proved superior to intensive behavioral treatment alone while medication management alone was not (The MTA Cooperative Group 1999). Most clinicians recommend a combination of treatments. The use of behavior management in treatment may not have a direct effect on the underlying biological basis of ADHD. It is possible that the relearning that a child experiences through behavior management allows for modification of underlying neural networks. This topic is an important one for future research.

4. Conclusion

ADHD is a complex and prevalent neurobehavioral disorder that presents in childhood and may persist into adulthood. The condition frequently co-exists with other behavioral and cognitive disorders. Evidence of a biological basis for the disorder is mounting through the use of neural imaging studies and genetic analysis. Conceptualizing the disorder as a mismatch of the child's underlying personal characteristics and the environment does not necessarily negate the possibility of a biological basis for ADHD. Management of the disorder includes stimulant medications that operate on neural pathways putatively involved in the etiology of the disorder. Behavior management may operate at the psychosocial level but have an influence on neurological organization.

See also: Anxiety Disorder in Children; Attention-deficit/Hyperactivity Disorder (ADHD); Attention, Neural Basis of; Child and Adolescent Psychiatry, Principles of; Developmental Psychopathology: Child Psychology Aspects; Ergonomics, Cognitive Psychology of; Neurotransmitters; Prefrontal Cortex Development and Development of Cognitive Function

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H. M. Feldman

Attention: Models

'Attention' is a general term for selectivity in perception. The selectivity implies that at any instant a perceiving organism focuses on certain aspects of the stimulus situation to the exclusion of other aspects. In this article, theoretical models of attention are reviewed and their development is described.

1. Theoretical Beginnings

The first modern theory of attention was the *filter* theory of Broadbent (1958) (see Figure 1). In this theory, information flows from the senses through many parallel input channels into a short-term mem-

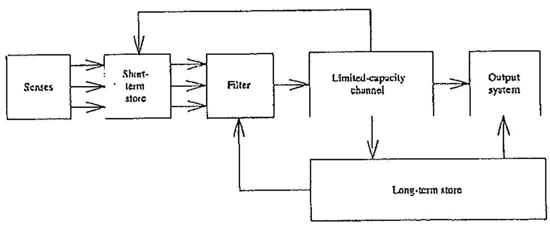

Figure 1
Flow diagram illustrating the filter theory of Broadbent (1958)

ory store. The short-term store can hold the information for a period of the order of seconds. Later in the system there is a *limited-capacity channel*, whose capacity for transmitting information is much smaller than the total capacity of the parallel input channels. Between the short-term memory and the limited-capacity channel is a selective filter which acts as an all-or-none switch that selects information from just one of the parallel input channels at a time.

Broadbent (1958) defined an input channel as a class of sensory events that share a simple physical feature (e.g., a position in auditory space). Except for analysis of such features, stimuli on unattended channels should not be perceived. This conjecture accounted for results of studies in the early 1950s by E. C. Cherry on the ability to attend to one speaker in the presence of others (the *cocktail party problem*). Cherry asked his subjects to repeat a prose message while they heard it, rather than waiting until it finished. When the message to be repeated (*shadowed*) was presented to one ear while a message to be ignored was presented to the other ear (*dichotic* presentation), subjects typically were unable to recall any words from the unattended message.

Later studies by Moray (1969) and others showed that subjectively important words (e.g., the subject's own name) tended to be recognized even if presented on the nonshadowed channel. To accommodate such findings, A. M. Treisman developed a variation of filter theory in which the filter operates in a graded rather than an all-or-none fashion. In Treisman's *attenuation* theory, unattended messages are weakened rather than blocked from further analyses. Both selected and attenuated messages are transmitted to a pattern recognition system with word recognition units. Because thresholds of recognition units for important words are lowered, important words tend to be recognized even if appearing in attenuated messages.

In the filter theories of Broadbent and Treisman, attentional selection occurs at an earlier stage of processing than pattern recognition. Such theories are called *early-selection* theories. In *late-selection* theories, attentional selection occurs later in processing than pattern recognition. The first late-selection theory was outlined by J. A. Deutsch and D. Deutsch in 1963. Deutsch and Deutsch argued that the early filtering mechanism in Treisman's theory was redundant. They proposed that attended and unattended messages receive the same amount of analysis by the pattern recognition system. However, after a stimulus has been recognized, the importance of the stimulus is retrieved and the stimulus with the greatest importance is selected for further processing, including conscious awareness.

The theories of Broadbent, Treisman, and Deutsch and Deutsch set the stage for the development of more specific, quantitative models of attention. Most of these models were based on experimental findings on visual processing: data on our ability to *divide* attention between multiple, simultaneous targets and data on our ability to *focus* attention on targets rather than distractors.

2. *Serial Models*

In serial models of attention, only one stimulus is attended at a time. This section examines the development from simple serial models to selective serial models.

2.1 *Simple Serial Models*

In visual *whole-report* experiments by G. Sperling in the early 1960s, subjects were instructed to report as many letters as possible from a briefly exposed array of unrelated letters followed by a pattern mask. The number of correctly reported letters depended on the stimulus-onset asynchrony (SOA) between the letter array and the mask. Corrected for guessing, the score appeared to be zero when the SOA was below a certain threshold. As the SOA exceeded the threshold, the mean score initially increased at a high rate of about one letter per 10–15 ms. The mean score leveled off as it approached a value of about four letters or the number of letters in the stimulus, whichever was smaller.

Sperling proposed a simple serial model to account for the initial strong and approximately linear increase in mean score as SOA exceeded threshold. By this model, the subject encodes one letter at a time, requiring 10–15 ms to encode a letter. The serial encoding is interrupted when the stimulus is terminated by the mask or when the number of encoded letters reaches the immediate memory span of the subject.

Simple serial models for *visual search* were developed in the 1960s by W. K. Estes, S. Sternberg, and others. In most experiments on visual search, the subject is instructed to indicate 'as quickly as possible' whether or not a certain type of target is present in a display. Positive (target present) and negative (target absent) reaction times are analyzed as functions of the number of items in the display (*display set size*).

By a simple serial model, items are scanned one by one. As each item is scanned, it is classified as a target or as a distractor. A negative response is initiated if and when all items have been scanned and classified as distractors. Thus, the number of items processed before a negative response is initiated equals the display set size, N. Accordingly, the rate of increase in mean negative reaction time as a function of display set size equals the mean time taken to process one item, Δt.

In a *self-terminating* serial search process, a positive response is initiated as soon as a target is found. As the order in which items are scanned is independent of

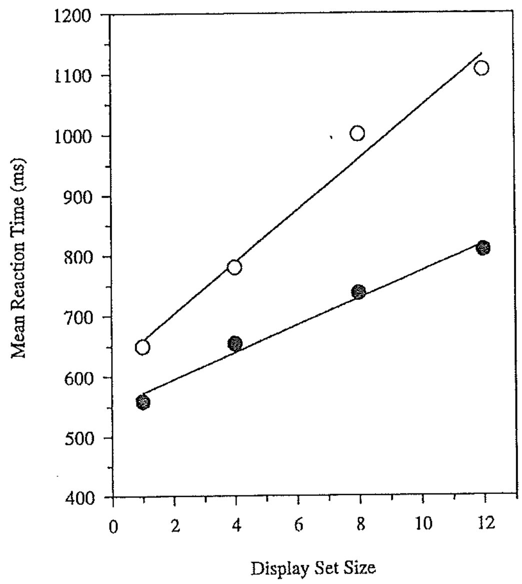

Figure 2
Positive and negative mean reaction times as functions of display set size in visual search for a T in one of four possible orientations among similarly rotated Ls (The observed reaction times were read from Wolfe 1994, Figure 1b. The slopes of the fitted least squares lines are 22 ms/item and 43 ms/item, respectively)

their status as targets vs. distractors, the number of items processed before a positive response is initiated varies randomly between 1 and N and averages $(1+N)/2$. Thus, the rate of increase in mean positive reaction time as a function of display set size equals one half of the mean time taken to process one time, $\Delta t/2$. A representative pair of search reaction time functions with a positive-to-negative slope ratio of about 1:2 is illustrated in Fig. 2.

A. M. Treisman has introduced a distinction between feature and conjunction search. In *feature* search, the target possesses a simple physical feature (e.g., a particular color, shape, or size) not shared by any of the distractors. For example, the target can be a red T among black Ts. In *conjunction search*, the target differs from the distractors by possessing a predesignated conjunction of physical features (e.g., both a particular color and a particular shape), but the target is not unique in any of the component features of the conjunction (i.e., in color or in shape). For example, the target can be a red T among black Ts and red Xs.

Many experiments on conjunction search have yielded positive and negative mean reaction times that are approximately linear functions of display set size with substantial slopes and positive-to-negative slope ratios of about 1:2. This pattern conforms to predictions from simple self-terminating serial models, and Treisman and co-workers have concluded that conjunction search is performed by scanning items one at a time. Experiments on feature search with low target-distractor discriminability have yielded a similar pattern of results.

2.2 *Selective Serial Models*

In selective serial models, items in the stimulus display are attended one at a time, but the sequential order in which items are attended depends on their status as targets vs. distractors: When a target and a distractor compete for attention, the target is more likely to win.

The first selective serial model of visual search was published by J. E. Hoffman in 1978. It was motivated by findings from C. W. Eriksen's laboratory on the time taken to shift attention in response to a visual cue. The findings cast doubt on the notion that attention can be shifted from item to item at the high rates presumed in simple (nonselective) serial models of processing.

In Hoffman's model, visual search is a two-stage process in which a parallel evaluation of the entire stimulus display guides a slow serial processor. The parallel evaluation is preattentive and quick, but error prone. For each item in the display, the outcome is an overall measure of the similarity between this item and the prespecified targets. Items are transferred one by one to the second stage of processing. The serial transfer mechanism is slow (about one item per 100 ms), but it makes search efficient by transferring items in order of decreasing overall similarity to the prespecified targets. Thus, if there is a target in the display, the target is likely to be among the first items that are transferred to the second stage of processing.

J. M. Wolfe, K. R. Cave, and S. L. Franzel have proposed a selective serial model, which they called *Guided Search* (cf. Wolfe 1994). The model combines elements of the two-stage model of Hoffman with elements of the *feature integration* theory of Treisman and co-workers (cf. Treisman 1988). As in feature integration theory, simple stimulus features such as color, size, and orientation are registered automatically, without attention, and in parallel across the visual field. Registration of objects (items defined by conjunctions of features) requires a further stage of processing at which attention is directed serially to each object. As in Hoffman's model, the outcome of the first, parallel stage of processing guides the serial processing at the second stage. The guidance works as follows.

For each feature dimension (e.g., color, size, or orientation), the parallel stage generates an array of activation values (attention values). The array forms a map of the visual field. Each activation value is a sum of a bottom-up and a top-down component. For a particular location within a map for a given feature dimension, the bottom-up component is a measure of differences between the value of the feature at that location and values of the same feature at other locations. The top-down component for a feature dimension at a particular location is a measure of the difference between the value of the feature at that location and the target value for the feature dimension. After activations have been calculated in separate maps for each feature dimension, they are summed across feature dimensions to produce a single overall activation map. In simulations, a certain level of gaussian noise is also added at each location. The final overall activation values represent the evaluation given by the parallel stage of how likely the stimulus at each location is to be the target.

The serial stage processes the items one by one in order of decreasing activation in the overall activation map. Each item it processes gets classified as a target or as a distractor. The serial processing continues until a target is found or until all items with activations above a certain value have been processed.

The guided search model accounts for many findings from experiments on visual search. It was motivated, in particular, by demonstrations of fast conjunction search. Some demonstrations of fast conjunction search are accommodated by assuming that for some feature dimensions, top-down control is very effective. Other demonstrations are accommodated by assuming that in some subjects, the level of gaussian noise is very low.

3. *Parallel Models*

In parallel models of attention, several stimuli can be attended at the same time. This section examines the development from simple parallel (independent-channels) models to limited-capacity parallel models and race-based models of selection.

3.1 *Independent Channels Model*

The first detailed parallel model of visual processing of multi-item displays was the Independent Channels model developed by C. W. Eriksen and co-workers in the 1960s. It was based on the assumption that display items presented to separated foveal areas are processed in parallel and independently up to and including the stage of pattern recognition. The assumption implies that the way in which a display item is processed is independent of random variations in the way in which other display items are processed. It also implies that the way in which an item is processed is independent of display set size.

The notion of independent channels (*unlimited-capacity parallel processing*) is used mainly to account for cases in which visual search is highly efficient (small effects of display set size). This includes cases of feature search with high target-distractor discriminability. In a theory proposed by R. M. Shiffrin and W. Schneider in 1977, it also includes cases of search for more complex targets such as particular alphanumeric characters when subjects have been trained consistently in detecting those particular targets.

In the theory of Shiffrin and Schneider, slow, serial, *controlled search* for particular items can develop into fast, parallel *automatic detection* of the same items. Automatic detection occurs without subject control and without stressing the capacity limitations of the system. The development of automatic detection presupposes that the mapping of stimuli to responses is consistent rather than varied over trials.

3.2 *Evidence from Automatic Interference*

Empirical support for the assumption of parallel processing has come from demonstrations by Eriksen and others of *Stroop-like interference* in processing of multi-item displays. In the original task developed by J. R. Stroop in the 1930s, subjects are asked to name the color of the ink used to print a word. The *Stroop effect* denotes the fact that the task is more difficult when the word itself is the name of a different color (e.g., *red* printed in blue) than when the word does not refer to a color or refers to the color shown by the ink (*blue* printed in blue).

The original Stroop task concerns selective attention to a particular feature of an item (*featural attention*). In the *flankers task* of Eriksen, subjects are asked to focus attention on a target presented in a known spatial location (*spatial attention*). Usually, the target is a letter presented at fixation, and the subject is required to make a speeded binary classification of the letter (e.g., move a lever in one direction if the letter is a T or a K but in the opposite direction if the letter is an S or a C). The target is flanked by letters that should be ignored. However, the task is more difficult when the flankers are *response-incompatible* with the target (Ss or Cs flanking a T) than when the flankers are *neutral* (e.g., Xs flanking a T) or *response-compatible* with the target (Ts or Ks flanking a T). Eriksen suggested that the flankers are processed in parallel with the target up to and including the stage of pattern recognition.

3.3 *Limited-capacity Models*

The linear relations between mean reaction time and display set size predicted by simple serial models are hard to explain by parallel models with independent channels (unlimited-capacity parallel models). However, the linear relations can be explained by parallel models with *limited processing capacity*. In 1969, the following example was published independently by J. T. Townsend and R. C. Atkinson, and his co-workers.

Consider a display of N items that are processed in parallel. Let the processing speed for an item (technically, the 'hazard function' for the processing time of the item; cf. Townsend and Ashby 1983) equal the amount of processing capacity devoted to that item, and suppose the total processing capacity spread across items in the display is a constant C. Then the time taken to complete processing of the first item is exponentially distributed with rate parameter C. Suppose that when the first completion occurs, the processing capacity is redistributed among the remaining N–1 items. Then the time from the first to the second completion is exponentially distributed with the same rate parameter C. Let the process repeat until all N items have been completed. If so, then the mean time taken to complete processing of the N items increases linearly with display set size N.

In 1977, M. L. Shaw and P. Shaw proposed a model for *Optimal Allocation of Cognitive Resources to Spatial Locations* that showed how limited-capacity models could be extended to situations in which the probability that a target occurs at a given location varies across display locations. In such situations, capacity was assumed to be allocated and reallocated among display items so that performance is optimized.

In the model of Shaw and Shaw, attention can be split among noncontiguous locations in the visual field. Processing capacity can be allocated to several separated locations at the same time. C. W. Eriksen and co-workers have proposed an alternative conception, a *zoom lens* model of the visual attentional field. In this conception, the attentional field can vary in size from an area subtending less than 1° of visual angle to the full size of the visual field. Because total processing capacity is limited, the amount of processing capacity allocated to a given attended location decreases as the size of the attentional field increases. However, the attentional field cannot to be split among noncontiguous locations. Direct tests of this hypothesis have been attempted, but the issue is still open.

3.4 Race Models of Selection

In race models of selection from multi-item displays, display items are processed in parallel and attentional selection is made of those items that first finish processing (the winners of the race). Thus, selection of targets rather than distractors is based on processing of targets being faster than processing of distractors.

In 1988, H. Shibuya and C. Bundesen proposed a fixed-capacity independent race model (*FIRM*). The model describes the processing of a stimulus display as follows. First, an *attentional weight* is computed for each item in the display. The weight is a measure of the strength of the sensory evidence that the item is a target. Then the available processing capacity (a total amount of C items/s) is distributed across the items in proportion to their weights. The amount of processing capacity that is allocated to an item determines how fast the item can be encoded into visual short-term memory (VSTM). Finally, the encoding race between the items takes place. The time taken to encode an item is assumed to be exponentially distributed with a rate parameter equal to the amount of processing capacity that is allocated to the item. The items that are selected (i.e., stored in VSTM) are those items whose encoding processes complete before the stimulus presentation terminates and before VSTM has been filled up.

Detailed tests of FIRM have been made in *partial-report* experiments in which subjects report as many targets as possible from a briefly exposed display showing a mixture of targets (e.g., red letters) and distractors (e.g., black letters). FIRM has provided accurate accounts of effects of selection criterion, exposure duration, and numbers of targets and distractors in the display (see Fig. 3).

3.5 Theory of Visual Attention (TVA)

The theory of visual attention (*TVA*) proposed by Bundesen (1990) is a generalization of FIRM. In TVA, both visual recognition and selection of items in the visual field consist in making *perceptual categorizations* (i.e., encoding categorizations into VSTM). When one makes the perceptual categorization that a given item belongs to a certain category, the item is said (a) to be selected, and (b) to be recognized as a member of the category.

Recognition and selection depend on the outcome of a biased race between possible perceptual categorizations. The rate at which a possible categorization ('item x belongs to category i') is processed increases with (a) the strength of the sensory evidence that supports the categorization, (b) the subject's bias for assigning objects to category i, and (c) the attentional weight of item x. When a possible categorization completes processing, the categorization enters VSTM if memory space is available there. The span of VSTM is limited to about four items. Competition between mutually incompatible categorizations of the same item are resolved in favor of the first-completing categorization.

TVA accounts for many findings on single-stimulus recognition, whole report, partial report, search, and detection. The theory has been extended by G. D. Logan to encompass aspects of perception and memory as well as attention.

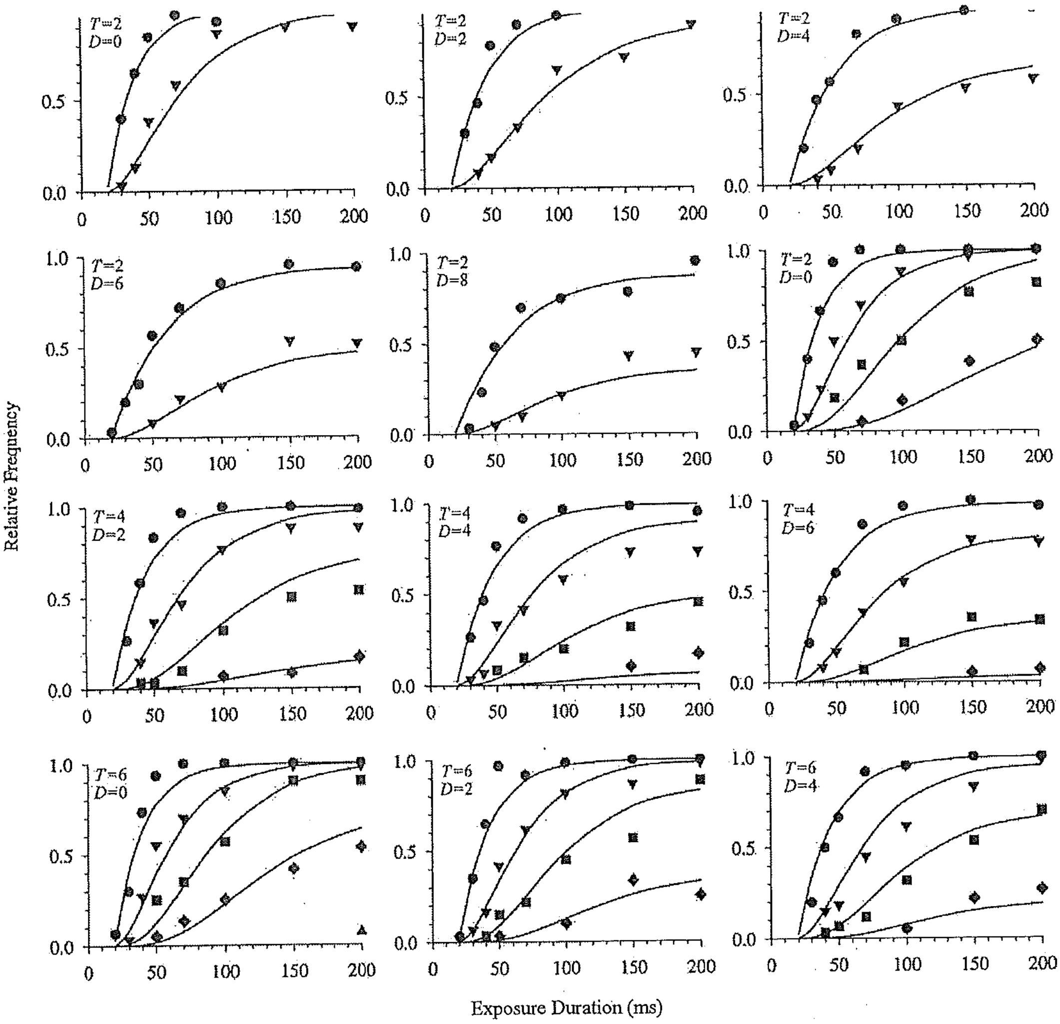

Figure 3
Relative frequency of scores of *j* or more (correctly reported targets) as a function of exposure duration with *j*, number of targets *T*, and number of distractors *D* as parameters in partial report of digits among letters (Parameters *T* and *D* vary between panels. Parameter *j* is 1 (circles), 2 (downward pointing triangles), 3 (squares), 4 (diamonds), or 5 (upward pointing triangle). Smooth curves represent a theoretical fit to the data by the fixed-capacity independent race model (FIRM). For clarity, observed frequencies less than 0.02 were omitted from the figure. Source: Visual selection from multi-element displays: Measuring and modeling effects of exposure duration by Shibuya and Bundesen 1988, *Journal of Experimental Psychology: Human Perception and Performance*, p. 595. ©American Psychological Association)

4. *Neural Network Models*

Formal models like TVA are highly abstract. Neural network modeling is an attempt to theorize at a level that is closer to neurobiology. In neural network models, information processing consists in a flow of activation through a network of neuronlike units that are linked together by facilitatory and inhibitory connections.

A simple way of implementing attentional selection in a neural network is by arranging the connections so that (a) units representing mutually compatible categorizations of the same item facilitate each other but (b) units representing incompatible categorizations inhibit each other, and (c) units representing categorizations of different items also inhibit each other. Search for a red target, for example, can then be done by preactivating units representing redness. If a red target is present, the preactivation will directly facilitate the correct categorization of the target with respect to color. Indirectly the preactivation will facilitate categorizations of the target with respect to other properties than color but inhibit categorizations of any other items than the target (*integrated competition*; Duncan 1996).

Many neural network models of attention have appeared since the mid-1980s. Good examples are the model for selective attention and pattern recognition by K. Fukushima, the multiple object recognition and attentional selection model (MORSEL) of Mozer (1991), the selective attention model (SLAM) of R. H. Phaf, A. H. C. van der Heijden, and P. T. W. Hudson, and the search via recursive rejection model (SERR) of G. W. Humphreys and H. J. Müller.

5. Conclusion

Current models of attention have sprung from the theoretical framework developed by Broadbent in the 1950s. The first detailed models of visual attention were the serial scanning models of Sperling, Estes, and others and the independent channels model developed by Eriksen and co-workers. Early tests of the models brought important discoveries but no simple resolution of the serial vs. parallel processing issue. Attempts to integrate the empirical findings led to selective serial models and to parallel models with differential attentional weighting, including race models of selection. No extant model has accounted for the full range of empirical findings but substantial progress has been made.

See also: Attention and Action; Attention: Models; Attention: Multiple Resources; Broadbent, Donald Eric (1926–93); Dual Task Performance; Interference and Inhibition, Psychology of; Working Memory, Neural Basis of; Working Memory, Psychology of

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C. Bundesen

Attention: Multiple Resources

Among the diverse conceptions of attention, a major one considers that selective attention is a consequence of the limited-capacity resources of our mental proces-

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