empirical work. Before the growth of formal psychology departments at the beginning of the 20th century, psychology had been the domain of physicists, physicians, and other scientists who brought with them powerful skills from other domains. Early 20th century psychology had developed a new domain of study, but not yet an appreciation for the crucial importance of technical advances for making new discoveries in the new domain. Finally, in the second half of the 20th century, psychophysicists returned to some of the principles of the original psychophysicists by formulating and working out detailed computational models of perception. Again the initial impetus came from nonpsychologists.

B. Physiological and Computational Models of Early Vision

A revolution in the style of perceptual observations, in the computational theory to explain them, and in the neurophysiology that underlay them occurred in the period immediately following World War II (see also Nakayama, chap. 10, this volume). In 1953, Kuffler (1953) discovered the center-surround receptive fields of cat ganglion cells. There were in two types: ON-cells fired when light fell on the center of their receptive field and ceased firing when light fell on the annular surround; OFF-cells responded similarly to reductions (rather than increases) in light. The center-surround concept was quickly generalized to limulus (Hartline, Wagner, & Ratliff, 1956) where lateral inhibition had been overlooked for more than 20 years by Hartline and his collaborators. Vision physiology was propelled forward by Hubel and Wiesel (1962, 1965, 1968), who discovered the elongated receptive fields of the simple cells in cat occipital cortex and subsequently in monkey V1. This opened the gate to a flood of single neuron studies that at century's end is still growing exponentially.

From a computational point of view, it seems likely that ON- and OFF-ganglion cells operate as a push–pull pair in which one member signals an increase in stimulation and the other a decrease (Sperling, 1970, Appendix B). The computational analog of a Kuffler ON–OFF pair of center-surround ganglion cells is a spatial-frequency bandpass filter. Such filters can also be viewed as an outgrowth of the mathematical processes of spatial interaction that had been proposed by Mach (Mach 1865; Ratliff, 1965). Here, they are incorporated into the most elementary computational model for visual processes, illustrated in Figure 4a. The basic model consists of a linear filter followed by a detector (Sperling, 1964). The reason for using linear filters is that it is quite easy to measure the input–output properties of an unknown linear filter with either sine waves or impulses. After the initial measurement, the response of the filter to any waveform whatever can be readily computed.

Among the defining properties of a linear filter is "sinewaves in, sinewaves out." Therefore, a linear filter cannot serve as a model of psychophysical performance; observers in psychophysical experiments do not output sine waves. Typically, observers report binary decisions, "yes, I see it" or "no I don't." To make a computational model of the detection performance, the linear filter(s) must be paired with

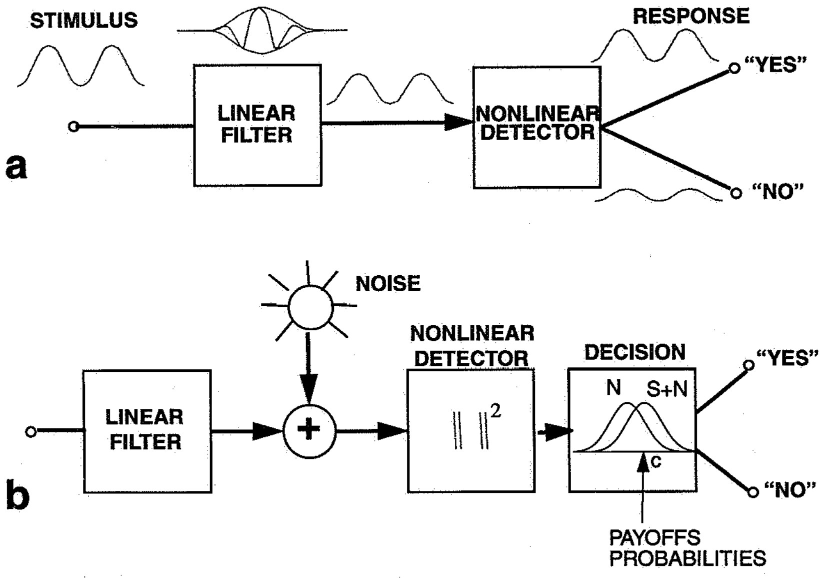

FIGURE 4 (a) A simple model for sensory thresholds and related paradigms. For determining spatial thresholds of a low-contrast stimuli, such as sine gratings or isolated bars, the linear filter typically is assumed to be a smoothed 2-D Laplacian or a Gabor function to represent a Kuffler center-surround receptive field. Subsequently, the detection component reports detection ("yes") if the filter output exceeds a threshold, otherwise, the detector reports nondetection ("no"). (b) A decision theory elaboration of the threshold model. Internal noise (N) is added to the output of the linear filter. The combined signal is processed by a nonlinear detector (typically, a device that measures energy), which outputs positive real numbers (typically, the amount of energy). The Decision box illustrates the probability density distribution of energy on trials with signal S + N and on trials without signal N. If the energy value on a particular trial exceeds a criterion (c), the Decision component outputs a "yes" (to indicate detection); otherwise it outputs "no." The numerical value of c is determined by rewards, probabilities, past outcomes, and the like. (Reproduced with permission of G. Sperling.)

a nonlinear detector that computes a decision from the output of the linear filter. In the earliest models, the decision component was a simple threshold device. When its input exceeded the threshold, it produced a positive response (e.g., the detector's output was +1 indicating detection); otherwise the detector output was zero.

C. Illustrations of the Power of a Linear System Model: Flicker Vision

Computational models, involving linear filtering and sinewave analysis, were introduced to vision researchers by two engineers: Otto Schade at RCA applied linear analysis to description of spatial images (1948, 1956, 1958). DeLange (1952, 1958a,b), an engineer at Phillips who conducted vision experiments privately in his basement, proposed a linear model for flicker vision. Compared to what had come before, the power of this simple model is illustrated by three examples.

1. In 1953, Carney Landis published his bibliography of flicker fusion that contained more than a thousand citations. Yet, for every new waveform that might be investigated, the only way to determine whether it would be seen as flickering or not was empirical; there was no theory. The simple model of Figure 4a, with the flicker filter as described by DeLange, made a prediction for every conceivable waveform. It is an interesting parenthetical note that Ives, a Bell Labs engineer involved in the development of television, published data (Ives, 1922a) and proposed a theory of temporal vision (Ives, 1922b) that anticipated DeLange by 30 years. Unfortunately, the vision community of the early 20th century was technically unprepared to appreciate such developments and, except for an isolated follow-up by Cobb (1934), Ives's pioneering work was overlooked.

2. The photochemical theory of Hecht (prominent in the 1950s) held that flicker vision was governed by a photochemical process in which a receptor pigment became exhausted during the light-on portion of the flicker cycle and recovered in light-off portion of the cycle. In terms of linear theory, Hecht's process was equivalent to what is called a single "RC-stage." DeLange's empirical measurements of flicker sensitivity determined the threshold modulation amplitude of a sine wave flickering field versus its temporal frequency. His graph of log threshold amplitude versus log frequency had a slope of −8 at higher temporal frequencies, which would result from 8 or more RC stages in series, not from a single RC stage. Hecht's single RC-stage theory is dramatically falsified.

3. The limit of human flicker fusion is about 60–70 Hz or so, never significantly higher, frequently lower. Yet, a remarkable new phenomenon was reported (Brown & Forsyth, 1959) that assertedly required a revision of flicker theory. Two lights were set to flicker at frequencies too high to detect the flicker. Nevertheless, when these two invisible flickers were alternated in a combination stimulus, the previously invisible flicker became visible. Unfortunately, the authors (and the referees who accepted this article for publication in *Science*) did not understand linear filters. It

never occurred to them that this result was a simple, but counterintuitive corollary of a linear filter model, such as DeLange's (Levinson, 1959). In the mid-20th century, the study of perception was rediscovering what the 19th-century perceptionists (mostly physicists) had originally taken for granted: The analysis of perception requires the same computational tools as engineering and the hard sciences.

D. Multiple Channel and Detection Models

In the retina, Kuffler's center-surround cells occur in a great range of sizes, as do Hubel-Wiesel simple cells. The obvious extension to psychophysics was made by Campbell and Robson (1964, 1968), who discovered that when an observer stares at a grating with a particular spatial frequency, the observer becomes less sensitive to gratings of this and similar frequencies, but there is little change in sensitivity for gratings that differ in spatial frequency by a factor of more than two or three (see also Nakayama, chap. 10, this volume). This observation requires an elaboration of the simple filter model. Many spatial-frequency tuned filters, called channels, operate as visual processors. A visual stimulus is analyzed concurrently by many parallel channels, and a decision is based on the combination of their outputs. This important elaboration of the linear filter model is necessary to explain many phenomena of visual perception, from adaptation and masking, and is particularly significant for modeling object recognition.[1]

Another new development of the 1950s focused on the decision component of the filter-plus-detector models. Wald (1947, 1950) originally devised a sequential decision theory for military applications in World War II. Wald died prematurely in a plane crash; his methods were elaborated and applied to psychophysics by Tanner, Swets, and Green, where they became known as signal detection theory (SDT) (e.g., Green & Swets, 1966). The SDT model (Fig. 4b) and subsequent ideal detector models have replaced the simpler threshold model (Fig. 4a).

An enormous amount of research in visual psychophysics during the second half of the 20th century has focused on working out the properties of these extremely simple models: bandpass linear filtering (multiple channels) followed by a detector that implements a detector based on elementary signal detection theory. Signal detection theory was originally one-dimensional. When more than one channel is involved in a decision, a multidimensional theory is required—a significant complication (see Sperling & Dosher, 1986, and Graham, 1989, for reviews).

E. First-Order Perception of Motion

The 1950s saw the first computational model of visual motion perception. It was proposed by Reichardt (originally with Hassenstein, 1956) to account for insect

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[1] Channel combination models have been extensively investigated in audition (see Sperling & Dosher, 1986, for a review), but this parallel development has been largely overlooked by vision scientists.

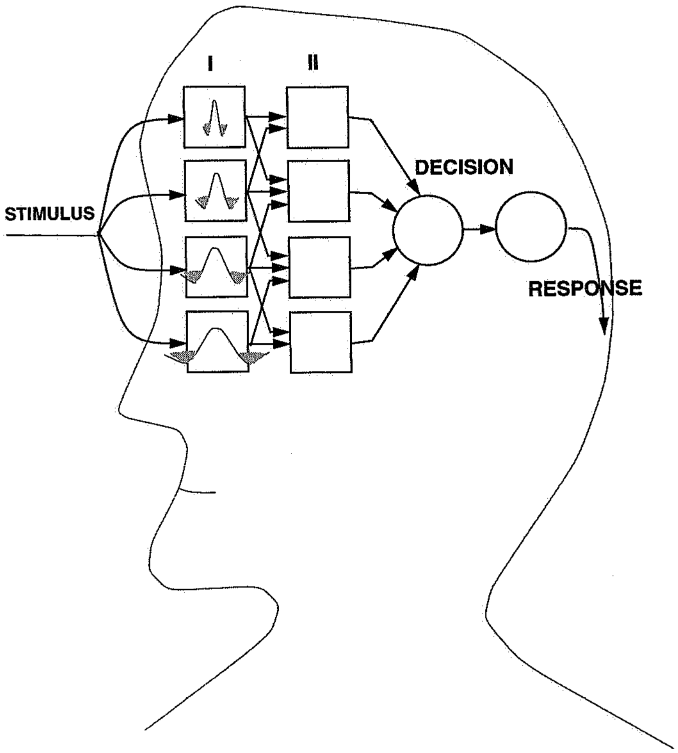


FIGURE 5 Channels. Center-surround receptive fields of ganglion cells and lateral geniculate cells occur in a wide range of sizes. Their outputs are processed in size-specific "channels" for several stages (I, II) before signals processed by receptive fields of different size combine. (Reproduced with permission of G. Sperling.)

vision (Reichardt, 1957). It, too, was an engineering model based on linear filters, although it incorporated a stage of multiplication, which is a highly nonlinear operation. The basic principle of this model is universal to visual motion models—the comparison of a visual input from one location with the time-delayed input from an adjacent location (Fig. 6). What was new was its implementation in terms of linear filters and its architecture of two subunits, tuned to opposite directions of motion, whose outputs were subtracted to form the final output.

There were at least half a dozen attempts to apply the Reichardt model to human vision, but a successful transposition was delayed by 30 years until van Santen and Sperling (1984). The problem was that human vision is not perfectly described by linear filters. There are two significant nonlinearities prior to visual motion computation—light adaptation and contrast gain control—that perturb measurements of the motion computation (see Fig. 7 and Sperling, 1989). Light adaptation usually does not vary unintentionally within a psychophysical experiment, so it has not

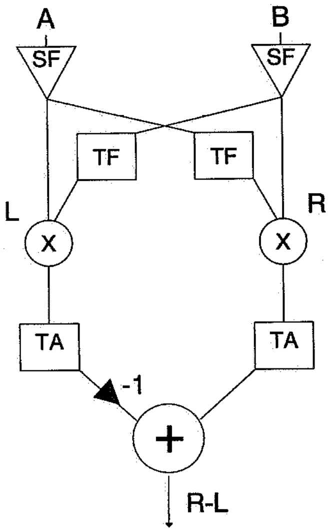


FIGURE 6 Reichardt motion model. The Reichardt model embodies one of a number of equivalent, and nearly equivalent, algorithms for motion extraction. It consists of two subunits: R responds positively to rightward movement; L responds positively to leftward movement. An input signal is extracted at two locations by spatiotemporal filters SF_1 and SF_2. When the time taken by a rightward-moving object to pass from SF_1 to SF_2 equals the delay imposed by the internal temporal delay filter (TF), the delayed and nondelayed signals arrive simultaneously at the multiplier, and thereby produce a large positive output. TA represents an optional Temporal Averaging/smoothing filter. Subtraction of the L subunit's response from the R subunit's response results in a Reichardt output that is positive for rightward movement, negative for leftward movement, and zero for nonmoving static or flickering stimuli. [Adapted from Fig. 2B in J. van Santen & G. Sperling (1984). Temporal covariance model of human motion perception. *J. Op. Soc. Am. A, 1, 5,* 453; with permission.]

been a problem for the linear-filter-plus-detector theories. But contrast gain-control mechanisms are important. The first-order motion system that detects ordinary translation (see below) begins to saturate at extremely small contrasts (4% according to Nakayama & Silverman, 1985; between 1% and 2% according to Lu & Sperling, 1997).

There is a compelling evolutionary basis for contrast gain control. Ideally, most judgments would be completely independent of stimulus contrast (e.g., judgments of motion direction or velocity) or judgments of the distance between two points. In practice, even an ideal visual system could achieve independence of contrast only when a sufficient number of photons were received (i.e., for contrasts greater than some small threshold contrast). Therefore, contrast gain control can usefully operate only above a threshold contrast. Below this threshold contrast, there is no significant contrast gain control, and only in this limited range can motion mechanisms be probed by inputs that are unperturbed by contrast gain control.

As humans routinely detect first-order motion with contrasts of 0.2% (1 part in

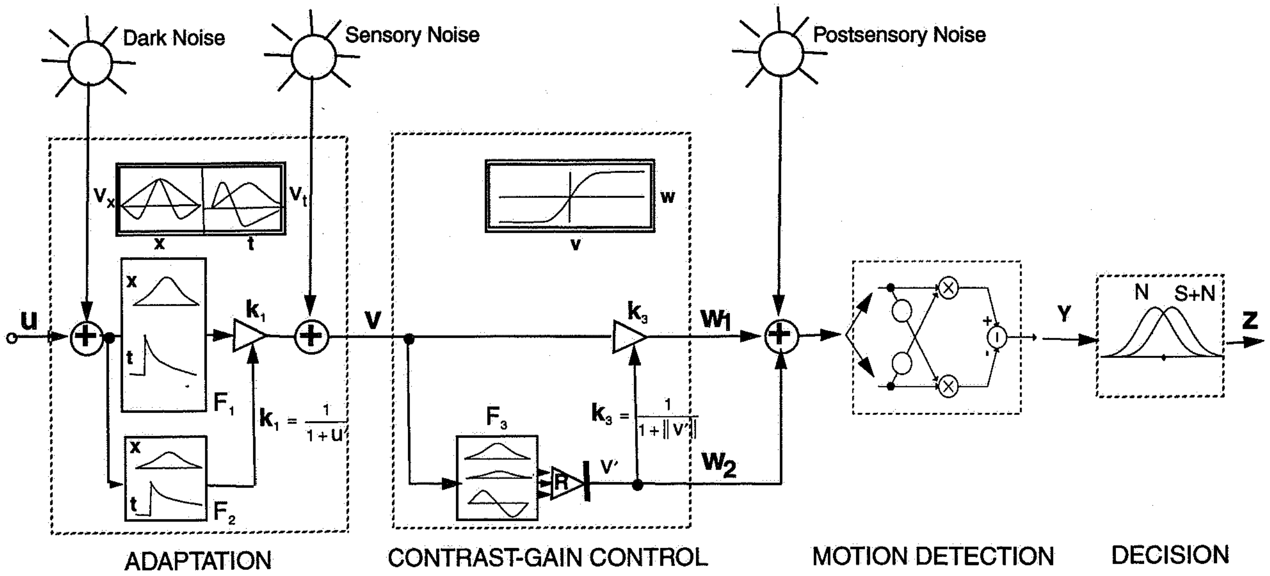


FIGURE 7 Four stages of visual processing: Adaptation, contrast gain control, motion detection, and a decision stage. The x and t, respectively, indicate spatial and temporal filters; the triangles k_i represent gain control mechanisms in which the signal on the horizontal path is divided by the signal in the vertical path, the sun symbols represent sources of random noise, and the + signs represent addition. Graphs within double outline boxes represent the aggregate characteristics of the component. Thus, V_x versus x indicates the spatial receptive field. The solid monophasic line represents the receptive field at low luminances; the lighter triphasic line represents the receptive field at high luminances. The symbol R in the triangle of the gain-control path represents rectification (absolute value computation) and the addition of rectified inputs in various different phase relations. F indicates a set of filters (receptive fields); the boldface letters, U, V, W, Y, Z, are used to designate the inputs/outputs at various stages within the system. [Adapted from Fig. 2 in G. Sperling (1989). Three stages and two systems of visual processing. *Spatial Vision, 4,* 186; with permission.]

500), there is ample dynamic range to explore the motion mechanism with very low contrast stimuli that bypass gain-control nonlinearities. For such low-contrast stimuli, it can be shown that the Reichardt model holds exactly. (See van Santen & Sperling, 1984, for three demonstrations of counterintuitive displays that demonstrate Reichardt properties of human motion perception: immunity of sine wave motion perception to an added stationary sine wave pedestal of the same spatial frequency; immunity to added homogeneous flicker if the flicker has a different temporal frequency; and motion amplitudes at adjacent locations multiply to determine motion strength).

To denote the formal similarity of dynamic motion perception to static slant perception, we note that a monocular motion stimulus is a cube in 3D space, x,y,t where x and y are spatial dimensions, and t is time. If we consider translatory motion of a simple visual stimulus (such as a tall vertical bar), then its motion is represented as a slanted line in x,t space (Watson & Ahumada, 1983). The decision as to whether there is motion to the left or right in x,t is equivalent to a decision of whether the line slants from upper left to lower right or vice versa in x,y (Fig. 8a, b).

A Hubel-Weisel simple cell is a cortical neuron that has an oriented receptive field, as illustrated in Figure 8c-f. A linear-filter mechanism that can determine line slant in x,y is the implementation of the Hubel-Wiesel simple cell as an oriented bandpass filter. Even though a Hubel-Wiesel filter seems ideally suited for detecting slant, by itself, it is insufficient. Depending on where a line happens to fall on the filter, the output may be either negative, positive, or zero. Adding filters to cover many possible spatial locations, so that some, at least, will be perfectly placed, does not the solve the problem. Some are perfectly placed to have maximal positive outputs, others to have maximal negative output, and so the expected (average) output is zero. The obvious solution is not simply to add outputs, but to rectify them first, that is, to discard the sign of the filter outputs before combining them. Squaring the outputs accomplishes this with great mathematical elegance; the sum of squared outputs is called "power" or "energy." When outputs of filters with a only a particular orientation are squared and summed, the summed output is "directional power." For biological systems, perfect squaring is unnecessary; a wide range of monotonically increasing functions of the absolute value would be quite adequate.

A model for the slant detection in which the direction power is computed for competing orientations was proposed by Granlund and Knutsen (1983). Adelson and Bergen (1985), unaware of their work, proposed the equivalent model for the computation of motion direction, in which the hypothetical filters were slanted in x,t instead of as Hubel-Wiesel filters) in x,y. A remarkable fact is that these differently motivated and differently constructed motion models [elaborated by Reichardt (van Santen-Sperling) and Adelson-Bergen], are computationally equivalent. Indeed, it was also shown (van Santen & Sperling, 1985), that an elaboration of the mathematically elegant Watson-Ahumada motion detection filter based on Hilbert transforms also was equivalent to the Reichardt model. From an input–output point

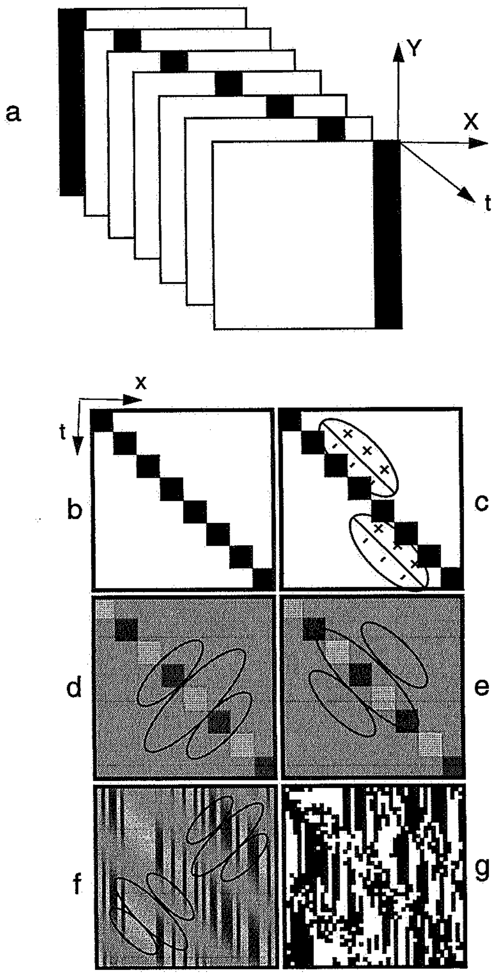


FIGURE 8 First- and second-order motion and texture stimuli. (a) Eight frames of a vertical bar that moves from left to right as a function of time (t). The last frame is shown in its entirety, the previous frames are mostly obscured. (b) An x-t cross-section of (a). (c) An x-t cross-section of (a) with Hubel-Wiesel edge filters superimposed in two different phase relationships. The filter outputs are either positive or negative depending on where they happen to fall in the stimulus. Notice also the equivalence of the problem of direction-of-motion detection in x-t with the direction-of-slant detection in x-y. (d) A "reversed phi" stimulus. A moving bar changes from white-on-gray to black-on-gray in successive frames. The Hubel-Wiesel line filter superimposed on the reversed phi stimulus illustrates it has a large output and therefore "perceives" slant from upper right to lower left, the so-called Fourier direction. Human perceive motion or slant in the Fourier direction when the stimulus is extremely small or viewed in peripheral vision, and in the nonFourier direction under normal viewing. (e) Reversed phi stimulus with a Hubel-Wiesel filter oriented in the non-Fourier direction to illustrate that its output will be approximately zero. Nevertheless, this is the direction in which humans normally perceive motion (or slant). (f,g) Drift-balanced and microbalanced stimuli for which Hubel-Wiesel receptive fields oriented at +45° and −45° have exactly equal expected outputs. Detection of left-to-right motion or upper-left to lower-right slant necessarily requires second-order motion or texture processing. [Adapted from Fig. 1 in C. Chubb & G. Sperling (1989). Two motion perception mechanisms revealed through distance-driven reversal of apparent motion, *Proc. NAS USA, 86,* 2986; with permission of the authors.]

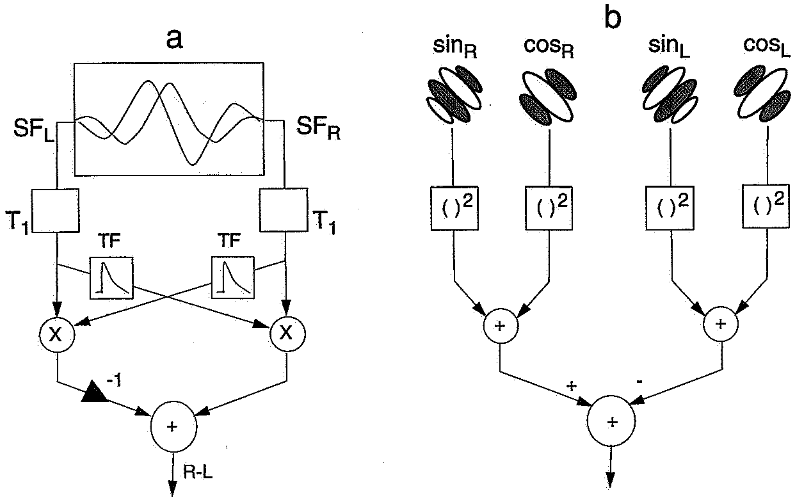


FIGURE 9 Two equivalent motion models. (a) Reichardt motion model. Spatial filters (receptive fields) are indicated as sine SF_L and cosine SF_R Gabor functions. T_1 indicates a temporal filter (incorporated into filter SF in Fig. 6), other details as in Fig. 6. (b) A directional energy detector (after Granlund & Knutsen, 1983). In the *x,y* (spatial) domain, it computes rightward- versus leftward-slanting orientation power. In x,y, $\sin_R$ and $\cos_R$ indicate rightward slanting Hubel-Wiesel receptive fields (spatial band-pass filters), and $\sin_L$, $\cos_L$ are leftward-slanting receptive fields. $( )^2$ indicates squaring and + indicates summation. Interpreting the coordinates as x,t yields a direction motion-energy detector that determines the rightward minus leftward motion power. (Reprinted with permission of G. Sperling.)

of view, these three theories of first-order motion are equivalent. Of course, which of these, if any, corresponds to the biological mechanisms that sense motion is not yet resolved.

F. Second-Order Perceptual Processes

A further development in psychophysical research has been the discovery of second-order processes of perception. In first-order visual perception, the unit on which processing is based is the amount of light reaching any small area, i.e., the units of first-order processing are photons.

In second-order perception, the units of processing are features. Typically, a visual feature is a small patch of a particular kind of texture. However, features are defined not by logical analysis of visual stimuli but by the analyses performed by second-order neural systems. We call a particular kind of visual micropattern a feature if there are (second-order) neurons that process it analogously to the way that (first-order) neurons process photons.

The study of second-order perception was an outgrowth of the advent of computer-controlled graphic displays. New display technology made it easy to create texture stimuli that were invisible to first-order processes, but which elicited analogous (second-order) perceptual responses to first-order stimuli. For example, spatial interactions, such as lateral brightness induction, Mach bands, Chevreul illusions, and the Craik-O'Brien Cornsweet illusion, can be reproduced in stimuli that have no systematic variations in luminance (Chubb, Sperling, & Solomon, 1989; Lu & Sperling, 1996a) but that vary systematically in *texture contrast* as a function of space (Figs. 10 and 11).

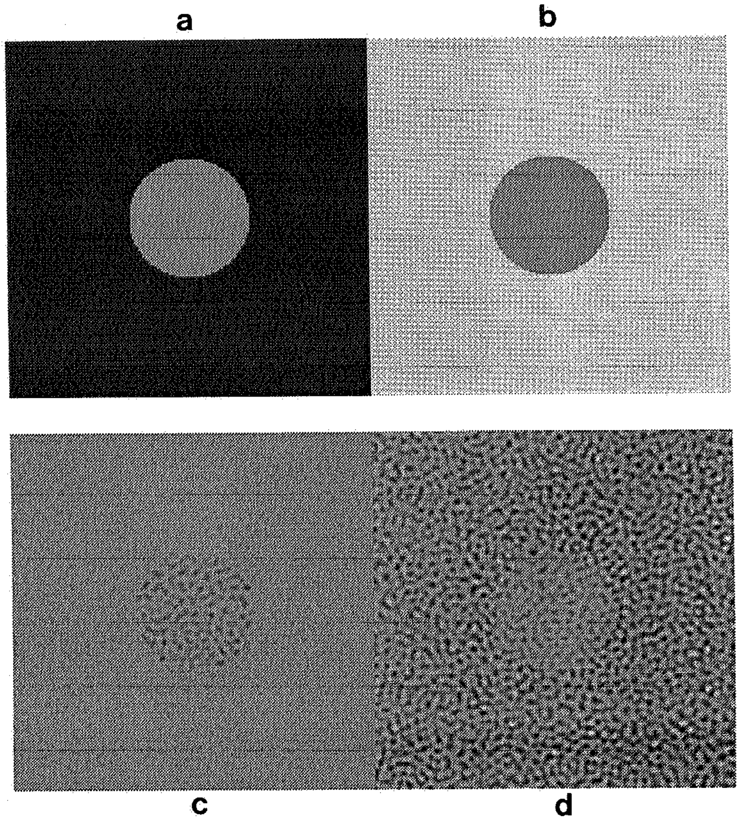
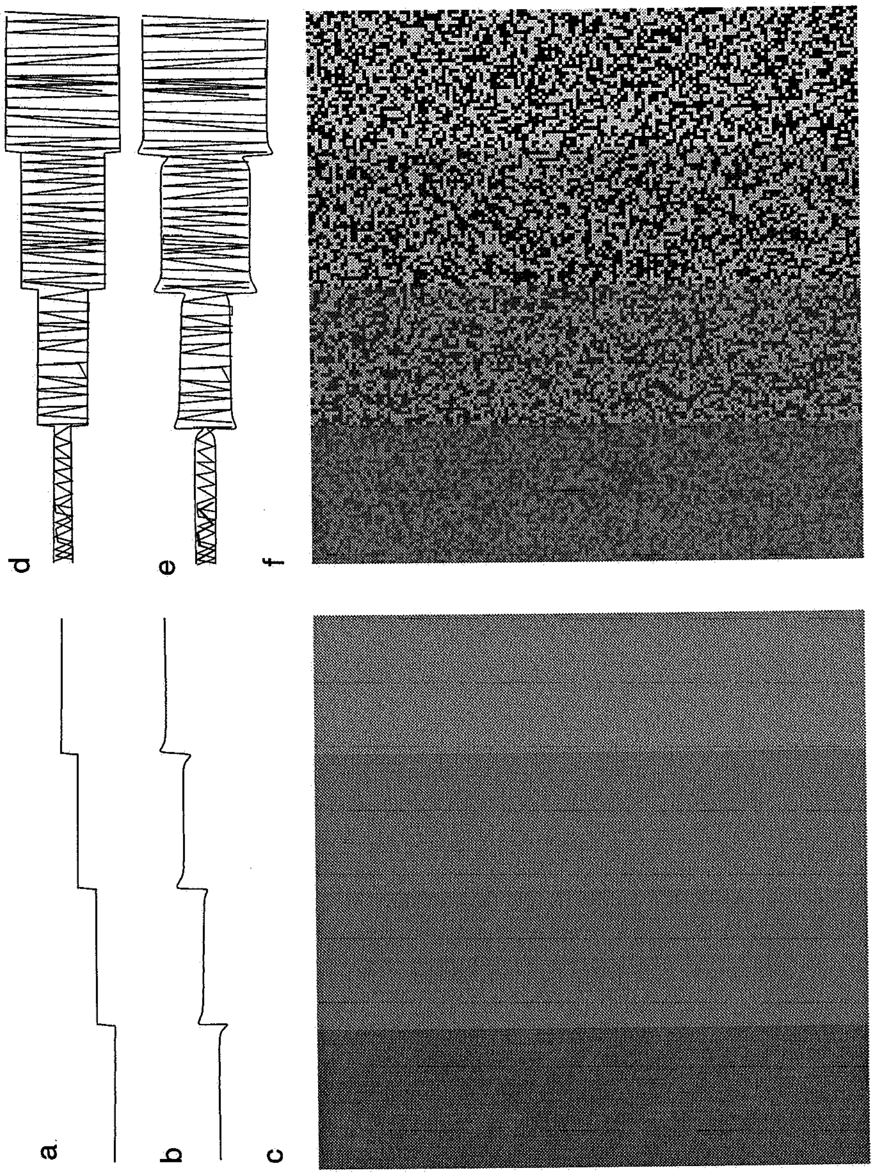


FIGURE 10 Classical lightness illusion (a,b) and the analogous second-order "contrast–contrast" illusion (c, d). The central disks in (a) and (b) have the same luminance, but the surround in (b) reflects more photons than the surround of (a). In sensory systems, active neurons tend to inhibit their neighbors, so the (more inhibited) central disk in (b) appears less bright than the (less inhibited) disk in (a). In (c) and (d), the expected luminance is the same everywhere, and the contrast of both central disks is the same. Only the surrounds differ. In second-order illusions, features take the role of photons in first-order illusions. In (d) the greater abundance of features in the surround, due to its higher contrast, makes its inner disk appear to be of lower contrast than the disk in (c). [Adapted from Fig. 1 in C. Chubb, G. Sperling, and J. Solomon (1989). Texture interactions determine perceived contrast. *Proc. NAS USA, 86,* 9632; with permission of the authors.]


a
b
c
d
e
f

Second-order processes have been most studied in the domain of motion perception, in which parallel first- and second-order processing systems have been discovered. Both of these are primarily monocular, fast, and both approach the theoretical limits in their efficiency of utilizing stimulus information that actually reaches the retina (Geisler, 1989; Solomon & Sperling, 1994). Both first- and second-order motion systems are activated by highly specific stimulus properties (Fig. 12).

Motion is processed at higher levels by a third-order motion system. The third-order motion system is much slower and less sensitive than the first- or second-order motion system, but is indifferent to the eye of origin of successive stimuli and it has amazing versatility. The mechanism of third-order motion depends on an automatic figure–ground computation. That is, for purposes of further processing, the visual system divides the visual stimulus into areas that are marked as "figure" (which are then forwarded to shape and object recognition modules) and into parts that are unmarked—the ground upon which figures appear. The ground is not further analyzed. Classical illusions such as Rubin vases (see also Cutting & Massironi, chap. 6, this volume; Hochberg, chap. 9, this volume) result from stimuli that admit two alternative, stable figure–ground divisions that produce very differently perceived figures. The figure–ground computation is performed automatically on every visual input, whether or not the input is noisy or ambiguous. The result of figure–ground computations is recorded in a "salience field," a representation of the visual field in which salient areas (e.g., figure) are marked, and the background is unmarked.

Third-order motion is an automatic computation that records translations of marked areas. Similarly, the object recognition process takes its input only from marked locations. Attention interacts with both of these processes, third-order motion and object recognition, by determining which features are more salient and therefore more likely to be marked. All these relations are illustrated in Figure 13.

G. Development of Motion Models

The point of this exposition is not to inform the reader of the specific details of these complex processes; for these, there are reviews (Sperling, Chubb, Solomon, &

FIGURE 11 First- and second-order Chevreul illusions. In (a) and (c), the luminance increases stepwise but the brightness appears "scalloped" as in (b). That is, the bright side of the edge appears brighter than equally luminous neighboring areas and the dark side appears dimmer than equally luminous neighboring areas. In (d) and (f), contrast increases stepwise, expected luminance remaining constant throughout. The apparent contrast appears correspondingly scalloped at the contrast steps as in (e). [(a) and (b) reprinted from Fig. 1 in Z. Lu and G. Sperling (1996). Second-order illusions: Mach Bands, Chevreul, and Craik-O'Brien-Cornsweet. *Vision Research, 36, 4,* 560; (c) and (f) reprinted from Fig. 4 in Z. Lu and G. Sperling (1996). Second-order illusions: Mach Bands, Chevreul, and Craik-O'Brien-Cornsweet. *Vision Research, 36, 4,* 566; and (d) and (e) reprinted from Fig. 2 in Z. Lu and G. Sperling (1996). Second-order illusions: Mach Bands, Chevreul, and Craik-O'Brien-Cornsweet. *Vision Research, 36, 4,* 561; with kind permission from Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington OX5 1GB, UK.]

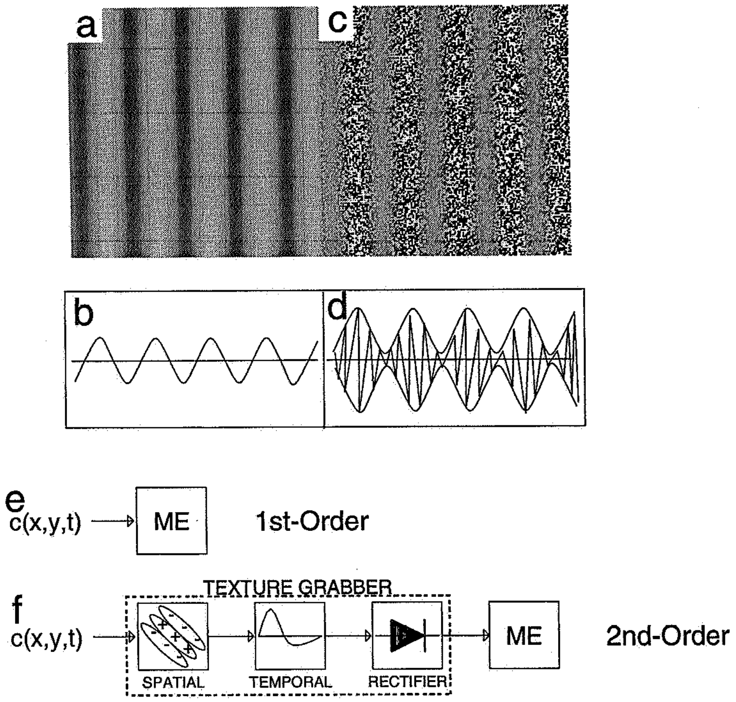


FIGURE 12 First- and second-order motion stimuli. (a) A single-frame of a first-order stimulus—a sinusoidally modulated luminance grating. (b) A graphical representation of the sinusoidal modulation of (a). (c) A single-frame of a second-order stimulus—a contrast-modulated random-texture grating. (d) A graphical representation of one horizontal line of (c). The random function represents the *carrier* texture: its envelope is the modulator. To create an impression of motion, the modulators in (b) and (d) translate horizontally from frame-to-frame. (e) A motion energy (ME) computation suffices to extract motion. (f) Second-order contrast-modulation motion is detected by first extracting the textural features (via a "texture grabber" represented by the first three boxes in [f]), and then computing ME of the features equivalently to computing the ME of photons in first-order motion. The texture grabber consists of three stages: an ordinary linear spatial filter, (SPATIAL box), a temporal bandpass filter (TEMPORAL box), and rectification (absolute value or square). [Reprinted from Fig. 2 in Z. Lu and G. Sperling (1995). The functional architecture of human visual motion perception. *Vision Research, 35, 19,* 2699; with kind permission from Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington OX5 1GB, UK.]

Lu, 1994; Lu & Sperling, 1996b) and source papers (Chubb & Sperling, 1988; Lu & Sperling, 1995a; Lu & Sperling, 1995b). Rather it is to illustrate how, during the course of a century, the study of motion has progressed from the description of the phenomenon of two flash apparent motion by Exner (1875), a relatively straightforward objective description, to the mentalism of Wertheimer and the Gestaltists (as manifest in their reliance on introspective observations, i.e., "pure objectless phi motion"), to the first computational description by Reichardt in the 1950s, and to

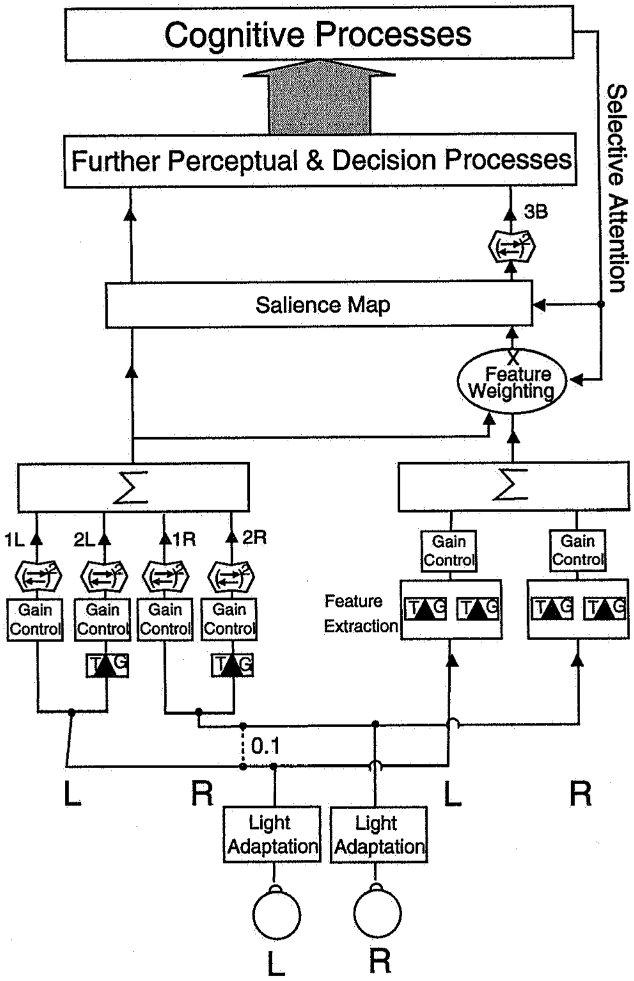


FIGURE 13 The functional architecture of the brain system that determines motion direction. The most critical components, motion energy extractors (e.g., Reichardt models $(\rightleftarrows)^2$ texture grabbers (TG) are defined in Figs. 12 and 9). Signals arriving at the left (L) and right (R) eyes are first analyzed separately for first- and second-order motion content resulting in L and R first- and second-order signals (1L, 2L, 1R, 2R); these are combined in Σ according to rules not yet fully understood. The right half of Figure 13 illustrates the combination of texture features before motion extraction, feature weighting that is modified by the state of attention, and a representation of the most significant features (figure versus ground) in a salience map. The third-order motion system, which has only about $\frac{1}{3}$ the speed and resolution and $\frac{1}{10}$ the sensitivity of the first- and second-order motion systems, takes the output of the salience maps as its input and computes third-order motion. [Reprinted from Fig. 13 in Z. Lu and G. Sperling (1995). The functional architecture of human visual motion perception. *Vision Research, 35, 19,* 2719; with kind permission from Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington OX5 1GB, UK.]

the working out of the consequences of computational models in the second half of the century.

The representation of knowledge about perception of motion direction has resulted in models of ever increasing complexity. The Reichardt model of the 1950s (Fig. 6) has nine components (boxes). The Reichard model appears five times as a component of in the motion architecture model of the 1990s (Fig. 13). A texture grabber has three components and appears six times in Figure 13. Thus 9 of the 23 components of Figure 13 expand immediately to 69 subcomponents, and the most complex components have not been expanded.

Figure 13 represents just one local spatial region. It is reproduced in every visual neighborhood, thousands of times in all. As soon as neighboring processing is considered, spatial interactions come into play. The entire motion-architecture model of Figure 13, with all its neighboring reproductions and interactions, represents just one channel—one level of resolution in a pyramid structure. The whole architecture is repeated, at least in first-order motion perception, at many different levels of resolution. A model that simultaneously incorporates both spatial relations and different levels of resolution is obviously enormously more complex and will involve many spatial and vertical processes that are not represented in the simplified architecture of Figure 13. And all this complexity arises from a model merely of the perception of motion direction; velocity is not even considered. The closing years of the 20th century have seen an explosion of computation models for more complex aspects of motion perception, such as the perception of velocity, of three-dimensional structure from two-dimensional motion, the perception of visual heading from motion flow fields, and so on. The step-by-step substantiation, elaboration, and integration of such models seems to be one important direction for the study of motion perception in the 21st century. It is a harbinger of developments to come in the study of other sensory processes, and it illuminates the enormous difference between theories of the 19th and 21st centuries.

III. VISUAL ATTENTION

A. Early Conceptions of Attention

Unlike perception, which had an extensive empirical development by the late 19th century, the study of attention largely began with the questions and observations of the mentalists near the turn of the century. Attention and its relation to consciousness was actively discussed. William James (1890) said,

> 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. . . . One principal object comes then into the focus of consciousness, others are temporarily suppressed. (pp. 403–404)

Unfortunately, although everyone knew what attention was, there was very little agreement about what they knew. The psychologists of the period, such as James, Wundt, Tichener, and Ladd, who based their accounts on introspective observations, failed to agree on either the effects of attention or its mechanisms. To quote Kulpe (1895/1921):

> Every psychologist of any independence at the present time analyses and derives attention in his own way. Some reduce it to . . . sensations of muscular contraction or of strain; others regard it as an emotion, which exercises an especial influence upon the motor side of our activity. Another, psychophysical theory makes it the primary office of attention to reinforce excitation in the sensory centres; and a fourth hypothesis characterises its positive function as a process of inhibition. (p. 423)

An intriguing observation of that period that is perhaps typical of the introspective approach is described by Wilhelm Wundt in the late 1800s (translated into English, 1912/1924, pp. 19–22). Wundt asked his reader to fixate the *o* in the center of an array of letters (Fig. 14), and to maintain fixation while moving the "subjective-fixation" of attention to the *n* on the right-hand side. By introspection, the letters surrounding the *n* were "perceive[d] more clearly," whereas the letters elsewhere "seem to retreat into the darker field of consciousness." (p. 21). Wundt was aware that visual acuity falls off away from the point of fixation of the eye, and that attention, although ordinarily coordinated with eye movements, can be separated from fixation. Attention to locations in space is one major theme of this section, and the relation of attention and eye movements is considered later in the section.

B. Documenting an Effect of Attention: Response Time and Detection

Logical, practical, and theoretical difficulties arise from Wundt's observation. Visual distribution and extent of the area of visual clarity might be difficult or impossible to ascertain with introspective measures, because the evaluation of the clarity of an

```
        t h m
    m v x w a s f
  l g i c s f p d t
z r a e n p r h v z l
r f u c t h f b n d s
k h e p n o t v b s i
n z l u c r k m d g n
d i n i w g e t v r f
  s a t f l b p n k
    m d w c k t g
      p a v e r
```

FIGURE 14 A stimulus devised by Wundt (1912/1924, p. 19) to illustrate that attention could move independent of the eye, and that the point of "subjective fixation" of attention creates an impression of perceptual clarity. The observer was asked to fixate the central *o* and attend to the letter *n* one up and four to the right, and observe the gradient of attention. [Following Wundt (1912/1924). p. 19.]

unattended location, the necessary control, would require shifting at least some attention to the unattended location—a paradox. However, introspection itself is not the problem. Introspection enters the 21st century in good health and with a firm basis under the guise of sensory scaling. As practiced in the 20th century, sensory scaling involves two methods: relating real numbers to perceived sensory quality or intensity, and judging various modes of equivalence of different sensory experiences. These are forms of introspection in which the possible range of response is extremely restricted. When some of these methods of refined introspection have been applied to attention, the results have been disappointing. Judgments of appearance seem to be remarkably indifferent to the state of attention (e.g., Prinzmetal, Amiri, Allen, Nwachuki, & Bodanske, 1995, find that reports of stimulus properties such as color are essentially the same, though perhaps less variable, for attended as compared to unattended conditions). Failing to replicate Wundt's casual introspective observation under the more rigorous conditions typical of scaling experiments is a practical problem, but it may be due to the logical paradox alluded to above.

From the point of view of evolution, the subjective qualities of perception are not the relevant consideration; what matters is whether or not responses to stimuli are competent and adaptive. Measurement of the behavioral consequences of focusing visual attention at a given location awaited the development of appropriate experimental methods for the measurement of accuracy and—after the reintroduction of reaction time (RT) measures into psychology in the 1960s—RT.

Perhaps the first serious experimental attempt to assess the consequences of distribution of attention over the visual field was by Mertens (1956). His observers fixated a central point and were asked to detect a weak flash of light that could occur in one of four positions corresponding to the corners of a square around fixation. Observers judged whether or not a flash occurred during a test trial. Mertens contrasted a focused attention condition in which the observer knew that flashes could occur in only one known location with a divided attention condition in which the observer knew that the flash could occur at any location. Merton concluded that focused attention impaired detection. Unfortunately, Mertens's conclusion was incorrect, because he considered only hits, and not false alarms (i.e., he was unaware of signal detection theory). We will return to Mertens and his conclusion after further development.

In the 1970s, Posner and his students (e.g., Posner, Nissen, & Ogden, 1978) measured the consequences of focusing attention on certain locations in visual space using RT rather than response accuracy. An illustration of his paradigm and some sample results are shown in Figure 15. Observers fixated on a central cross. The test stimulus was a flash of light that appeared on most but not all trials; the flash was either to the right or the left of fixation. Observers pressed a single key as soon as they saw any flash (go–no-go paradigm). To manipulate the distribution of attention, a left- or right-pointing cue arrow appeared prior to the light flash on some trials; the arrow indicated the likely location of the flash, and observers were

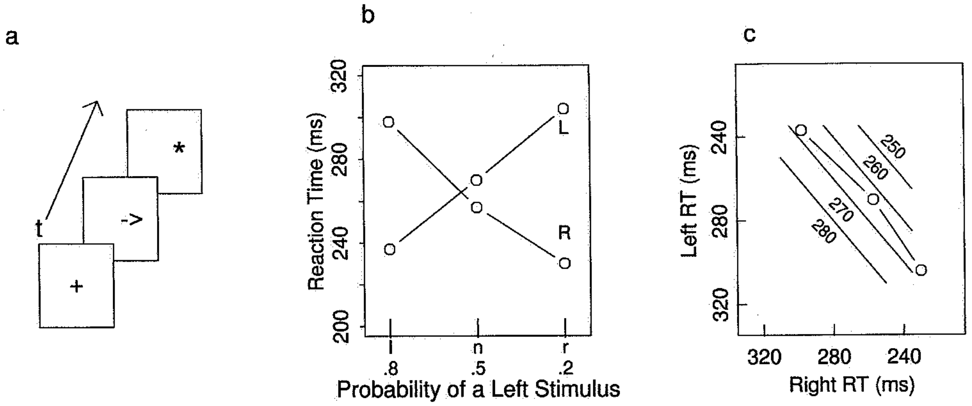


FIGURE 15 (a) An illustration of Posner, Nissen, and Odgen's (1976) paradigm for measuring the consequences for response latency of focusing attention on a location in space. (b) Sample response time (RT) data showing the costs and benefits of focal attention. R, right; L, left. (After Sperling & Dosher, 1986, Fig. 2.18a.) (c) Regraphing of the data that further illustrates the trade-off in RT data, along with utility contours. (After Fig. 2.18 in Sperling and Dosher (1986), with permission of the authors.)

expected to attend to that location. On the 80% of trials when the flash occurs in the attended location, mean RT is rather fast whereas RT on the 20% of trials when the flash occurs in the unattended location is rather slow; RTs for uncued trials are intermediate. RTs were about 240 ms for attended flashes, 300 ms for unattended flashes, and 270 ms for uncued flashes. Accuracies were generally ignored. Posner interpreted RT differences as the "costs" or "benefits" (relative to uncued performance) of attention to a location in space.

Go–no-go experiments, with their emphasis on empirical documentation of the consequences of attention, represent an advance in experimental methodology. Yet both the Mertens and the Posner et al. investigations lacked the theoretical tools necessary for unambiguous interpretation. As explained below, several alternative interpretations of these results are possible.

The experiments relate to—but do not answer—a host of questions: how quickly is attention deployed, how is attention distributed spatially, and, importantly, does attention improve clarity or sensitivity or does it change which information is selected for subsequent decision or memory? Progress on each of these questions is taken up in turn.

C. Episodes of Attention: Attention Switching

An observer's decision to focus attention on a particular location in space, either in response to a cue in an experiment such as Posner's, or to acquire new information in natural situations, initiates a new attentional episode. Attention is switched from its current state to a new focus. It is now known that the time course of a switch of visual attention is not instantaneous. It involves the opening and closing of an

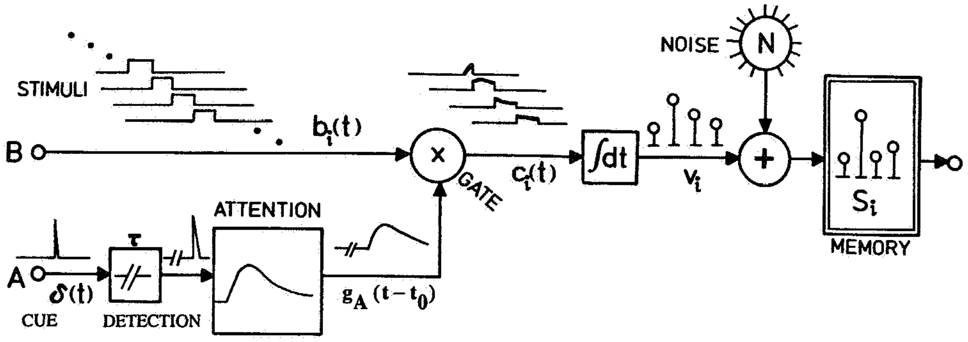


FIGURE 16 An attention-gating model. When an attention cue appears in input stream A, the attention-modulating system gates information from a second stream of visual input, B, into memory for report. In the figure, *t* refers to time, $\delta(t)$ and τ are processing delays, $g_A(t - t_0)$ describes the attention gate; $b_i(t)$ and $c_i(t)$ are weighted inputs; and v_i and S_i are item strengths. [From Fig. 11 in G. Sperling and E. Weichselgartner (1995). Episodic theory of the dynamics of spatial attention, *Psychological Review, 102, 3,* 524; with permission of the American Psychological Association.]

attention "gate" that selectively admits information from one part of the visual field to further processing or to memory.

The temporal characteristics of a switch of attention were treated quantitatively by Reeves and Sperling (1986). In their gating model (Fig. 16), a cue to switch attention produces, after a short delay, the opening of a gate at the cued location. Information at the newly attended location is gated into memory. The memorial representation is the basis for conscious awareness of information at the cued location.

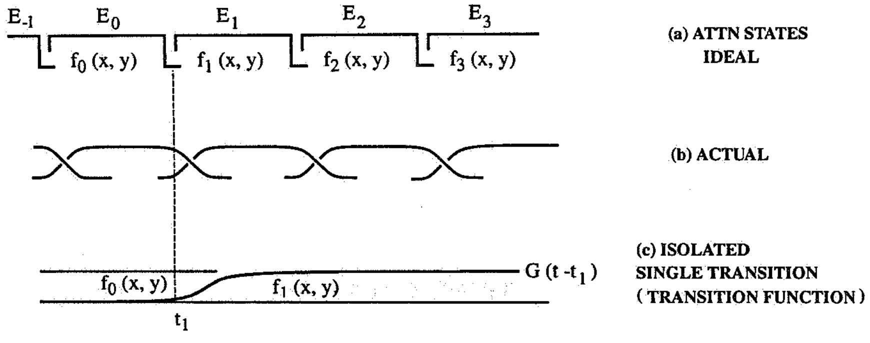
In Reeves and Sperling's experiments, a target item occurs in one sequence of letters and, as soon as the target appears, observers must report the next item or items that appear in a second, spatially separated sequence. The delay in opening the attention gate, as well as the temporally continuous operation of the gate, can be inferred from the item(s) the observer reports from the newly attended location. These observations tell us about the temporal aspects of attention as a process that controls the flow of information into memory, an important phenomenon that is further discussed in section IV.

D. Spatial and Temporal Distribution of Attention

As a consequence of improvements in both data collection and in process models, Wundt's initial question about the spatial extent of focused attention can now be quantitatively answered within a more general "episodic" model of attention (Sperling & Weichselgartner, 1995). Spatial attention is regarded as a sequence of discrete states, quite analogous to the fixation states of the eyes in sequences of saccadic eye movements. The model allows the estimation of the spatial distribution of attention and of the time course of switching attention from one location to another.

At any given time, the observer is in a particular attentional state associated with a spatial attention function defined at each position in space, $f(x,y)$. The switch from one attentional state to another is described by a temporal transition function. Each attentional state defines an attentional episode, and a transition from one state to another demarks one episode from the next (Fig. 17). Figure 18 illustrates hypothetical distributions of attention to two different locations in space (e.g., left and right) during two attentional episodes, one before and one after a switch of attention.

The episodic model of attentional distribution and attentional switching accounts closely for many sets of attentional data. Estimated spatial attention functions

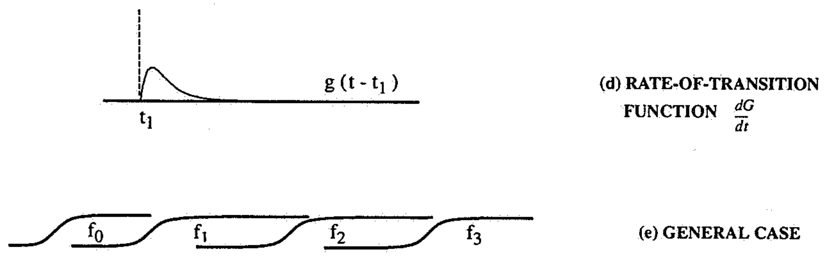


(a) ATTN STATES IDEAL

(b) ACTUAL

(c) ISOLATED SINGLE TRANSITION (TRANSITION FUNCTION)

$$A(x, y, t) = E_0 + E_1 = f_0(x, y)\,[1 - G(t-t_1)] + f_1(x, y)\,G(t-t_1) \qquad \text{(EQ 1)}$$

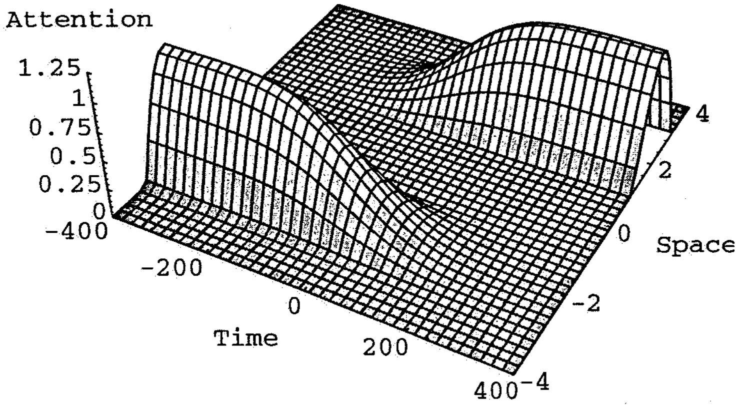


(d) RATE-OF-TRANSITION FUNCTION $\frac{dG}{dt}$

(e) GENERAL CASE

$$A(x, y, t) = \sum_{i=-\infty}^{\infty} E_i = \sum_{i=-\infty}^{\infty} f_i(x, y)\,[G_i(t-t_i) - G_{i+1}(t-t_{i+1})] \qquad \text{(EQ 2)}$$

FIGURE 17 An episodic theory of attention. (a) a series of attention states, with idealized instantaneous shifts of attention between states; (b) actual attention episodes with non-instantaneous attention shifts; (c) details of a single attention transition function; (d) corresponding rate of transition function for a single transition; (e) general case of transition between episodes. [From Fig. 2 in G. Sperling and E. Weichselgartner (1995). Episodic theory of the dynamics of spatial attention. *Psychological Review, 102, 3,* 505; with permission of the American Psychological Association.]



Quantal

FIGURE 18 The spatial attention functions (e.g., for a left or right location) and the temporal transition function as they shift (from left to right) in the Sperling and Weichselgartner (1995) model. The spatial attention functions are graphed as attentional weight or effectiveness as a function of the two variables time and spatial location. [From Fig. 1 in G. Sperling and E. Weichselgartner (1995). Episodic theory of the dynamics of spatial attention. *Psychological Review, 102, 3,* 504; with permission of the American Psychological Association.]

generally look similar to that depicted in Figure 18, but are of course sensitive in part to experimental manipulations and the nature of the behavioral measure. The distribution of targets over space (Sperling & Weichselgartner, 1995) and the focus required by the task (LaBerge & Brown, 1989) affect the spatial distribution of attention.

An important relationship holds between the spatial and temporal properties of attention. The spatial attention functions and temporal transition functions estimated for a wide range of experiments (e.g., Lyon, 1987; Shulman, Remington, & McLean, 1979; Tsal, 1983) are space–time separable (e.g., the functions represent "quantal" movements of attention). Attention is focused around one location and then, at the time of a switch in focus, attention is focused around the next location. Contrary to a number of early speculations (Shulman, Remington, & McLean, 1979; Tsal, 1983), moving attention from one location to the next is not accomplished in an analog manner—attention does not move through the intermediate locations (Sperling & Weichselgartner, 1995). Visual attention operates like a bank of stationary spotlights in which only one light may be turned on at a time. As one spotlight turns off, another spotlight focused at a different location turns on.

With continuing investigation, the earlier attention-gating model (Fig. 16) has evolved into much more detailed model (Fig. 19). The quantitative form of the model allows the estimation of both the spatial and temporal aspects of attention and attention shifts, and the same model with the same parameters applies to a wide variety of experimental designs and situations.

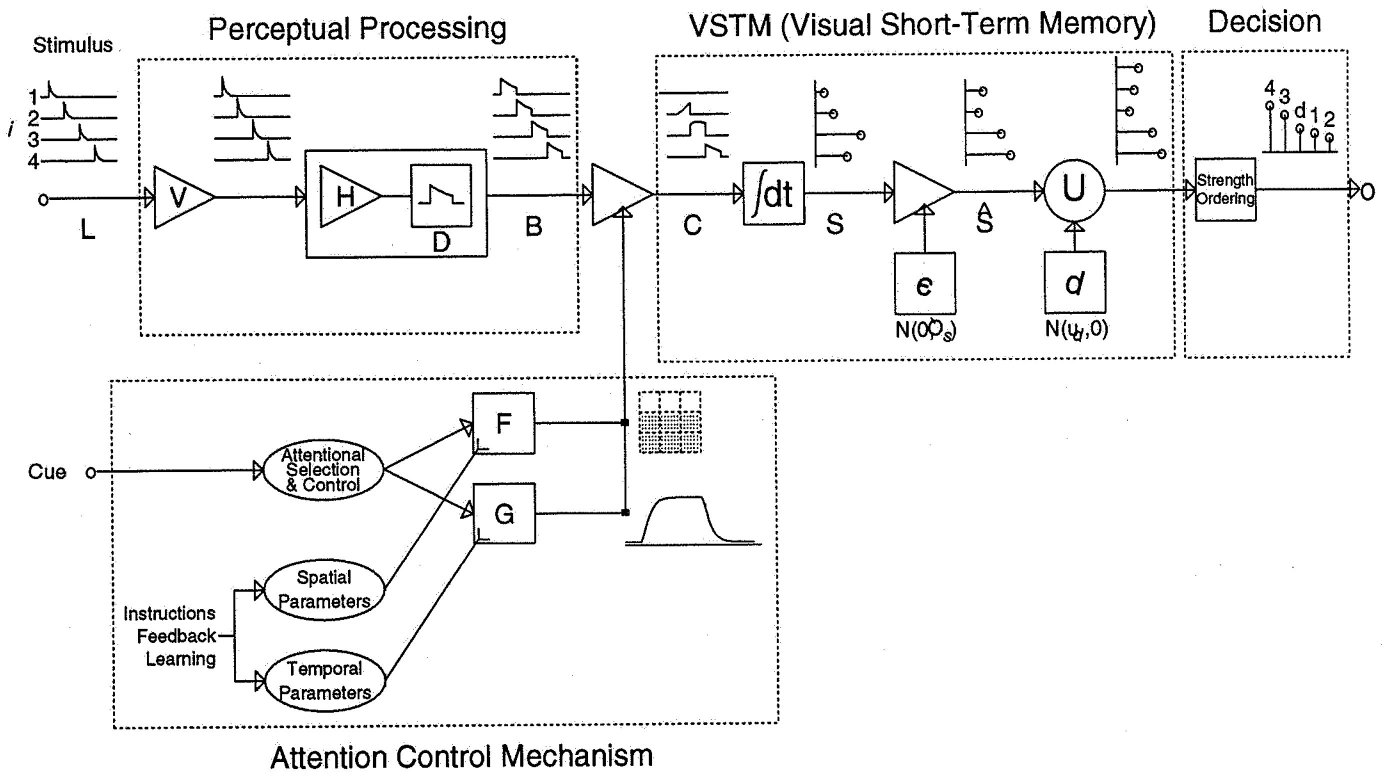


FIGURE 19 An elaborated attention-gating model specifying the details of the attention-gating function in terms of spatial and temporal parameters of attention shifts. (Reprinted with permission of G. Sperling.)

As in visual perception, the history of theorizing in spatial attention began with catalogs of phenomena and vague verbal interpretations and has progressed to well-specified models of performance applicable to a wide range of stimulus situations. Like the motion models, the attention models of Reeves and Sperling (1986) and Sperling and Weichselgartner (1995) are quantifiable, specific, and embody a complex information-processing architecture. However, like the early attempts by Mertens, Posner, and others, the attention-gating models do not distinguish between different mechanisms that may underlie the measurable changes in behavior. In particular, they do not distinguish between changes in the perceptual strength (clarity) of stimuli and changes in the criteria or thresholds for response, or the entrance into a memory store.

E. Bias versus Discrimination in Detection Accuracy and Reaction Time

James felt that attention to some objects was accompanied by the suppression of other objects—a notion of limited capacity. Hence, perceptual "clarity" was improved for attended objects and reduced for unattended ones. The strong form of the perceptual clarity claim must demonstrate attentionally manipulated changes in sensory strength, or discriminability. (There are other interpretations of the term clarity. For example, Treisman (1986) argues that the features of multifeature stimuli are bound together only in the focus of attention. See Hochberg, chap. 9, this volume, for a discussion.) Distinguishing between attentional modulation of perceptual clarity and other attentional changes requires the application of signal detection theory. As discussed above (section II), signal detection theory was introduced into psychology in the 1960s in the domain of auditory psychophysics (Green & Swets, 1966). In the SDT framework, differences in detection performance as a function of attention reflect either changes in perceptual strength (discriminability) or changes in criterion (bias), or both. Signal detection theory provides a way of estimating the strength of a stimulus in the face of changes in performance that reflect only changes in decision rules or criteria. (Additionally, the number of signal and noise sources may be an issue, see below.)

Suppose an observer is asked to respond when she sees a weak flash of light. In SDT the evidence for a light flash occurring during the trial interval is represented on a unidimensional scale of perceptual strength. The distribution of perceptual strengths (often assumed to be gaussian) is higher if the light flash actually occurred (signal) than if it did not (noise) (Fig. 20a). If the subjective evidence or strength sampled on a particular trial is above a criterion then the observer says that a flash occurred, otherwise they do not. The number of detection responses obviously depends not only on the visibility (intensity or duration) of the flash, but on the criterion (lax or strict) that the subject adopts for a response. A lax criterion may produce many "detect" responses even for a relatively weak stimulus, whereas a strict criterion may produce few "detect" responses even for a relatively stronger stimulus.

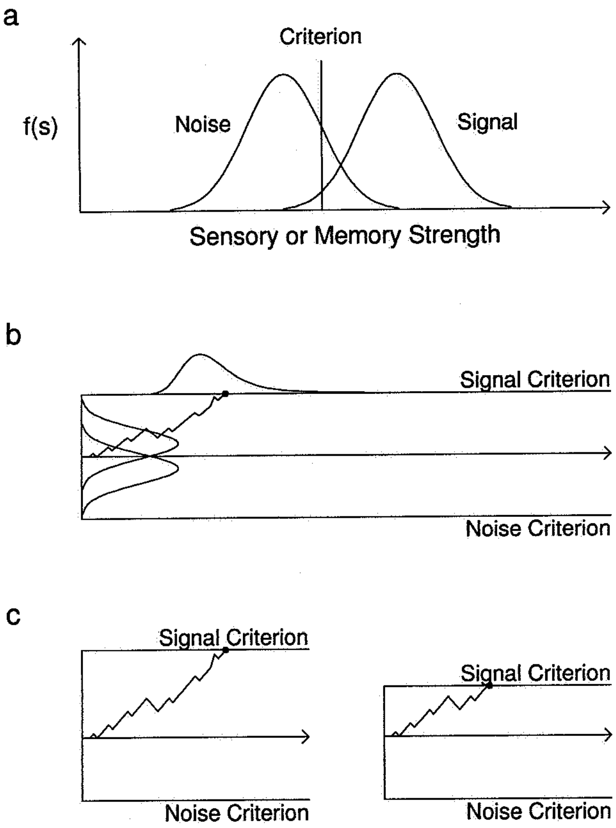


FIGURE 20 Principles of signal-detection theory account for decision structure. (a) Distributions of evidence or strength for target-present (signal) and target-absent (noise) trials, along with one possible criterion. (b) A random walk or diffusion model with similar signal-detection assumptions. Information is sampled over time, resulting in a decision whenever the cumulated information reaches either a signal or noise evidence criterion. (c) A set of random walks that can account for the costs and benefits when the observer is cued to expect a signal on the right, and changes the distance to the information boundaries accordingly; the left portion represents the long response times when a signal appears unexpectedly on the left, and the right portion the shorter response times when a signal appears on the right as expected. (With permission of B. Dosher.)

SDT is critical to the correct understanding of a number of attentional paradigms. In Mertens's flash detection experiment, attending to a single cued location was contrasted with dispersed attention where no single location was the focus. In Posner's experiment, performance with dispersed (uncued) attention was compared with performance when the target occurred in an attended or an unattended location. An SDT analysis makes clear that at least two things other than perceptual strength might account for differences between conditions: changes in criteria, or bias, and changes in sources of noise in the decision process.

F. Criterion Shifts or Bias

Attentional instructions may cause the observer to shift criteria, and this may affect performance without any changes in perceptual strength of the stimuli. In the Posner experiment, when observers are cued to expect a flash on the right, observers may simply lower their criterion for sensory evidence on the right and raise their criterion for evidence on the left. A model of response times that is related in spirit to SDT incorporates bias, and can accomodate a cost–benefit relation in response times is also illustrated in Figure 20. This form of RT model (Fig. 20b) is called either a random walk or diffusion model (Ratcliff, 1978). The trade-off between left and right RTs is nearly perfect (Fig. 15c), as well as completely consistent with a reasonable interpretation of the utility of overall performance given the trade-off in speed and the probabilities of each stimulus (see Sperling & Dosher, 1986, for a full development). In the Mertens experiment, analogously, the criterion for a flash-present response should be lower for the focused than for the dispersed attention condition in order to equate false alarm rates.

Changes in criterion or bias are attentional effects in the sense that they are behavioral changes reflecting a voluntary attentional manipulation. They change performance in the absence of changes in perceptual strength, and do not necessarily reflect the operation of a limited-capacity attentional mechanism.

G. Decision Noise

When the experimental situation is even somewhat complicated—involving either several possible very different stimuli or several locations for a simple stimulus—the multiple-channel architectures similar to those outlined for visual perception (Fig. 5) pose added sources of complication. In these situations, a second explanation for changes in performance in different attentional conditions involves *decision noise.* This is a nonperceptual explanation in that it does not assume any change in the perceptual processes themselves, but merely reflects the necessity of processing multiple sources of information. Decision noise is relevant when attention to many objects is contrasted with attention to a single object. It reflects structural changes in the decision rules with changing attentional instructions.

In the Mertens experiment, for example, the observer is dealing with only one evidence sample if the location of a signal flash is known. The sample of perceptual strength from the single known location is either from the signal or from the noise distribution. In trials where the signal location is not cued, four evidence samples are relevant, one from each of the four possible locations. The four samples are drawn either from one signal and three noise distributions or from four noise distributions (Fig. 21). The number of noise samples turns out to be critical, because it determines the number of sources of false alarms errors (saying target when there was none). Even if perceptual strength and decision criteria were identical in the two situations, an observer would exhibit more false alarm errors on unknown-

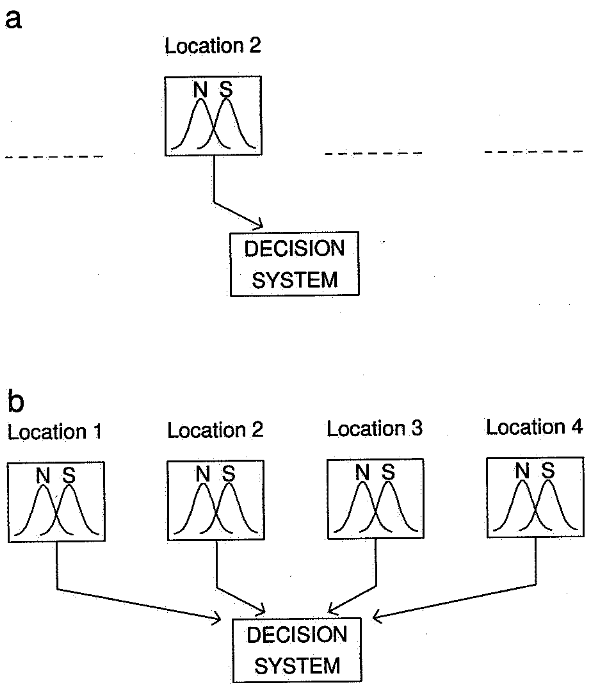


FIGURE 21 Preformance losses may reflect the decision structure in multichannel paradigms. (a) Illustrates signal detection with one known location (one channel); the stimulus may be either noise or signal on any trial. (b) Illustrates signal detection from four possible locations (four channel architecture); the stimulus may be either noise (noise in all locations) or a signal (signal in one location and noise in the remaining three) on any trial. Integrating observations from the four locations increases the sources of false alarms, producing performance deficits that reflect statistical decision loss rather than differences in the perceptual representation of the stimulus. (With permission of B. Dosher.)

location trials than on known-location trials because there are more chances to sample a high value of perceptual strength from the noise distribution from four locations than from one. Sometimes observers attempt to equate false alarm errors for the known- and unknown-location conditions; to do this they must raise their criterion on unknown-location trials. Although this may equate false alarms, it also necessarily leads to fewer correct detection responses. In either case, these decrements in performance reflect structural differences in the decision rules used in the two kinds of trials, not true differences in perceptual strength or discriminability. These decrements are called either decision noise or uncertainty loss.

In order to demonstrate that attention improves discrimination—or alternatively that spreading attention over many locations results in reduced discrimination because it is difficult to attend to too many things at once—decision or uncertainty loss must be estimated and factored out, or otherwise taken into account in the interpretation. Sperling and Dosher (1986) provide an overview of theoretical approaches to the estimation of decision loss and also describe classes of experiments that circumvent the issue of decision loss.

Often, decrements in performance associated with an increase in the number of attended locations do not exceed the loss due to decision noise (Graham, 1989; Palmer, 1994; Palmer, Ames, & Lindsay, 1993; Shaw, 1980, 1984). In some cases, a single target such as a flash is tested at one of several locations; in others, the target is shown among a certain number of distractors. In the latter case, sensory factors such as lateral masking must be eliminated or controlled. For many simple tasks, such as detection based on intensity increments, line orientation, target size, or target color, decrements in performance are almost exactly as predicted by decision noise calculations (Palmer, 1994; Palmer et al., 1993; Shaw, 1984). Certain more complex detection tasks do show discriminability differences between attended and unattended locations, presumably due to attentional capacity limitations (Downing, 1988; Shaw, 1984). The form and causes of attentional changes in perceptual discrimination in the more complex tasks are just beginning to be understood.

H. Attention Operating Characteristics

Verbal statements that attention is limited in processing capacity are traceable back to the turn of the century. These verbal statements have given way to methodological and formal developments that allow a full characterization of not just the extent to which performance on several subtasks depends on a limited capacity resource, but a precise evaluation of the nature of the trade-off between task performances.

A powerful methodological alternative to the SDT analyses of decision noise (leading to somewhat complex forms of decision or output models) involves the concurrent measurement of performance in two tasks (see Sperling & Dosher, 1986, for a full development). Concurrent measurements in two tasks that may be competing for attention evaluates the attention operating characteristic (AOC). The purpose of an AOC is to evaluate whether the two tasks can be performed together, or whether they require competing attentional capacity. Figure 22 illustrates an idealized AOC. The *x*-axis is performance on Task A; the *y*-axis is performance on Task B. Baseline conditions (solid circles) measure how well each task is done alone. If two tasks can be done simultaneously without loss, then joint performance will fall at the independence point (open circle). If the two tasks make competing demands on attention, the performance will fall below and to the left of the independence point. Joint performance should be measured under several attentional instructions (solid triangles), for example, 20–80%, 50–50%, and 80–20% Task A–Task B performance, from top-left to bottom-right. Systematic changes with instructions directly demonstrate *cognitive* attentional control over the joint performance of the two tasks.

The AOC is a powerful method for evaluating whether competing attentional resources are required for two tasks. In an early example (Figure 23a–c), Sperling and Melchner (1978) examined how observers searched for a digit among letters in

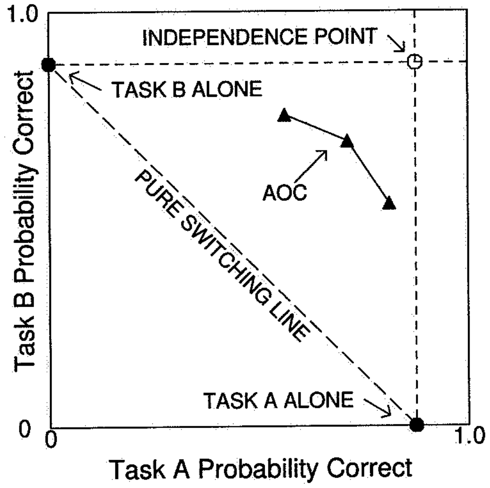


FIGURE 22 Attention operating characteristic (AOC) for the concurrent performance of two tasks. In this illustration, performance on both Task A and Task B are measured as percent correct. Baseline performance (solid circles) is measured for each task performed alone. The other marks represent performance for concurrent performance. The dashed line connecting the baseline accuracies represent the performances achievable by performing Task A on a proportion *p* of trials and Task B on proportion 1-p. The *ideal point* (open circle) represents no loss for task combination. Hypothetical joint performance (solid triangles) represents the outcome for joint performance of partially interfering tasks under instructions to emphasize (from left to right) Task B, give equal emphasis, and emphasize Task A. (Reprinted with permission of the authors.)

two spatially distinct parts of a long sequence of alphanumeric displays. Task A consisted in searching an outer ring of characters, while Task B consisted in searching an inner square of letters. So long as characters in the inner square and the outer ring were the same size, the two tasks could be performed with little loss (near the independence point). In contrast, if characters in the inner square were smaller and those in the outer ring larger, performance was substantially below the independence point. It is difficult to attend to two spatial scales simultaneously if both identity and location must be reported (Farrell & Pelli, 1993). And if the observer must search for a letter among digits in the inner square and a digit among letters in the outer square, performance is near the line connecting the two baseline points, indicating that observers can (probabilistically) do one or the other task but not both.

These powerful new methods have provided answers to a host of classic questions. For example, a line of related research using AOCs demonstrates that attentional selection is generally mediated by selecting a location, and that selection by physical features such as color or size is comparatively weak unless the color or size can be used to identify and then attentively select a stable set of locations (Shih & Sperling, 1996). In these studies, simply knowing in advance the color or size of a target stimulus is only beneficial when that color or size is associated with a predictable location.

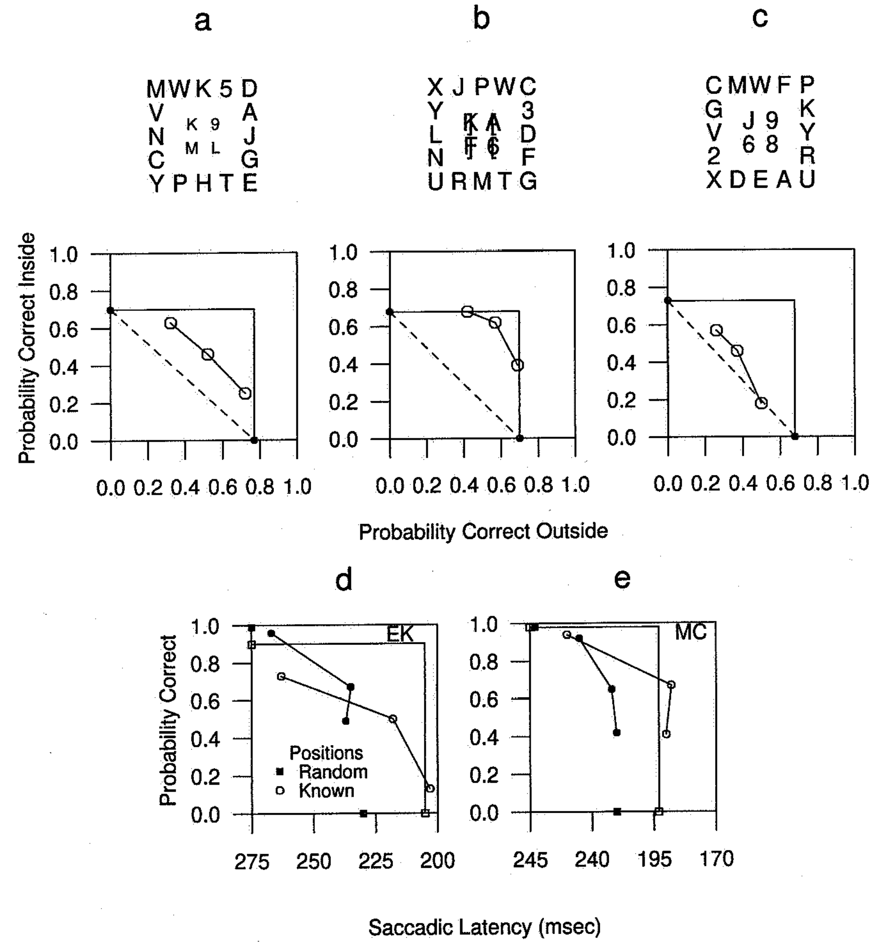


FIGURE 23 Observed AOCs for two concurrent visual search tasks and for concurrent cued report task and a cued saccade task. (a–c) Detection performance, respectively, of searching for a digit among letters in a small inner array and a large outer array; of searching for a digit among letters among a large masked inner array and a large outer array; and of searching for a letter among digits in a large inner array and of a digit among letters in a large outer array (Sperling & Melchner, 1978). Task interference is high when dealing simultaneously with small and large characters, or when the search targets and distractors are mapped oppositely in the two tasks. [Reprinted from Fig. 1 in G. Sperling and M. J. Melchner (1978). The attention operating characteristic: Examples from visual search. *Science, 202,* 316; with permission of the American Association for the Advancement of Science.] (d–e) AOCs for two subjects reporting a letter from one cued location and making a saccade to another (Kowler, Anderson, Dosher, & Blaser, 1995). Distance of the AOC from the ideal point demonstrates that letter identification and programming the target location for the saccade compete for the same resources. [Adapted from E. Kowler, E. Anderson, B. Dosher, and E. Blaser (1995). The role of attention in the programming of saccades. *Vision Research, 35, 13,* 11; with kind permission from Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington OX5 1GB, UK.]

Another example answers a number of classic questions about the extent to which movements of attention are coupled to movements of the eyes. This application of the methods also illustrates the use of two quite different task measurements to define an AOC. Using AOCs, Kowler, Anderson, Dosher, and Blaser (1995) demonstrated that looking for a target and moving the eye to a new location compete for the same visual attention resources. The two task measurements were percent correct in target identification at a cued location and aspects of saccadic performance, such as saccadic RT (msec) (Fig. 23d–e). When the target to be identified and the goal of the saccade are at different locations, there are attentional trade-offs in performance. Although attention can move independently of the eye when the eye is fixed, the eye cannot move independently of visual attention: the location of the upcoming saccade must be attended briefly (see also Remington, 1980; Hoffman & Subramaniam, 1995).

I. Neural Models of Attention

As illustrated in the previous discussion, theoretical mechanisms and empirical measurements of attention have both advanced significantly over the last several decades. A related strand of work is examining how mechanisms of attention are instantiated in the brain. There are a number of approaches to correlating behaviorally determined attention mechanisms with brain mechanisms: evaluating performance loss with brain lesions; measurement of brain activity during attentional processing; and the development of neural computational models of attention. A few brief examples illustrate the nature of current approaches.

Based largely on performance in brain-lesioned populations, Posner and colleagues (e.g., Posner & Petersen, 1990) claim several attentional subsystems: sensory orienting, signal detection, and vigilance subsystems. The orienting subsystem is thought to primarily support effects of spatial attention, such as those illustrated in Figure 15. Posner and Peterson suggest that a posterior subsystem (including parietal cortex, pulvinar and superior colliculus) mediates spatial orienting. Patients with lesions of these areas may exhibit abnormalities in patterns of movements of attention and of the eyes.

Event-related brain potentials (ERPs) provide one measure of brain activity. Hillyard and colleagues find that spatial focus of attention results in amplified or weakened responses to attended and unattended stimuli during even the first few milliseconds of ERP responses to the stimuli (Hillyard, Mangun, Woldorff, & Luck, 1995). They (Mangun & Hillyard, 1990) also find ERP correlates of attentional allocation in the later processing of more complex arrays. Observer's AOCs were measured under attentional instructions to favor the left, evaluate left and right equally, or favor the right portion of a letter array. ERP markers, especially long RT (350 ms and later) components, show amplitudes that correspond to target detection performance for left and right field letter arrays in an evoked potential AOC.

The relationship between behavioral models and neural substrates is just beginning to be elucidated. A deeper integration of biological and behavioral mechanisms is a dominant future direction.

IV. IMMEDIATE MEMORY

A. The Attentional Gate

Attention selects or gates information (regions, inputs) for subsequent processing by a variety of higher-order perceptual and cognitive processes.

Some selected inputs are further perceptually processed. Take two diverse examples: In visual search, attention may identify a subset of stimuli for subsequent evaluation (e.g., red items when searching for a red O among black Os and red Xs) (see Dosher, 1996; Wright & Main, 1996; and Hochberg, chap. 9, this volume, section IV.B). In motion perception, attentional selection may determine the perceived direction of motion of motion-ambiguous displays (Lu & Sperling, 1995a).

Primarily, however, attention gates information into memory. The strong relation between attention and immediate memory was recognized early. "We cannot deny that *an object once attended to will remain in memory,* whilst one inattentively allowed to pass will leave no traces behind" (James, 1890/1950, p. 427.) Immediate memory, memory for the order of very rapid stimuli, and even our inferences about sensory memory are partially determined by attentional gating.

B. Consciousness and Immediate Memory

In the early views of the introspecitionists, consciousness, attention, and immediate memory were intertwined (see Mandler, chap. 3, this volume). Objects that were attended were also conscious, although recently attended objects or objects at the edge of attention might fade from or fail to achieve consciousness. Objects or thoughts in primary or immediate memory were also conscious, or alternately, those items in consciousness also occupied primary memory (James, 1890/1904). In a recent related view (Cowan, 1993), short-term memory corresponds to currently or recently active long-term memory representations, and the currently active set is the focus of attention.

Based partly on introspection and partly on early attempts at experimentation, fundamental limits on information pickup were asserted by Wundt (1912/1924), Titchener (1919), and Woodworth (1921), who cite values between four and six items as the limit on the "scope," "span," or "range" of attention or consciousness. "Six simple impressions form the limit for the scope of attention" (Wundt, 1912/1924, p. 31). "The maximal range of the visual attention . . . comprises six impressions" (Titchener, 1919, p. 289). "He can tell four or five, and beyond that makes many mistakes" (Woodworth, 1921, p. 262). These values arose variously from experimental paradigms that today we would label subitization (counting or estimation of number from a single glance), sensory memory (reporting items from a briefly displayed array), and short-term or working memory (repeating items in order from a printed or spoken list).

Beginning the century with these intuitive notions of information limits and rudimentary experiments, theoretical progress has involved the recognition and isolation of functional subcomponents of attention and memory systems, and empirical progress has involved the development of paradigms and behavioral measurements. The development of models of memory structures, and of the component processes of encoding and retrieval for those structures, has paralleled the development of techniques for treating observable response accuracies and response times. These new models embody more detailed information flow diagrams, analogous to those seen for the processes in perception and attention.

C. Gating Brief Displays into Memory

When a display is presented only very briefly, attentional mechanisms may be the primary determinant of which information is encoded into short-term memory. Models of performance with brief displays distinguish perceptual processes, visual memory, and working memory structures (Fig. 19). Each structure imposes its own limits on the maintenance and report of incoming information.

Visual sensory memory, sometimes called iconic memory, is a short-lived (0.25–2 sec) representation of visual information that is eliminated by visual masking (Sperling, 1960). Experiments investigating visual sensory memory use briefly flashed displays, often several rows of letters. In uninstructed report conditions, four to five items can typically be reported. The reports represent unselective transfer in the sense that the particular items gated to working memory and report systems reflect stereotyped readout preferences—left to right, near the center. In instructed report conditions, a tone cues a particular row for report. When the instructional tone occurs, gating into working memory becomes selective. When a cue that appears *after* the offset of the brief stimulus is still useful in determining readout, there must be continued availability of information in visual sensory memory.

Accuracy of report (percent correct, or estimated number of letters available) systematically increases as a visual mask is delayed, and systematically decreases as the report cue is delayed after simulus offset, in a regular, interactive fashion. These systematic effects are well explained by computational models that describe the clarity of the sensory memory, the elimination of sensory memory by masking, and an attentional gating mechanism that transfers information from different locations in the display depending on whether the transfer is uninstructed or instructed by the cue (Gegenfurtner & Sperling, 1993). The acquisition of information from displays with complex time functions and contrast manipulations (e.g., blank intervals, intensity manipulations, etc.) reflects similar mechanisms of availability and information gating (Busey & Loftus, 1994; Loftus & Ruthruff, 1994). As in the case of flicker fusion in perception, these models make predictions about a wide variety of display manipulations.

As in the case of flicker fusion, a good model can provide an obvious explanation for an otherwise inexplicable set of findings. For example, attentional gating sometimes produces very distinctive illusory perceptions. In an experiment by Reeves and Sperling (1986) (as described in section III), two series of briefly displayed letters or digits appeared in different locations. The observer switched attention to the target location as soon as a cue appeared in the cuing location. In some conditions, observers were asked to report the first four items seen. For rapid rates of display (<200 ms per item), temporal order is not accurately or explicitly encoded, and paradoxical and systematic misperceptions of order occur. If the first item after the cue to switch were labeled A, and the subsequent items were labeled B, C, etc., observers might report that the first four items after the cue were, in order, D, E, C, F. This does not reflect guessing about order, since the report order is stable over trials.

The attentional gate explains this sort of illusory percept, as illustrated in Figure 24. At some delay following processing of the cue to switch attention to the target location, the attention gate opens and then closes, transferring information from the sensory representation into working memory and the report system. Information transfer reflects the amount of processing allowed by the gate: items that appear while the gate is fully open are transferred to memory with higher strength, whereas those that appear while the gate is only partially open are transferred to memory with lower strength. In the absense of explicit coding for order, perceived order reflects memory strength.

In sum, performances where brief displays prevent observers from extending information acquisition naturally over time are now understood as an interaction between several systems: perceptual processes resulting in a perceptual representation, a visual (or auditory) memory, and attentional gating of information into the more durable working memory system that supports verbal report. Ther are now models for a variety of display situations, and those models are computational and detailed, accounting for large bodies of parametric data.

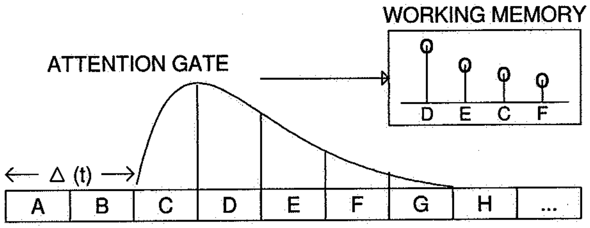


FIGURE 24 The attention gate determines the percept of stimulus order for very rapid displays where explicit order coding is deficient. A rapid sequence of items is shown along with the function for the attention gate. The area under the function determines item strength; for rapid presentation where order is not encoded explicitly, item strength determines perceived order. [Reprinted from Fig. 15 in A. Reeves and G. Sperling (1986). Attention gating in short-term visual memory. *Psychological Review, 93, 2,* 195; with permission of the American Psychological Association.]

D. Limitations of Immediate Memory

When information acquisition is not limited by brief displays, immediate memory itself limits performance. Beginning with the introspective notions of immediate or primary memory and consciousness (James, 1890/1950), ideas about short-term or working memory have shifted radically over the last several decades.

Miller's (1956) influential paper, "Magical number seven," was one of the first examples of the introduction of capacity limitations into psychological theory. That paper solidified the notion that short-term memory reflected a capacity limit on the number of items, and did not depend strongly on other properties of those items.

Miller focused on measurements of short-term memory capacity that required a serially presented set of items to be repeated immediately in the correct order, called immediate memory span. He rejected the notion that the memory span was influenced by the "information content." Information content was calculated based on an information-theoretic notion of predictability. In the information-theoretic sense, items drawn from small sets like the digits carry less information than items from very large sets, such as all English nouns. Miller claimed relatively small differences in measured span for items from these quite different materials sets. In short-term memory limits, an item was an item, so long as it corresponded to a known and labelable object. (Capacity for novel items is substantially reduced.)

This conception of short-term memory was further developed in the context of a system model (Atkinson & Shiffrin, 1968) distinguishing between sensory memory, short-term memory, and long-term memory, and proposing a set of control processes involved in transfer from one system to another. Taken together, these developments supported a conception of short-term memory as a memory system with a small number of "slots" capable of storing (or pointing to) items expressible as long-term memory codes.

E. Retrieval Limits of Immediate Memory

Task performance reflects not just representation in memory, but recovery from memory as well. Complete models of the memory system include processes of both storage and retrieval. Contemporaneous with the theoretical view that short-term memory was a system with a capacity of "seven plus or minus two" items, the question of the availability of those items became paramount. Were the items in short-term memory also in the focus of attention or consciousness? Were the items then immediately available, as suggested by introspectionist accounts, or were further limits imposed by the demands of recovery from memory?

In a ground-breaking study that reintroduced RT as a psychological measure of performance, Sternberg (1966) reasoned that accessibility of the items in short-term memory could be inferred from the time required to recognize an item. His claim was a startling one—that short-term memory was characterized by a limit in retrieval: Items were not immediately available, but rather were recognized by sequentially comparing a test item to all items held in short-term memory (Sternberg, 1966).

In his experiments, observers were shown a list of items one after the next (Fig. 25a). Each item was attended and transfered into short-term store. In response to a test item occurring 1–2 sec later, the observer pressed one key if the test item was a list member, and another if it was not. Mean response times increased linearly with the size of the memory load, or list length, for both list members and nonmembers. Critically, the added time per item was essentially identical whether the test item was a member or nonmember (Fig. 25b).

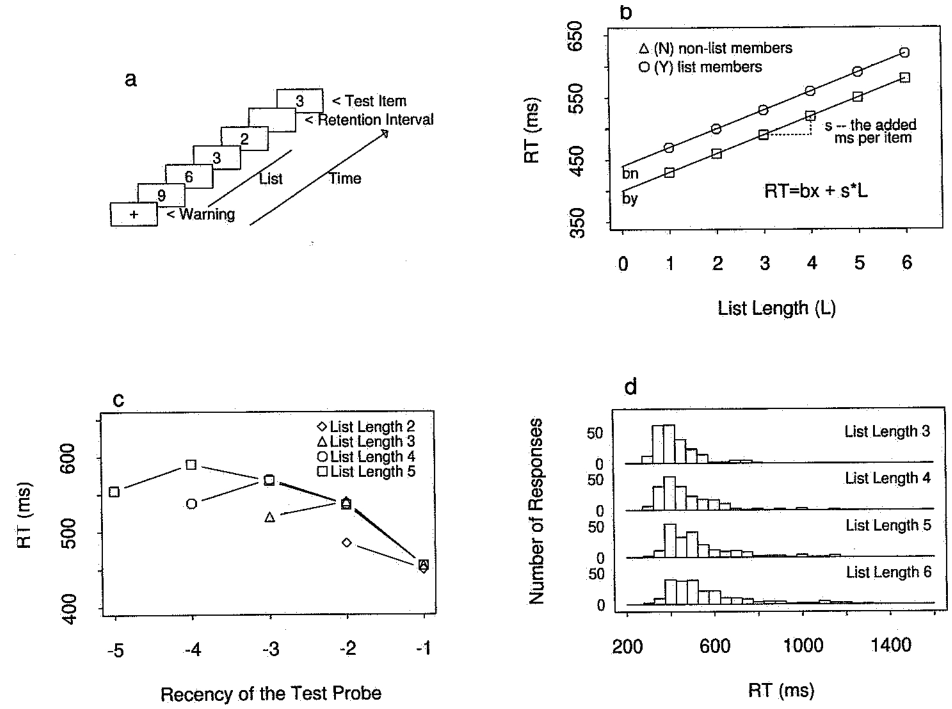


FIGURE 25 Measurement of retrieval time for items in immediate or short-term memory. (a) A paradigm from Sternberg (1966) for testing the availability of items in immediate memory. Observers decide whether the test probe is a list member or nonmember and press a response key. (b) Average response times (RT) increase approximately linearly with immediate memory load (list length) for both members and nonmembers. One view suggested that test probes were compared serially and exhaustively with each item in immediate memory. (c) Average RT for different list positions and memory loads (list lengths) strongly reflect recency. The abscissa indicates the position in the list of the test probe measured from the position of the test (the last list member is −1, the next to the last is −2, etc.). (d) RT distributions for different memory loads show that the differences are in the long tails of the distributions. The fastest times are the same and differentially reflect tests of the last list item (following Hockley, 1984). [Adapted by permission of Macmillan Reference USA, a Simon & Schuster Macmillan Company, from Figures 1 and 3 in B. Dosher and B. McElree (1992). Memory search: Retrieval processes in short term and long term recognition. *Encyclopedia of Learning and Memory* (L. R. Squire, Editor in Chief). Copyright © 1992 by Macmillan Publishing Company.]

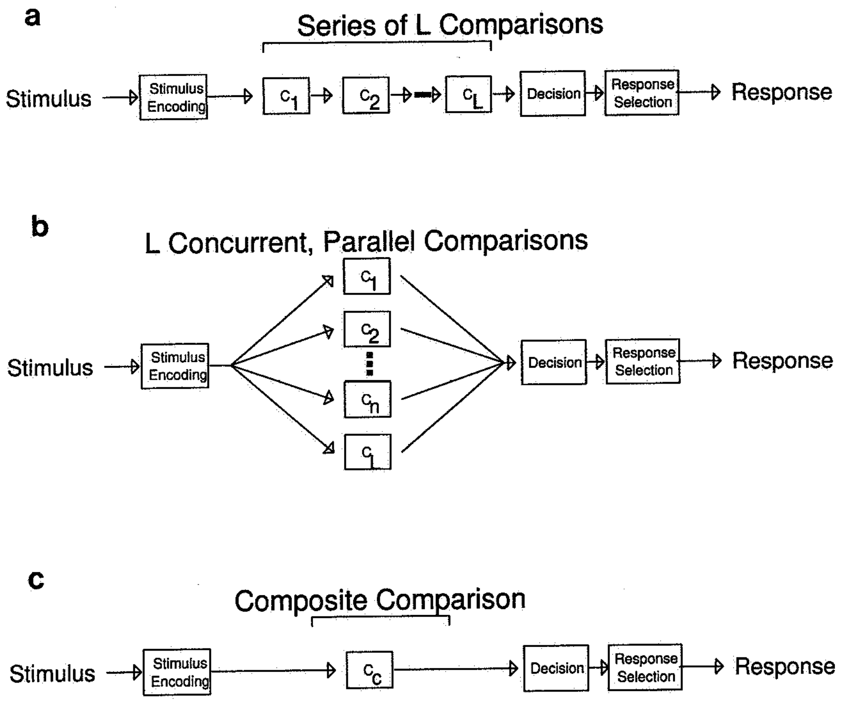


FIGURE 26 Serial and parallel retrieval mechanisms for comparing a test item with the memory representation of a list in memory. Certain parallel retrieval mechanisms can mimic serial mechanisms at the level of average response time for a list length (Townsend & Ashby, 1983). (a) a serial exhaustive comparison mechanism in which the test item is compared, in series, to each member of the memory list (Sternberg, 1966); (b) A parallel comparison mechanism in which the test item is compared at the same time with all elements in memory; (c) Recognition as direct access to a relevant memory in which all items in the list are stored in a single composite memory representation (McElree & Dosher, 1989). [Adapted by permission of Macmillan Reference USA, a Simon & Schuster Macmillan Company, from Figure 2 in B. Dosher and B. McElree (1992). Memory search: Retrieval processes in short term and long term recognition. *Encyclopedia of Learning and Memory* (L. R. Squire, Editor in Chief). Copyright © 1992 by Macmillan Publishing Company.]

Sternberg reasoned that an item was recognized as being in immediate memory by a serial and exhaustive comparison process (Fig. 26). The process was serial because each added memory item increased response time by an equal amount. The process was exhaustive because if comparisons terminated upon finding a match, then on average a list member should be found halfway through the search; this leads to a two-to-one relationship in slopes between recognition of nonmembers and members. Sternberg also argued that access of ordered information (say the item that came after the probe item in the list) also involved a sequential comparison process.

Taken together, the accuracy and the response time data suggested that short-term memory is item-limited and that items in the memory are not immediately available, but require a recovery process. The consequence of access to item information that involves serial and exhaustive processing is that adding items to short-term memory must be accompanied by increasing access times. Attractive though it may be, Sternberg's model is incorrect. The kinds of measurements needed to reject the model and the revised model of immediate memory limitations are considered next. These advances followed theoretical developments regarding the observable consequences of different processing architectures and methodological advancements allowing a more sophisticated measurement of the time course of retrieval.

F. Developing Reaction Time and Accuracy Methods

In Sternberg's method, only the size of the short-term memory load varied; the test display and the response were equivalent for all conditions. This design eliminated some of the complexities of prior attempts to interpret response times. This demonstration case was critical in the reintroduction of response time into the arsenal of empirical approaches in psychology (Sternberg, 1969).

However, accuracy and RT are not independent. They are simply two measurable aspects of the same behavior. In important theoretical advances during the 1970s and 1980s, models of response time *and* accuracy were developed, ambiguities in interpretation were documented, and elaborated response paradigms were invented (see Luce, 1986, for a review).

Townsend and Ashby (1983) articulated the equivalence, at the level of average response times, of certain parallel processing architectures—in which processes occur simultaneously—to serial processing architectures of the sort proposed by Sternberg. Distinguishing between serial and parallel architectures and their variants requires a closer examination of the data, possibly including the distributional properties of response times, the relation between response time and accuracy for responses, and the trade-off between processing time and accuracy when speed–accuracy relationships are explicitly manipulated.

G. The Revised Model of Short-Term Memory Retrieval

The initial conclusion that retrieval from immediate memory reflected a serial comparison process to items contained in the short-term memory buffer has been replaced with a revised model in which retrieval from immediate memory reflects a set of parallel comparisons with an active subset of memory items. Support for this revised model includes some clear illustrations of the development of RT and accuracy technologies.

Two sets of observations about immediate memory performance rule out serial and exhaustive comparisons as a retrieval limit: (a) RT and accuracy vary systematically with the item recency (e.g., Monsell, 1978) (Fig. 25c); and (b) the fastest responses are about the same for different memory loads (e.g., Hockley, 1984) (Fig.

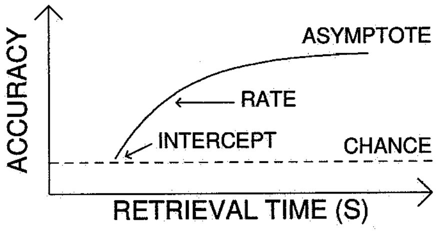


FIGURE 27 Idealized speed–accuracy trade-off functions measure the full time course of retrieval speed and limits in memory accuracy. The intercept measures the first point at which information is available, the rate of information accrual is measured by the fast-rising portion, and the asymptote measures the limits in memory accuracy. [Reprinted from Fig. 3 in B. A. Dosher (1982). Effect of sentence size and network distance on retrieval speed. *JEP: Learning, Memory and Cognition, 8, 3,* 176; with permission of the American Psychological Association.]

25d). Neither observation is consistent with an exhaustive serial comparison process. The RT differences over list position or recency coexist perfectly with the approximately linear increases in average RT as a function of memory load in Figure 25b (Dosher & McElree, 1992). The linear increases reflect the decreasing average recency of items from longer lists.

Elaborated response methods allow the direct measurement of increases in accuracy with additional processing times. In one method (Dosher, 1976, 1981; Reed, 1973), observers are interrupted at various times during recognition, and accuracy is measured as a dependent variable (Fig. 27). This yields functions relating accuracy to the time spent in processing, often called speed–accuracy trade-off (SAT) functions (see also Wickelgren, 1977). SAT data allow the estimation of when the first information is beginning to be available (intercept), how quickly information accrues over time (rate), and the limit on memory accuracy (asymptote).

These powerful elaborated response methods revealed that immediate memory access reflects a parallel, direct access process of retrieval for recognition. Figure 28 shows SAT functions for different list positions for list loads of 3, 4, 5, and 6 items (Dosher & McElree, 1992; McElree & Dosher, 1989). Information begins to be available at the same time for all memory loads and list positions, and information accrues at the same rate for all memory loads and list positions, except for the most recent item. The most recent item (immediate repetition) is more immediately available. Items in the memory load differ only in ultimate accuracy of memory. More recent items are most accurately recognized, and less recent items are successively less so. That is, Sternberg felt that all items in short-term memory were represented with equal accuracy, but that they were recovered by a serial scanning process. Instead, the availability of items is different for items in different positions of the list, with the most recent items being stronger, but items are accessed via a parallel or direct-access matching process.

These results led directly to very different conclusions about how items are stored in and retrieved from short-term memory. Following Miller, the item is taken as the

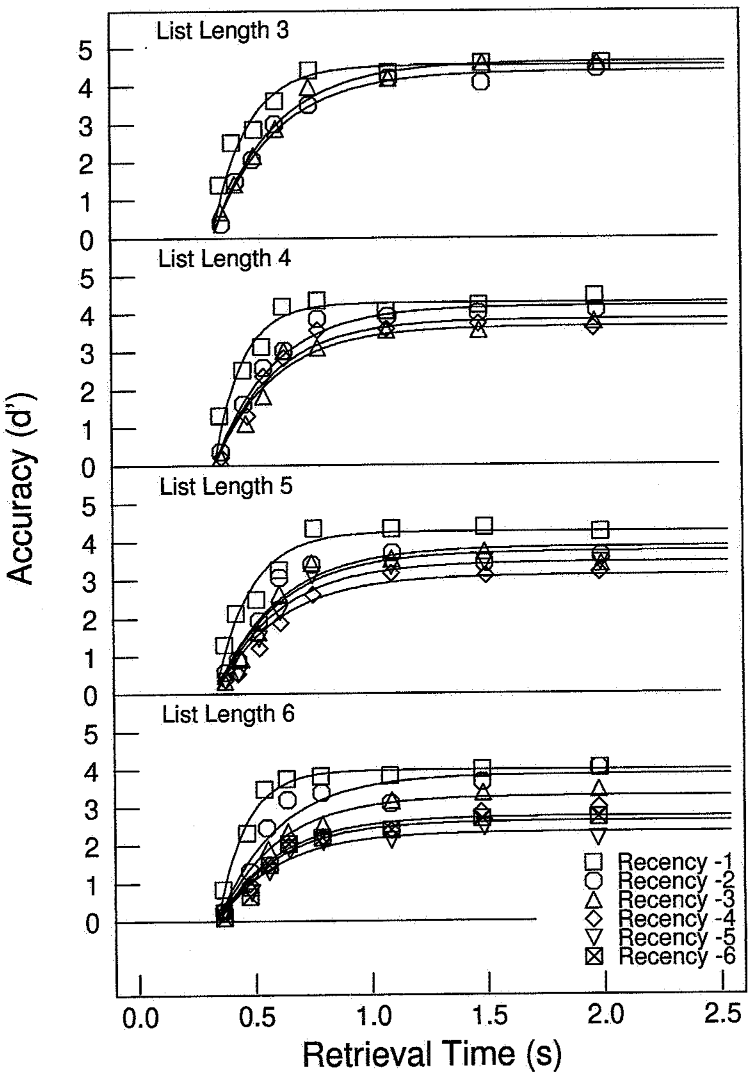


FIGURE 28 Full retrieval functions for immediate memory retrieval in recognition. (Data from McElree & Dosher, 1989). The retrieval speed is independent of memory load and list position, except that the most recent item is retrieved very quickly. Memory accuracy (ultimate availability) varies with recency. [Reprinted from Figs. 7 & 12 in B. McElree and B. A. Dosher (1989). Serial position and set size in short-term memory: The time course of recognition. *JEP: General, 118, 4,* (pp. 357 & 364); with permission of the American Psychological Association.]

unit of memory (rather than the information content carried by each item). However, unlike certain early conceptions of working memory, immediate memory in the revised model does not consist of a buffer of a certain size. Rather, items are activated or encoded as a consequence of attending those items (gating them into memory) during study. The limits in the number of items available for report reflect forgetting of items that were once attended and encoded into memory during stimulus input, but whose representations have since become weaker. The strength of the memory representations for items is decremented as new items are processed (due to specific interference) and as time passes (due to generalized processing interference).

Figure 29 shows a process model of short-term working memory and the interrelated modules of perceptual processing, attentional gating, and very short-term memory subsystems. Each of these componens, to a greater or lesser degree, can be expanded to show key subcomponents. The perceptual processing, attention gating, and the very short-term visual memory modules are shown only schematically (but

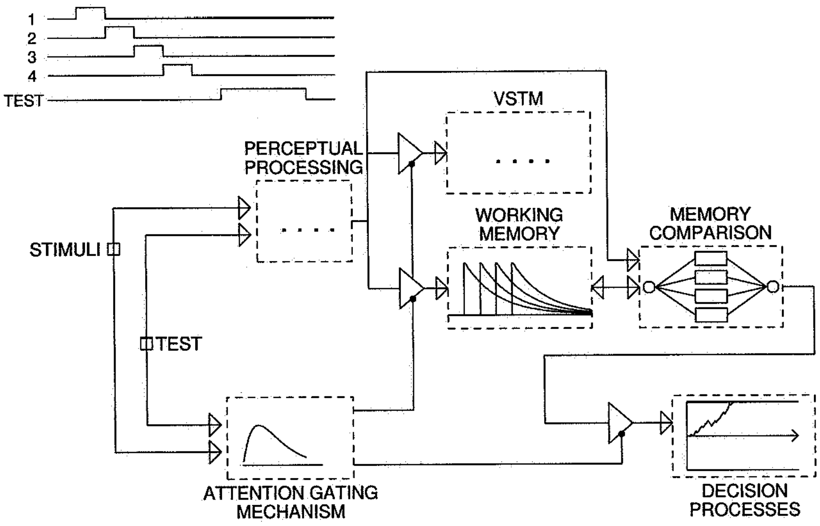


FIGURE 29 A direct access model of working memory, its dependence on attention gating, and the corresponding decision mechanism. Incoming stimulus items are shown on the upper left. Perceptual processing modules are merely sketched in; the relevant perceptual processing subcomponents depend on the task. An attention-gating process similar to that shown in Figure 19 routes stimulus information into very short-term memory (sensory memory), working memory, and the memory comparison and decision processes. Working memory consists of a set of memory traces activated at the time of study and subsequently undergoing loss of strength or activation as later items are processed or recalled. Memory comparison modules show parallel comparison operations as subcomponents. The output of the comparison module drives a decision module; this decision structure, combined with strength information from the comparison module, determines the accuracy and latency of recognition responses. (Reprinted with permission of B. Dosher.)

see earlier figures). Working memory is shown as a set of activated memory traces undergoing loss in activation or strength over time. In recognition, retrieval occurs by a parallel process of direct access or direct comparison of the test item with memory. The result of the comparison process(es) drives a decision unit with associated patterns of response times and accuracies.

The average item in a larger "memory load" is less available simply by virtue of the fact that some items in the larger loads will have been processed less recently than any item in a smaller load, and those less recent items suffer some loss. Again, this is shown as activated items in the working memory module undergoing loss. Immediate recognition paradigms largely reflect loss during the continuing process of list exposure. Limits on immediate memory measured by ordered recall or span reflect memory loss not just during the list presentation, but memory loss during rehearsal periods and during output as well (Dosher, 1994). Estimated spans depend on the stimuli (almost eight for digits, as low as three for nonsense trigrams or unlabelable visual forms), and may depend on various characteristics such as the degree of interference between stimuli (affecting forgetting rates) and the length of the articulatory code for the stimuli (Baddeley, 1986), which affects the time delays at output (Dosher & Ma, 1996).

H. The Development of Memory Models

In sum, we began the century with a set of empirically observed limits on verbal report and some fairly vague ideas about possible causes of those limits. At the end of this century, empirical and theoretical developments support a quite different and more specific understanding of a host of short-term processing limits. Various task limits are now understood to reflect limits in one of several different processing modules, including very short-term visual or auditory memory, attention gating, and working memory. The subcomponents of several of the major component modules are quite precisely known; process models support a wide class of both qualitative and quantitative predictions, only some of which have been touched on here.

V. CONCLUSIONS

This abbreviated review provided an overview of the development of experimental methodology and theory during the 20th century with examples chosen from three areas of psychology: computational models of visual motion perception, visual attention, and short-term memory systems. The developments in these areas have strong elements of similarity. In each case, the century begins with a set of base observations—some empirical, many introspective—and with some vague, often competing, verbal notions about how to characterize the corresponding mental mechanisms. In each case, a period of rapid development and refinement began after World War II and has continued to the present, resulting in relatively complex process models of those mechanisms, coupled with the introduction of elaborated empirical methods for testing and analysis. In psychology and biology, unlike classical physics, an increase in knowledge is normally accompanied by increased complexity of theory (Sperling, 1997). Simple models have been systematically replaced by more complex models. A model component called simply "memory" expands into "coding, storage, and retrieval," and each of these processes is further expanded as both the control structures and the internal structures are made explicit. In Figure 13, a component that in an earlier model might simply have been called "motion detection" is expanded into three motion-direction systems involving five separate motion–energy components and six separate texture-grabber components, each of which again expands into numerous subcomponents. It is hoped that this explosive increase in complexity will eventually bring information-processing architectures into convergence with neural-processing architectures, which are undergoing their own parallel explosive increase in complexity.

Commentaries on progress in psychology often include a quote from James or Wundt to illustrate the prescience of the early psychologists, and to implicitly suggest that we know little more now than was known in 1900. It should be abundantly clear from this review how misguided this view is. The problems of vision, attention, and memory have not been resolved, nor are they likely to be resolved in the next century. But our understanding of these problems, the data that are now available, and the kinds of theories that are under consideration are enormously different from and improved over those that were available at the end of the 19th century.

In physics, one of the fruits of improved knowledge of atomic structure was an atomic bomb. Knowledge about visual processes certainly has been helpful in the design of photographic media and video communication systems but, on the whole, improved understanding of human information processing has not yet yielded any practical fruits with the impact of an atomic bomb. The lure of practical discovery to be made in the future has diverted considerable resources to the study of human information processing. Perhaps there are great practical rewards awaiting. Perhaps the study of the mechanisms of the human mind will continue to command our attention simply because of its intrinsic interest.

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