2

HUMAN INFORMATION PROCESSING: AN OVERVIEW FOR HUMAN–COMPUTER INTERACTION

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> It is natural for an applied psychology of human–computer interaction to be based theoretically on information-processing psychology.
> —Card, Moran, and Newell (1983, p. 13)

Human–computer interaction (HCI) is fundamentally an information processing task. In interacting with a computer, the human has specific goals and subgoals in mind. The user initiates the interaction by giving the computer commands that are directed toward accomplishing those goals. The commands may activate software programs designed to allow specific types of tasks, such as word processing or statistical analysis, to be performed. The resulting computer output, typically displayed on a screen, must provide adequate information for the user to complete the next step, or the user must enter another command to obtain the desired output from the computer. The sequence of interactions to accomplish the goals may be long and complex, and several alternative sequences, differing in efficiency, may be used to achieve these goals. During the interaction, the user is required to identify displayed information, select responses based on the displayed information, and execute those responses. The user must search the displayed information and attend to the appropriate aspects of it. She or he must also recall the commands and resulting consequences of those commands for different programs, remember information specific to the task that is being performed, and make decisions and solve problems during the process. For the interaction between the computer and user to be efficient, the interface must be designed in accordance with the user's information processing capabilities.

HUMAN INFORMATION PROCESSING APPROACH

The rise of the human information processing approach in psychology is closely coupled with the rise of the fields of cognitive psychology, human factors, and human engineering. Although research that can be classified as falling within these fields has been conducted since the last half of the 19th century, their formalization dates back to World War II (see Hoffman & Deffenbacher, 1992). As part of the war efforts, experimental psychologists worked along with engineers on applications associated with using the sophisticated equipment being developed. As a consequence, the psychologists were exposed not only to applied problems, but also to the techniques and views being developed in areas such as communications engineering. Many of the concepts from engineering, such as the notion of transmission of information through a limited capacity communications channel, were seen as applicable to analyses of human performance.

The human information processing approach is based on the idea that human performance, from displayed information to a response, is a function of several processing stages. The nature of these stages, how they are arranged, and the factors that influence how quickly and accurately a particular stage operates, can be discovered through appropriate research methods. It is often said that the central metaphor of the information processing approach is that a human is like a computer (e.g., Lachman, Lachman, & Butterfield, 1979). However, even more fundamental than the computer metaphor is the assumption that the human is a complex system that can be analyzed in terms of subsystems and their interrelation. This point is clearly evident in the work of researchers on attention and performance, such as Paul Fitts (1951) and Donald Broadbent (1958), who were among the first to adopt the information processing approach in the 1950s.

The systems perspective underlies not only human information processing but also human factors and HCI, providing a direct link between the basic and applied fields (Proctor & Van Zandt, 1994). Human factors in general, and HCI in particular, begin with the fundamental assumption that a human–machine system can be decomposed into machine and human subsystems, each of which can be analyzed further. The human information processing approach provides the concepts, methods, and theories for analyzing the processes involved in the human subsystem. Posner (1986) states, "Indeed, much of the impetus for the development of this kind of empirical study stemmed from the desire to integrate description of the human within overall systems" (p. V-6).

In the first half of the 20th century, the behaviorist approach predominated in psychology, particularly in the United States. Within this approach, numerous sophisticated theories of learning and behavior were developed that differed in many details (Bower & Hilgard, 1981). However, the research and theories of the behaviorist approach tended to minimize the emphasis on cognitive processes and were of limited value to the applied problems encountered in World War II. The information processing approach was adopted because it provided a way to examine topics of basic and applied concern such as attention that were relatively neglected during the behaviorist period. It continues to be the dominant approach in psychology, although contributions have been made from an alternative approach called the ecological perspective. The ecological perspective emphasizes the structure of the environment and the constraints of the environment on the interactions of the human with it. This perspective has had a recent impact on human factors through what is called ecological interface design (Flach, Hancock, Caird, & Vicente, 1995). We view the basic and applied research from the ecological perspective as valuable and complementary to that from the information processing perspective, but will not go into it in detail in this chapter.

Within HCI, human information processing analyses are used in two ways. First, empirical studies evaluate the information processing demands imposed by various tasks in which a human uses a computer. Second, computational models are developed to characterize human information processing when interacting with computers, and predict human performance with alternative interfaces. In this chapter, we survey methods used to study human information processing and summarize the major findings and the theoretical frameworks developed to explain them.

INFORMATION PROCESSING METHODS

Any theoretical approach makes certain presuppositions and tends to favor some methods and techniques over others. Information processing researchers have used behavioral and, to an increasing extent, psychophysiological measures, with an emphasis on chronometric (time-based) methods. There also has been a reliance on flow models that are often quantified through computer simulation or mathematical modeling.

Signal Detection Methods and Theory

One of the most useful methods for studying human information processing is that of signal detection (Macmillan & Creelman, 1991). In a signal detection task, some event is classified as a signal, and the subject's task is to detect whether the signal is present. Trials on which it is not present are called noise trials. The proportion of trials on which the signal is correctly identified as present is called the hit rate, and the proportion of trials on which the signal is incorrectly identified as present is called the false alarm rate. By using the hit rate and false alarm rate, it is possible to evaluate whether the effect of a variable is on discriminability or response bias.

Signal detection theory is often used as the basis for analyzing data from such tasks. This theory assumes that the response on each trial is a function of two discrete operations: encoding and decision. On the occurrence of the trial event, the subject collects the information presented and decides whether this information is sufficient to warrant a *signal present* response. The sample of information is assumed to provide a value along a continuum of evidence states regarding the likelihood of the signal being present. The noise trials form a probability distribution of states, as do the signal trials. The decision that must be made on a trial can be characterized as whether the event is from the signal or noise distribution. The subject is presumed to adopt a criterion value of evidence above which he or she responds *signal present* and below which he or she responds *signal absent*.

In the simplest form, the distributions are assumed to be normal and equal variance. In this case, a measure of detectability or discriminability, d', can be derived. This measure represents the difference in the means for the signal and noise distributions in standard deviation units. A measure of response bias, β, which represents the relative heights of the signal and noise distributions at the criterion, can also be calculated. This measure reflects the subject's overall willingness to say *signal present*, regardless of whether it actually is present. There are numerous alternative measures of detectability and bias based on different assumptions and theories, and many task variations to which they can be applied (see Macmillan & Creelman, 1991, for further discussion).

Signal detection analyses have been particularly useful because they can be applied to any task that can be characterized in terms of binary discriminations. For example, the proportion of words in a memory task correctly classified as old can be treated as a hit rate, and the proportion of new lures classified as old can be treated as a false alarm rate (Lockhart & Murdock, 1970). In cases such as these, the resulting analysis helps researchers determine whether variables are affecting discriminability or response bias.

An area of research in which signal detection methods have been widely used is that of vigilance (Parasuraman & Davies, 1977). In a typical vigilance task, a subject is asked to monitor a display for certain changes in it (e.g., the occurrence of a rare stimulus). The most common finding for vigilance tasks is called the vigilance decrement, in which the hit rate decreases as the time on the task increases. The classic example of this vigilance decrement is that, during World War II, British radar observers began to miss the enemy's radar signals after 30 minutes in a radar observation shift (Mackworth, 1948). Parasuraman and Davies concluded that, for many situations, signal detection analyses suggest that the primary cause of the vigilance decrement is an increasingly strict response criterion. That is, the false alarm rate as well as the hit rate decreases as a function of time on task. Perceptual sensitivity seems to be affected as well when the task requires the subject to compare rapidly presented events to information in memory to identify the events as a signals or nonsignals. Although signal detection theory can be used to help determine whether a variable affects encoding quality or decision, as in the vigilance example, it is important to keep in mind that the measures of discriminability and bias are based on certain theoretical assumptions. With regard to the vigilance decrement, Balakrishnan (1998) has argued, on the basis of an analysis that does not require the assumptions of signal detection theory, that the vigilance decrement is not a result of a biased placement of the response criterion, even when the signal occurs rarely and time on task increases.

Chronometric Methods

Chronometric methods, for which time is a factor, have been the most widely used methods for studying human information processing. Indeed, Lachman et al. (1979) portrayed reaction time as the main dependent measure of the information processing approach. Although many other measures have been used, reaction time still is widely used in part because of its sensitivity and in part because of the sophisticated techniques that have been developed for analyzing reaction time data.

A technique called the subtractive method, introduced by F. C. Donders (1868/1969) over a century ago, was revived in the 1950s and 1960s. This method provides a way to estimate the duration of a particular processing stage. The assumption of the subtractive method is that a series of discrete processing stages intervene between stimulus presentation and response execution. Through careful selection of tasks that differ in terms of a single stage, the reaction time for the easier task can be subtracted from that for the more difficult task to yield the time for the additional process. For example, Donders examined performance of two tasks, each of which used two stimuli. One was a go/no-go task in which a response was to be made to only one of the two stimuli; the other was a two-choice task in which one response was to be made to one stimulus and another response to the second stimulus. Donders reasoned that the choice task required a response-selection process that the go/no-go task did not and attributed the difference in reaction time for the two tasks to the response-selection stage.

The subtractive method has been used in recent years to estimate the durations of a variety of processes. One widely known application is Posner and Mitchell's (1967) use of the method to estimate the time to name letters. They had subjects classify pairs of letters as same or different. Reaction time to judge two physically identical letters (e.g., AA) as same was 70–100 ms shorter than that to judge two physically different letters (e.g., Aa) as same. Posner and Mitchell interpreted this difference in reaction time as the time to obtain name codes for the letters after the physical representations were formed. The subtractive method has also been used to estimate the rates of mental rotation (approximately 12-20 ms per degree of rotation; Shepard & Metzler, 1971) and memory search (approximately 40 ms per item; Sternberg, 1969). An application of the subtractive method to HCI would be, for example, to compare the time to find a target link on two web pages that are identical, except for the number of links displayed, and to attribute the extra time to the additional visual search required for the more complex web page.

The subtractive logic has several limitations (Pachella, 1974). First, it is only applicable when discrete, serial processing stages can be assumed. Second, the processing for the two tasks being compared must be equivalent except for the additional process that is being evaluated. This requires an assumption of pure insertion, which is that the additional process for the more complex of two tasks can be inserted without affecting the processes held in common by the two tasks. However, this assumption often is not justified.

Sternberg (1969) developed the additive factors method to allow determination of the processes involved in performing a task. The additive factors method avoids the problem of pure insertion because the crucial data are whether two variables affect reaction time for the same task in an additive or interactive manner. Sternberg assumed, as did Donders, that information processing occurs in a sequence of discrete stages, each of which produces a constant output that serves as input to the next stage in the sequence. With these assumptions, he showed that two variables that affect different stages should have additive effects on reaction time. In contrast, two variables that affect the same stage should have interactive effects on reaction time. Sternberg performed detailed analyses of memory search tasks in which a person holds a set of letters or digits in memory and responds to a target stimulus by indicating whether or not it is a member of the memory set. Based on the patterns of additive and interactive effects that he observed, Sternberg concluded that the processing in such tasks involves four stages: identification of the target, memory search, response selection, and response execution.

Both the subtractive and additive factors methods have been challenged on several grounds (Pachella, 1974). First, the assumption of discrete serial stages with constant output is difficult to justify in many situations. Second, both methods rely on analyses of reaction time only, without consideration of error rates. This can be problematic because performance is typically not error free, and, as described next, speed can be traded for accuracy. Despite these limitations, the methods have proved to be robust and useful (Sanders, 1998).

Speed-Accuracy Methods

The function relating response speed to accuracy is called the speed-accuracy operating characteristic (Pachella, 1974). The function, illustrated in Fig. 2.1, shows that very fast responses can be performed with chance accuracy, and accuracy will increase as responding slows down. Of importance is the fact that when accuracy is high, as in most reaction time studies, a small increase in errors can result in a large decrease in reaction time.

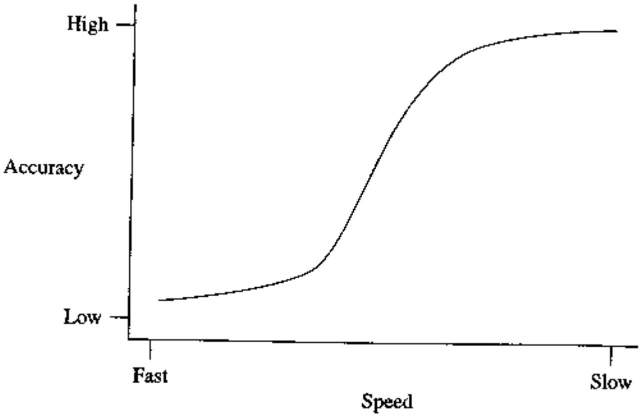

FIGURE 2.1. Speed-accuracy operating characteristic curve. Faster responding occurs at the cost of lower accuracy.

Several researchers have advocated that speed-accuracy studies be conducted instead of reaction time studies because they are potentially more informative, providing information about the intercept (time at which accuracy exceeds chance), asymptote (the maximal accuracy), and rate of ascension from the intercept to the asymptote, each of which may reflect different processes.

In speed-accuracy tradeoff studies, the speed-accuracy criterion is varied between blocks of trials by instructing subjects differently in different blocks regarding the relative importance of speed vs. accuracy, varying payoffs such that speed or accuracy is weighted more heavily, or imposing different reaction time deadlines (Wickelgren, 1977). Because the speed-accuracy criterion is manipulated in addition to any other variables of interest, many more trials must be conducted in a speed-accuracy study than in a reaction time study. Consequently, use of speed-accuracy methods has been restricted to situations in which the speed-accuracy relation is of major concern, rather than being widely adopted as the method of choice.

Psychophysiological Methods

In recent years, psychophysiological methods have come to be increasingly used in information processing research, as the apparatus and techniques for measuring physiological responses have become more sophisticated. Psychophysiological methods have the potential to provide details regarding the nature of processing by examining physiological activity as a task is being performed. The most widely used method currently involves measurement of electroencephalograms, which are recordings of changes in brain activity as a function of time measured by electrodes placed on the scalp (Rugg & Coles, 1995). Of most concern for information processing research are event-related potentials (ERPs), which are the changes in brain activity that are elicited by an event such as stimulus presentation or response initiation. ERPs are obtained by averaging across many trials of a task to remove background electroencephalogram noise and are thought to reflect postsynaptic potentials in the brain.

There are several features of the ERP that represent different aspects of processing. These features are labeled according to their polarity, positive (P) or negative (N), and their sequence or latency. The first positive (P1) and negative (N1) components are associated with early perceptual processes. They are called exogenous components because they occur in close temporal proximity to the stimulus event and have a stable latency with respect to it. Later components reflect cognitive processes and are called endogenous because they are a function of the task demands and have a more variable latency than the exogenous components. One such component that has been studied extensively is the P3 (or P300), which represents postperceptual processes. When an occasional target stimulus is interspersed in a stream of standards, the P3 is observed in response to targets, but not to standards. By comparing the effects of task manipulations on various ERP components, such as P3, their onset latencies, and their scalp distributions, relatively detailed inferences about the cognitive processes can be made.

One example of applying a P3 analysis to HCI is a study by Trimmel and Huber (1998). In their study, subjects performed three HCI tasks (text editing, programming, and playing Tetris) for 7 minutes each. They also performed comparable paper/pencil tasks in three other conditions. The P3 was measured after each experimental task by having subjects monitor a stream of high- and low-pitched tones, keeping count of each separately. The P3 varied as a function of type of task, as well as medium (computer vs. paper/pencil). The amplitude of the P3 was smaller following the HCI tasks than following the paper/pencil tasks, suggesting that the HCI tasks caused more fatigue or depletion of resources than the paper/pencil task. The P3 latency was shorter after the programming task than after the others, which the authors interpreted as an after-effect of highly focused attention.

Another measure that has been used extensively in studies of human information processing is the lateralized readiness potential (Eimer, 1998). This potential can be recorded in choice-reaction tasks that require a response with the left or right hand. It is a measure of differential activation of the lateral motor areas of the visual cortex that occurs shortly before and during execution of a response. The asymmetric activation favors the motor area contralateral to the hand making the response, because this is the area that controls the hand. Of importance, the lateralized readiness potential has been obtained in situations in which no overt response is ever executed, allowing it to be used as an index of covert, partial response activation. The lateralized readiness potential is thus a measure of the difference in activity from the two sides of the brain that can be used as an indicator of covert reaction tendencies, to determine whether a response has been prepared even when it is not actually executed. It can also be used to determine whether the effects of a variable are prior or subsequent to response preparation.

Electrophysiological measurements and recordings of magnetic fields do not have the spatial resolution needed to provide precise information about the brain structures that produce the recorded activity. Recently developed neuroimaging methods, including positron-emission tomography and functional magnetic resonance imaging, measure changes in blood flow associated with neuronal activity in different regions of the brain. These methods have poor temporal resolution, but much higher spatial resolution than the electrophysiological methods. Typically, both control and experimental tasks are performed, and the functional neuroanatomy of the cognitive processes is derived by subtracting the image during the control task from that during the experimental task. This subtractive method is based on many strong assumptions and has been questioned. Sartori and Umiltà (2000) have proposed to replace the subtractive method with the additive-factors method and what they call, the specific-effect method. For this latter method, the task that the subject is instructed to perform remains unchanged, but the processes required to perform it change. The logic of specific effects is to look for a crossover interaction between an independent variable and a brain area. Sartori and Umiltà argued that the specific-effect method should be used when investigating activations produced by different levels of a qualitative variable, whereas the additive-factor method should be used for quantitative variables. The use of these methods allows a researcher to distinguish between parallel and serial stages of processing and between local and distributed processing.

INFORMATION PROCESSING MODELS

Discrete and Continuous Stage Models

It is common to assume that the processing between stimuli and responses consists of a series of discrete stages for which the output for one stage serves as the input for the next, as Donders and Sternberg assumed. This assumption is made for the Model Human Processor (Card et al., 1983) and applications of the Executive-Process Interactive Control (EPIC) architecture (Meyer & Kieras, 1997), both of which have been applied to HCI. However, models can be developed that allow for successive processes to operate concurrently. A well-known model of this type is McClelland's (1979) cascade model, in which partial information at one subprocess, or stage, is transferred to the next. Each stage is continuously active, and its output is a continuous value that is always available to the next stage. The final stage results in selection of which of the possible alternative responses to execute.

In McClelland's (1979) cascade model, an independent variable may affect the rate of activation or the asymptotic level of activation within a particular stage. The activation rate determines the speed at which the final output is attained, and asymptotic level is analogous to the output in the discrete stage model. Even though the cascade model and discrete stage model make different assumptions about the relations among the processes, the patterns of interactions and additive effects in reaction time data can be interpreted in the same manner. That is, two variables that affect the rate parameter of the same stage will have interactive effects on reaction time. But, if the two variables affect the rate parameters of different stages, additive effects on reaction time will be observed. As long as the assumption is made that the final output of a stage does not vary as a function of the manipulations, then the additive factors logic can be used to interpret the reaction time patterns without the assumption of discrete stages.

According to J. Miller (1988), models of human information processing can be classified as discrete or continuous along three dimensions: Representation, transformation, and transmission. Representation refers to whether the input and output codes for the processing stage are continuous or discrete. Transformation refers to whether the operation performed by the processing stage (e.g., spatial transformation) is continuous or discrete. Transmission is classified as discrete if the processing of successive stages does not overlap temporally. The discrete stage model proposed by Sternberg (1969) has discrete representation and transmission, whereas the cascade model proposed by McClelland (1979) has continuous representation, transmission, and transformation.

Models can be intermediate to these two extremes. For example, J. Miller's (1988) asynchronous discrete coding model assumes that most stimuli are composed of features, and these features are identified separately. Discrete processing occurs for feature identification, but once a feature is identified, this information can be passed to response selection while the other features are still being identified.

Sequential Sampling Models

Sequential sampling models are able to account for both reaction time and accuracy, and consequently, the tradeoff between them (Van Zandt, Colonius, & Proctor, 2000). According to such models, information from the stimulus is sequentially sampled, resulting in a gradual accumulation of information on which selection of one of the alternative responses is based. A response is selected when the accumulated information exceeds a threshold amount required for that response. Factors that influence the quality of information processing have their effects on the rate at which the information accumulates, whereas factors that bias speed vs. accuracy or specific responses have their effects on the response thresholds.

Balakrishnan (1998) argued that sequential sampling may be a factor even when the experiment does not stress speed of responding. As described previously, he showed that an analysis of vigilance data that does not make the assumptions of signal detection theory suggests that attribution of the vigilance decrement to a change toward a more conservative response bias is incorrect. One reason why signal detection theory may lead to an incorrect conclusion is that the model assumes that the decision is based on a fixed sample of information, rather than information that is accumulating across time. Balakrishnan argued that even though there are no incentives to respond quickly in the typical vigilance task, subjects may choose not to wait until all of the stimulus information has been processed before responding. He proposed that a sequential sampling model, in which the subject continues to process the information until a stopping rule condition is satisfied, provides a better depiction. In this model, there are two potential sources of bias: the stopping rule and decision rule. Based on this model, Balakrishnan concluded that there is a response bias initially when the signal rate is low, and that the vigilance decrement is due to a gradual reduction of this response bias toward a more optimal decision during the timecourse of the vigil.

INFORMATION PROCESSING IN CHOICE-REACTION TASKS

In a typical choice-reaction task in which each stimulus is assigned to a unique response, it is common to distinguish between three stages of processing: stimulus identification, response selection, and response execution (Proctor & Van Zandt, 1994). The stimulus identification stage involves processes that are entirely dependent on properties of the stimuli. The response-selection stage concerns those processes involved in determining what responses are to be made to the stimuli. Response execution refers to the motor responses and their execution. Based on additive-factors logic, Sanders (1998) decomposes the stimulus identification stage into three subcategories, and the response execution stage into two subcategories, resulting in a total of six distinct stages (see Fig. 2.2).

Stimulus Identification

The preprocessing stage of stimulus identification refers to peripheral sensory processes involved in the conduction of the sensory signal along the afferent pathways to the sensory projection areas. These processes are affected by variables such as stimulus contrast and retinal location. As stimulus contrast, or intensity, increases, reaction time decreases until reaching and asymptote. For example, Bonin-Guillaume, Possamäi, Blin, and Hasbroucq (2000) had young and elderly subjects perform a two-choice reaction task, in which a left or right keypress was made to a bright or dim light positioned to the left or right. Stimulus intensity interacted with age group, with reaction times for the young adults being approximately 25 ms shorter to a bright stimulus than to a dim stimulus, and those for the older adults being approximately 50 ms shorter. The effect of stimulus intensity did not interact with variables that affect response selection and motor adjustment, suggesting that although the elderly subjects were slowed in sensory preprocessing, the deficiency in sensory preprocessing did not affect the efficiency of the other later processing stages.

Feature extraction involves lower level perceptual processing based in area V1 (the visual cortex) and other early visual cortical areas. Stimulus quality, word priming, and stimulus discriminability affect the feature extraction process. For example, manipulations of stimulus quality such as superimposing a grid, using dotted stimuli, with some dots shifted, etc., slow reaction time presumably by creating difficulty for the extraction of features. Identification itself is influenced by mental rotation and word frequency. Mental rotation refers to the finding that when a stimulus is rotated from the upright position, the time it takes to identify the stimulus increases as an approximately linear function of angular deviation from upright (Shepard & Metzler, 1971). This is presumed to affect a normalization process in which the image is mentally rotated in a continuous manner to the upright position.

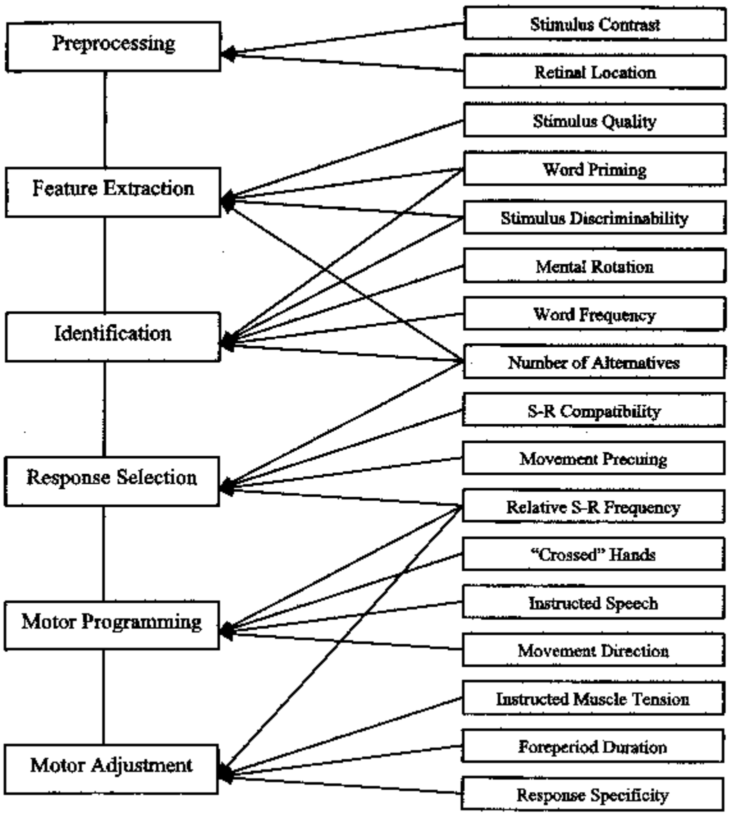

FIGURE 2.2. Information processing stages and variables that affect them, based on Sanders' (1998) taxonomy. S-R = stimulus-response.

Response Selection

Response selection refers to those processes involved in determining what response to make to a particular stimulus. It is affected by the variables of number of alternatives, stimulus-response compatibility, and precuing. As the number of stimulus-response alternatives increases, reaction time increases as a logarithmic function of the number of alternatives (Hick, 1952; Hyman, 1953). This relation is known as the Hick-Hyman law, which for N equally likely stimulus-response alternatives is:

$$RT = a + b\log_2 N, \tag{1}$$

where a is the base processing time and b is the amount that RT increases with increases in N. The slope of the Hick-Hyman function is influenced by many factors. For example, the slope decreases as subjects become practiced at a task (Teichner & Krebs, 1974).

One of the variables that affects the slope of the Hick-Hyman function is that of stimulus-response compatibility, a variable that has considerable impact on response-selection efficiency. Compatibility effects refer to differences in speed and accuracy of responding as a function of how natural, or compatible, the relation between stimuli and responses is. Two types of compatibility effects can be distinguished (Kornblum, Hasbroucq, & Osman, 1990). For one type, certain sets of stimuli are more compatible with certain sets of responses than with others. For example, the combinations of verbal-vocal and spatial-manual sets typically yield better performance than the combinations of verbal-manual and spatial-vocal sets (Wang & Proctor, 1996). For the other type, within a specific stimulus-response set, some mappings of individual stimuli to responses produce better performance than others. For example, if one stimulus has the meaning left, and the other the meaning right, performance is better if the left stimulus is mapped to the left response and the right stimulus to the right response, regardless of the stimulus and response modes.

Fitts and Seeger (1953) and Fitts and Deininger (1954) demonstrated both types of compatibility effects for spatially arranged display and response panels. However, it is not fully appreciated that compatibility effects occur for a wide variety of other stimulus-response sets. According to Kornblum et al. (1990), dimensional overlap (similarity) between the stimulus and response sets is the critical factor. When the sets have dimensional overlap, a stimulus will activate its corresponding response automatically. If this response is correct (compatible mapping), responding will be facilitated, but if it is not correct (incompatible mapping), responding will be inhibited. A second factor contributing to the advantage for the compatible mapping is that intentional translation of the stimulus into a response will occur quicker when the mapping is compatible than when it is not. Most contemporary models of stimulus-response compatibility incorporate both automatic and intentional response-selection routes (Hommel & Prinz, 1997), although they differ regarding the exact conditions under which each plays a role and the way in which they interact.

One reason why automatic activation is considered to contribute to compatibility effects is that such effects also occur when irrelevant stimulus information overlaps with the response set (Lu & Proctor, 1995). The most well-known phenomenon of this type is the Stroop color-naming effect, in which irrelevant color words that conflict with a to-be-named color produce considerable interference. A similar phenomenon, known as the Simon effect, occurs when stimulus location is irrelevant, but responses are spatial.

Compatibility effects are even more ubiquitous than the previous description would suggest. For completely unrelated stimulus and response sets that are structured, performance is better when structural correspondence is maintained (Reeve & Proctor, 1990). When stimuli and responses are ordered (e.g., a row of four stimulus locations and a row of four response locations), reaction time is faster when the stimulus-response mapping can be characterized by a rule (e.g., press the key at the mirror opposite location) than when the mapping is random (Duncan, 1977). Spatial compatibility effects also occur when display and response elements refer to orthogonal dimensions (Cho & Proctor, 2001). On the other hand, on occasion, stimulus-response compatibility effects sometimes do not occur under conditions in which one would expect them to occur. For example, when compatible and incompatible mappings are mixed within a single block, the typical compatibility effect is eliminated (Shaffer, 1965).

Because when and where compatibility effects are going to occur is not obvious, interface designers are likely to make poor decisions if they rely only on their intuitions. Payne (1995) had naïve subjects predict performance for four stimulus-response configurations that differed in terms of spatial mappings. For each configuration, a row of four stimulus locations was mapped to a row of four responses. In one condition, all four stimuli were mapped to the corresponding responses, and in a second condition, the stimuli were mapped to their mirror opposite response locations. In the remaining two conditions, mappings were mixed (i.e., two stimuli were mapped to their corresponding responses, and two to the opposite responses). Subjects correctly predicted that performance would be best for the compatible condition, but incorrectly predicted that performance would be better in the mixed conditions than in the mirror-opposite condition. Apparently, the subjects did not realize that there is a benefit when an "opposite" rule can be applied to all stimuli and that there are costs for the compatibly mapped pairs when mixed with incompatible pairs.

Vu and Proctor (2001) confirmed Payne's (1995) findings, but showed that after limited practice with the four mapping configurations, subjects were able to adjust their initial judgments of performance to more accurately match actual performance. The important point for HCI is that the designers need to be aware of the potential problems created by incompatibility between display and response elements because their effects are not always obvious. The designer can get a better feel for the relative compatibility of alternative arrangements by using them himself or herself. However, after the designer selects a few arrangements that would seem to yield good performance, the alternatives should be tested on groups of users.

Response Execution

Motor programming refers to specification of the physical response that is to be made. This process is affected by variables such as relative stimulus-response frequency and movement direction. One factor that apparently influences this stage is movement complexity. The longer the sequence of movements, that is to be made on occurrence of a stimulus in a choice-reaction task, the longer the reaction time (Sternberg, Monsell, Knoll, & Wright, 1978). This effect is thought to be due to the time required to load the movement sequence into a buffer before initiating the movements.

One of the most widely known relations attributed to response execution is Fitts' law for the time to make aimed movements to a target location (Fitts, 1954). This law, as originally specified by Fitts, is:

$$\text{Movement Time} = a + b\log_2(2D/W), \qquad (2)$$

where a and b are constants, D is distance to the target, and W is target width. However, there are slightly different derivations of the law. According to Fitts' law, movement time is a direct function of distance and an inverse function of target width. Fitts' law has been found to provide an accurate description of movement time in many situations, although alternatives have been proposed for certain situations. One of the factors that contributes to the increase in movement time as the index of difficulty increases is the need to make a corrective submovement based on feedback to hit the target location (Meyer, Abrams, Kornblum, Wright, & Smith, 1988).

Most HCI involves the users using text keys, step keys (arrows), a mouse, or a joystick to move a cursor to a target position. Consequently, the time to make these movements can be described in terms of Fitts' law. One implication of the law for interface design is that the slope of the function, b, may vary across different control devices, in which case, movement times will be faster for the devices that yield lower slopes. Card, English, and Burr (1978) conducted a study that evaluated how efficient text keys, step keys, a mouse, and a joystick are at a text selection task, in which users selected text by positioning the cursor on the desired area and pressing a button or key. They showed that the mouse was the most efficient and effective device for this task: Positioning time for the mouse and joystick could be accounted for by Fitts' law, with the slope of the function being less steep for the mouse; positioning time with the keys was proportional to the number of key strokes that had to be executed.

Another implication of Fitts' law is that anything that reduces the index of difficulty should decrease the time for motor movements. Walker, Smelcer, and Nilsen (1991) evaluated movement time and accuracy of menu selection for the mouse. Their results showed that reducing the distance to be traveled (which reduces the index of difficulty) by placing the initial cursor in the middle of the menu, rather than the top, improved movement time. In addition, placing a border around the menu item in which a click would still activate that item, and increasing the width of the border as the travel distance increases, also improved performance. The reduction in movement time by use of borders is predicted by Fitts' law because borders increase the size of the target area.

Gillan, Holden, Adam, Rudisill, and Magee (1992) noted that designers must be cautious when applying Fitts' law to HCI because factors other than distance and target size play a role when using a mouse. Specifically, they proposed that the critical factors in pointing and dragging are different than those in pointing and clicking [which was the main task in Card et al.'s (1978) study]. Gillan et al. showed that, for a text-selection task, both point-click and point-drag movement times can be accounted for by Fitts' law. For point-click sequences, the diagonal distance across the text object, rather than the horizontal distance, provided the best fit for pointing time. For point-drag, the vertical distance of the text provided the best fit. The reason why the horizontal distance is irrelevant is that the cursor must be positioned at the beginning of the string for the point-drag sequence. Thus, task requirements should be taken into account before applying Fitts' law to the interface design.

Motor adjustment is the last stage and deals with the transition from a central motor program to peripheral motor activity. Studies of motor adjustment have focused on the influence of foreperiod duration on motor preparation. In a typical study, a neutral warning signal is presented at various intervals prior to the onset of the imperative stimulus. Bertelson (1967) varied the duration of the warning foreperiod and found that reaction time reached a minimum at a warning interval of 150 ms and then increased slightly at the 200- and 300-ms foreperiods. However, the error rate increased to a maximum at the 150-ms foreperiod and decreased slightly at the longer foreperiods. This pattern, which is relatively typical, suggests that it takes time to attain a state of high motor preparation, and that this state reflects an increased readiness to respond quickly, but at the expense of accuracy.

MEMORY IN INFORMATION PROCESSING

Memory refers to effects of previous information on information processing. It may involve recollection of an immediately preceding event or one many years in the past, knowledge derived from everyday life experiences and education, or learned procedures to accomplish complex perceptual-motor tasks. Memory can be classified into several categories. Episodic memory refers to memory for a specific event, such as going to the movie last night, whereas semantic memory refers to general knowledge, such as what a movie is. Declarative memory is verbalizable knowledge, and procedural memory is knowledge that can be expressed nonverbally. In other words, declarative memory is knowing that something is the case, whereas procedural memory is knowing how to do something. For example, telling your friend your new phone number involves declarative memory, whereas riding a bicycle involves procedural knowledge. A memory test is regarded as explicit if a person is asked to judge whether a specific item or event has occurred before in a particular context; the test is implicit if the person is to make a judgment, such as whether a string of letters is a word or nonword, that can be made without reference to earlier priming events. In this section, we focus primarily on explicit episodic memory.

Three types of memory systems are commonly distinguished: Sensory stores, short-term memory (STM; or working memory), and long-term memory (LTM). Sensory stores, which we will not cover in detail, refer to brief modality-specific persistence of a sensory stimulus from which information can be retrieved for 1 or 2 s after offset of a stimulus (see Nairne, in press). STM and LTM are the main categories by which investigations of episodic memory are classified, and, as the terms imply, the distinction is based primarily on duration. The dominant view is that these are distinct systems that operate according to different principles, but there has been increasing debate over whether the processes involved in these two types of memories are the same or different.

Short-Term (Working) Memory

STM refers to representations that are currently being used or have recently been used and last for a short duration. A distinguishing characteristic of STM is that it is of limited capacity. This point was emphasized in G. A. Miller's (1956) classic article, "The Magical Number Seven Plus or Minus Two," in which he indicated that capacity is not simply a function of the number of items, but rather the number of chunks. For example, i, b, m are three letters, but most people can combine them to form one meaningful chunk of IBM. Consequently, memory span is similar for strings of unrelated letters and strings of meaningful acronyms or words. Researchers refer to the number of items that can be recalled correctly, in order, as memory span.

As most people are aware from personal experience, if distracted by another activity, information in STM can be forgotten quickly. Recall of a string of letters or single-syllable words that is within the memory span decreases to close to chance levels over a retention interval of 18 s when rehearsal is prevented by an unrelated distractor task (Brown, 1958; Murdock, 1961; Peterson & Peterson, 1959). This short-term forgetting was thought initially to be a consequence of decay of the memory trace due to prevention of rehearsal. However, Keppel and Underwood (1968) showed that proactive interference from items on previous lists is a significant contributor to forgetting. They found no forgetting at long retention intervals when only the first list in a series was examined, with the amount of forgetting being much larger for the second and third lists as proactive interference built up. Consistent with this interpretation, release from proactive inhibition (i.e., improved recall) occurs when the category of the to-be-remembered items on the current list differs from that of previous lists (D. D. Wickens, 1970).

The capacity limitation of STM noted by G. A. Miller (1956) is closely related to the need to rehearse the items. Research on determinants of the capacity limitation has shown that the memory span, the number of words that can be recalled correctly in order, varies as a function of word length. That is, the number of items that can be retained decreases as word length increases. Evidence has indicated that the capacity is the number of syllables that can be said in about 2 s (Baddeley, Thomson, & Buchanan, 1975; Schweickert & Boruff, 1980). That pronunciation rate is a critical factor suggests a time-based property of STM, which is consistent with a decay account. Consequently, the most widely accepted view is that both interference and decay contribute to short-term forgetting, with decay acting over the first few seconds of a retention interval and interference accounting for the largest part of the forgetting.

As the complexity of an HCI task increases, one consequence is to overload STM. Jacko (1997) and Jacko and Ward (1996) varied four different determinants of task complexity (multiple paths, multiple outcomes, conflicting interdependence among paths, or uncertain or probabilistic linkages) in a task that required use of a hierarchical menu to acquire specified information. When one determinant was present, performance was slowed by approximately 50%, and when two determinants were present in combination, performance was slowed further. That is, as the number of complexity determinants in the interface increased, performance decreased. Jacko and Ward attributed the decrease in performance for all four determinants to the increased STM load that they imposed.

The best-known model of STM is Baddeley and Hitch's (1974) working memory model, which partitions STM into three main parts: Central executive, phonological loop, and visuospatial sketchpad. The central executive is the least-defined component of the model, and is assumed to control and coordinate the actions of the phonological loop and visuospatial sketchpad. The phonological loop is composed of a phonological store that is responsible for storage of the to-be-remembered items, and an articulatory control process that is responsible for recoding verbal items to a phonological form and the rehearsal of those items. The items stored in the phonological store decay over a short interval and can be refreshed through rehearsal from the articulatory control process. The visuospatial sketchpad retains information regarding visual and spatial information, and it is involved in mental imagery.

The working memory model has been successful in explaining several phenomena of STM (Baddeley, 2000), for example, that the number of words that can be recalled is affected by word length. However, the model cannot explain why memory span for visually presented material is only slightly reduced when subjects engage in concurrent articulatory suppression (such as saying the words "the" aloud repeatedly). Articulatory suppression should monopolize the phonological loop, preventing any visual items from entering it. To account for findings of this type, Baddeley recently revised his working memory model to include an episodic buffer component. The revised model is shown in Fig. 2.3. The buffer is a limited capacity temporary store that can integrate information from the phonological loop, visuospatial sketchpad, and LTM. By attending to a given source of information in the episodic buffer, the central executive can create new cognitive representations that might be useful in problem-solving. Because the buffer was only recently introduced, there has not been much evidence in support or opposition to its assumed functions.

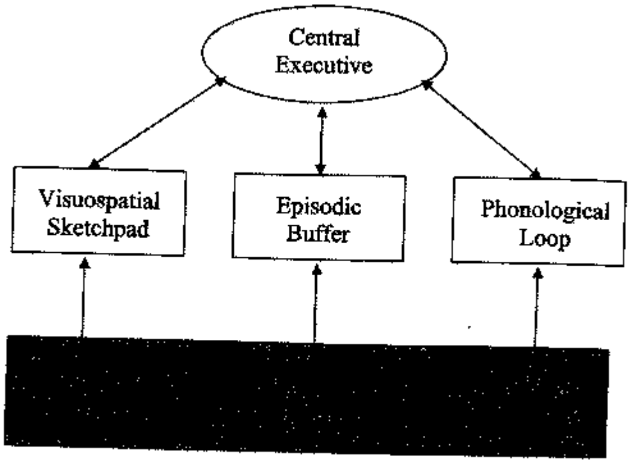

FIGURE 2.3. Baddeley's (2000) revised working memory model. LTM = long-term memory. From "The Episodic Buffer: A New Component of Working Memory?" by A. D. Baddeley, 2000, *Trends in Cognitive Sciences, 4*, p. 421. Copyright 2000 by Elsevier Science Ltd. Reprinted with permission.

Long-Term Memory

LTM refers to representations that can be remembered for durations longer than can be attributed to STM. LTM can involve information presented minutes ago or years ago. Initially, it was thought that the probability of an item being encoded into LTM was a direct function of the amount of time that it was in STM, or how much it was rehearsed. However, Craik and Watkins (1973) showed that rehearsal in itself is not sufficient, but rather that deep-level processing of the meaning of the material is the important factor in transferring items to LTM. They presented subjects with a list of words and instructed them that when the experimenter stopped the presentation of the words, they were to recall the last word starting with the letter *a*. The number of other words between instances of *a* words was varied, with the idea being that the amount of time a word was rehearsed would depend on the number of words before the next *a* word. At the end of the session, subjects were given a surprise recall test in which they were to recall all *a* words. The results showed that there was no effect of number of intervening words on recall, indicating that, although subjects rehearsed the words longer, their recall did not improve because they did not process the words deeply.

Craik and Watkins' (1973) results are consistent with the level of processing framework proposed by Craik and Lockhart (1972). According to this view, encoding proceeds in a series of analyses, from shallow perceptual features to deeper, semantic levels. The deeper the level of processing, the more strongly the item is encoded in memory. A key study supporting the levels of processing view is that of Hyde and Jenkins (1973). In their study, groups of subjects were presented a list of words for which they engaged in shallow processing (e.g., deciding whether each word contained a capital letter) or deep processing of it (e.g., identifying whether each word was a verb or a noun). Subjects were not told in advance that they would be asked to recall the words, but were given a surprise recall test at the end of the session. The results showed that the deep processing group recalled more words than the shallow processing group.

Another well-known principle for LTM is called encoding specificity. This principle states that the probability that a retrieval cue results in recollection of an earlier event is an increasing function of the match between the features encoded initially and those provided by the retrieval cue (Tulving & Thomson, 1973). An implication of this principle is that memory will be context dependent. Godden and Baddeley (1975) demonstrated a context-dependent memory effect by having divers learn a list of words either on land or under water, and recall the words on land or under water. Recall was higher for the group who learned on land when recall took place on land than under water. Similarly, recall was higher for the group who learned under water when recall took place under water than on land. A related principle is that of transfer appropriate processing, proposed initially by Morris, Bransford, and Franks (1977). They showed that, as typically found, deep-level, semantic judgments during study produced better performance than shallow rhyme judgments on a standard recognition memory test. However, when the memory test required decisions about whether the test words rhymed with studied words, the rhyme judgments led to better performance than the semantic judgments.

Recent research has confirmed that the levels of processing framework must be combined with the encoding specificity and transfer appropriate processing principles to explain the effects of processing performed during encoding. Although levels of processing has a strong effect on accuracy of explicit recall and recognition, Jacoby and Dallas (1981) found no effect on an implicit memory test. Later studies have shown a robust effect of levels of processing on implicit tests similar to that obtained for recall and recognition if the test is based on conceptual cues, rather than perceptual cues (see Challis, Velichkovsky, & Craik, 1996). Challis et al. constructed direct recognition tests, in which the words were graphemically, phonologically, or semantically similar to the studied words, that showed no levels of processing effect. They emphasized that to account for levels of processing results, it is necessary to specify the types of information produced by the levels of processing, the types of information required for the specific test, and how task instructions modify encoding and retrieval processes.

Other Factors Affecting Retrieval of Earlier Events

Memory researchers have studied many factors that influence long-term retention. Not surprisingly, episodic memory improves with repetition of items or events. Also, massed repetition (repeating the same item in a row) is less effective than spaced repetition (repeating the same item with one or more intervening items). This benefit for spaced repetition, called the spacing effect or lag effect, is widespread and occurs for both recall and recognition (Hintzman, 1974).

Another widely studied phenomenon is the generation effect, in which recall is better when subjects have to generate the to-be-remembered words rather than just studying the words as they are presented (Slamecka & Graf, 1978). In a generation effect experiment, subjects are divided into two groups: read and generate. Each group receives a series of words, with each word spelled out completely for the read group and missing letters for the generate group. An example is as follows:

Read group: CAT; ELEPHANT; GRAPE; CAKE
Generate group: C_T; E_E_H_NT; G_APE; CAK_

The typical results show that subjects in the generate group can recall more words than those in the read group. One application of the generation effect to HCI is that when a user needs a password for an account, the system should allow the user to generate the password rather than providing the user with one, because the user would be more likely to recall it in the former than latter case.

Events that precede or follow an event of interest can interfere with recall of that event. The former is referred to as proactive interference, and was discussed in the section on STM, and the latter is referred to as retroactive interference. One area of research in which retroactive interference is of central concern is that of eyewitness testimony. Loftus and Palmer (1974) showed that subsequent events could distort a person's memory of an event that the person witnessed. Subjects were shown a sequence of events depicting a car accident. Subsequently, they were asked the question, "How fast were the cars going when they ____ each other." When the verb *contacted* was used, subjects estimated the speed to be 32 mph, and only one-tenth of them reported seeing broken glass. However, when the verb *smashed* was used, the estimated speed increased to 41 mph, and almost one-third of the subjects reported seeing broken glass. Demonstrations like these indicate not only that retroactive interference can cause forgetting of events, but that it also can cause the memory of events to be changed. More recent research has shown that completely false memories can be implanted (see Roediger & McDermott, 1995).

Another phenomenon that influences recall is part-set cuing, in which providing people with a subset of the to-be-remembered items during recall impairs recall performance instead of enhancing it. Slamecka (1968) presented subjects with a list of words twice and had the control group recall as many words as they could. In the other groups, subjects were provided a subset of the words that were on the list and were asked to recall the remaining ones. Recall of the remaining words was worse for the subset groups than for the control group. One explanation for the impairment of recall by part-set cuing is that providing the subset of items disrupts normal retrieval strategies. With respect to the password example in the previous paragraph, these results suggest that, if cues are given to help recall, they should not contain any part of the password itself.

Mnemonic techniques can also be used to improve recall. The basic idea behind mnemonics is to connect the to-be-remembered material with an established organizational structure that can be easily accessible later on. Two widely used mnemonic techniques are the pegword method (Wood & Pratt, 1987) and the method of loci (Verhaeghen & Marcoen, 1996). In the pegword method, a familiar rhyme provides the organizational structure. A visual image is formed between each pegword in the rhyme and the associated target item. At recall, the rhyme is generated, and the associated items come to mind. For example, if you wanted to remember to buy a computer mouse, a printer cable, and diskettes, the peg could be the rhyme "one is a bun, two is a shoe, three is a tree," and you could visualize a computer mouse in a bun, a shoe laced with a printer cable, and a tree full of diskettes. For the method of loci, locations from a well-known place, such as your house, are associated with the to-be-remembered items. Although specific mnemonic techniques are limited in their usefulness, the basic ideas behind them (utilizing imagery, forming meaningful associations, and using consistent encoding and retrieval strategies) are of broad value for improving memory performance.

ATTENTION IN INFORMATION PROCESSING

Attention is increased awareness directed at a particular event or action to select it for increased processing. This processing may result in enhanced understanding of the event, improved performance of an action, or better memory for the event. Attention allows us to filter out unnecessary information so that we can focus on a particular aspect that is relevant to our goals. Several influential information processing models of attention have been proposed.

Models of Attention

In an influential study, Cherry (1953) presented different messages to each ear through headphones. Subjects were to repeat aloud one of the two messages while ignoring the other. When subsequently asked questions about the two messages, subjects were able to accurately describe the message to which they were attending, but could not describe anything except physical characteristics, such as gender of the speaker, about the unattended message.

To account for findings such as these, Broadbent (1958) developed the filter theory, which assumes that the nervous system acts as a single-channel processor. According to filter theory, information is received in a preattentive temporary store and then is selectively filtered, based on physical features such as spatial location, to allow only one input to access the channel. Broadbent's filter theory implies that the meaning of unattended messages is not identified, but later studies showed that the unattended message could be processed beyond the physical level, in at least some cases (Treisman, 1964).

To accommodate the finding that meaning of an unattended message can influence performance, Treisman (1964) reformulated filter theory into what is called the filter-attenuation theory. According to attenuation theory, early selection by filtering still precedes stimulus identification, but the filter only attenuates the information on unattended channels. This attenuated signal may be sufficient to allow identification if the stimulus is one with a low identification threshold, such as a person's name or an expected event. Deutsch and Deutsch (1963) proposed that unattended stimuli are always identified, and the bottleneck occurs in later processing, a view called late-selection theory. The difference between attenuation theory and late-selection theory is that the latter assumes that meaning is fully analyzed, but the former does not. Based on a review of the literature, Pashler (1998) recently concluded that the evidence supports early attenuation, but as an optional strategy rather than a structural bottleneck.

In divided attention tasks, a person must attend to multiple sources of information simultaneously. Kahneman (1973) proposed a unitary resource model that views attention as a single resource that can be divided up among different tasks in different amounts, based on task demands and voluntary allocation strategies. Unitary resource models provided the impetus for dual-task methodologies, such as performance operating characteristics, and mental workload analyses that are used widely in HCI (Eberts, 1994). The expectation is that multiple tasks should produce interference when their resource demands exceed the supply that is available.

Many studies have shown that it is easier to perform two tasks together when they use different stimulus or response modalities than when they use the same modalities. Performance is also better when one task is verbal and the other visuospatial than when they are the same type. These result patterns provide the basis for multiple resource models of attention such as that of C. D. Wickens (1984). According to multiple resource models, different attentional resources exist for different sensory-motor modalities and coding domains. Multiple resource theory captures the fact that multiple task performance typically is better when the tasks use different input–output modes than when they use the same modes. However, it is often criticized as being too flexible because new resources can be proposed arbitrarily to fit any finding of specificity of interference (Navon, 1984).

A widely used metaphor for visual attention is that of a spotlight that is presumed to direction attention to everything in its field (Posner & Cohen, 1984). Direction of attention is not necessarily the same as the direction of gaze, because the attentional spotlight can be directed independently of fixation. Studies show that when a location is cued as likely to contain a target stimulus, but then a probe stimulus is presented at another location, a spatial gradient surrounds the attended location such that items nearer to the focus of attention are processed more efficiently than those farther away from it (Yantis, 2000). The movement of the attentional spotlight to a location can be triggered by two types of cues: exogenous and endogenous. An exogenous cue is an external event such as the abrupt onset of a stimulus at a peripheral location that involuntarily draws the attentional spotlight to its location. Exogenous cues produce rapid performance benefits, which dissipate quickly, for stimuli presented at the cued location. An endogenous cue is typically a symbol such as a central arrowhead that must be identified before a voluntary shift in attention to the designated location can be made. The performance benefits for endogenous cues take longer to develop and are sustained for a longer period of time when the cues are relevant, indicating that their benefits are due to conscious control of the attentional spotlight (Klein & Shore, 2000).

In a visual search task, subjects are to detect whether a target is present among distractors. Treisman and Gelade (1980) developed Feature Integration Theory to explain the results from visual search studies. When the target is distinguished from the distractors by a basic feature such as color (feature search), reaction time, and error rate often show little increase as the number of distractors increases. However, when two or more features must be combined to distinguish the target from distractors (conjunctive search), reaction time and error rate typically increase sharply as the number of distractors increases. To account for these results, feature integration theory assumes that basic features of stimuli are encoded into feature maps in parallel across the visual field at a preattentive stage. Feature search can be based on this preattentive stage because a target-present response requires only detection of the feature. The second stage involves focusing attention on a specific location and combining features that occupy the location into objects. Attention is required for conjunctive search because responses cannot be based on detection of a single feature. According to feature integration theory, performance in conjunctive search tasks decreases as the number of distractors increases because attention must be moved sequentially across the search field until a target is detected or all items present have been searched. Feature integration theory served to generate a large amount of research on visual search that showed, as typically the case, that the situation is not as simple as depicted by the theory. This has resulted in modifications of the theory, as well as alternative theories. For example, Wolfe's (1994) Guided Search Theory maintains the distinction between an initial stage of feature maps and a second stage of attentional binding, but assumes that the second stage is guided by the initial feature analysis.

The role of attention in response selection has been investigated extensively using the psychological refractory period (PRP) paradigm (Pashler, 1998). In the PRP paradigm, a pair of choice-reaction tasks must be performed, and the stimulus-onset asynchrony (SOA) of the second stimulus is presented at different intervals. Reaction time for Task 2 is slowed at short SOAs, and this phenomenon is called the PRP effect. Experimental results have been interpreted with what is called locus of slack logic (Schweickert, 1978), which is an extension of additive factors logic to dual-task performance. The basic idea is that if a Task 2 variable has its effect prior to a bottleneck, that variable will have an underadditive interaction with SOA. This underadditivity occurs because, at short SOAs, the slack period during which post-bottleneck processing cannot begin can be used for continued processing for the more difficult condition. If a Task 2 variable has its effect after the bottleneck, the effect will be additive with SOA.

The most widely accepted account of the PRP effect is the response-selection bottleneck model (Pashler, 1998). The primary evidence for this model is that perceptual variables typically have underadditive interactions with SOA, implying that their effects are prior to the bottleneck. In contrast, post-perceptual variables typically have additive effects with SOA, implying that their effects are after the bottleneck. There has been dispute as to whether there is also a bottleneck at the later stage of response initiation (De Jong, 1993), and whether the apparent response-selection bottleneck is structural or simply a strategy adopted by subjects to comply with task instructions (Meyer & Kieras, 1997). This latter approach is consistent with the recent emphasis on the executive functions of attention in the coordination and control of cognitive processes (Monsell & Driver, 2000).

Automaticity and Practice

Attention demands are high when a person first performs a new task. However, these demands decrease and performance improves as the task is practiced. Because the quality of performance and attentional requirements change substantially as a function of practice, it is customary to describe performance as progressing from an initial cognitively demanding phase to a phase in which processing is automatic (Anderson, 1982; Fitts & Posner, 1967).

The time to perform virtually any task from choice-reaction time to solving geometry problems decreases with practice, with the largest benefits occurring early in practice. Newell and Rosenbloom (1981) proposed a power function to describe the changes in reaction time with practice:

$$\mathrm{RT} = BN^{-\alpha}, \tag{3}$$

where N is the number of practice trials, B is reaction time (RT) on the first trial, and α is the learning rate. Although the power function has become widely accepted as a law that describes the changes in reaction time, Heathcote, Brown, and Mewhort (2000) indicated that it does not fit the functions for individual performers adequately. They showed that exponential functions provided better fits than power functions to 40 individual data sets and proposed a new exponential law of practice. The defining characteristic of the exponential function is that the relative learning rate is a constant at all levels of practice, whereas, for the power function, the relative learning rate is a hyperbolically decreasing function of practice trials.

PROBLEM SOLVING AND DECISION MAKING

Beginning with the work of Newell and Simon (1972), it has been customary to analyze problem solving in terms of a problem space. The problem space consists of the following: (1) an initial state, (2) a goal state that is to be achieved, (3) operators for transforming the problem from the initial state to the goal state in a sequence of steps, and (4) constraints on application of the operators that must be satisfied. The problem-solving process itself is conceived of as a search for a path that connects the initial and goal states.

Because the size of a problem space increases exponentially with the complexity of the problem, most problem spaces are well beyond the capacity of STM. Consequently, for problem solving to be effective, search must be constrained to a limited number of possible solutions. A common way to constrain search is through the use of heuristics. For example, people often use a means-ends heuristic for which at each step, an operator is chosen that will move the current state closer to the goal state (Atwood & Polson, 1976). Such heuristics are called weak methods because they do not require much knowledge about the exact problem domain. Strong methods, such as those used by experts, rely on prior domain-specific knowledge and do not require much search because they are based on established principles applicable only to certain tasks.

The problem space must be an appropriate representation of the problem, if the problem is to be solved. One important method for obtaining an appropriate problem space is to use analogy or metaphor. Analogy enables a shift from a problem space that is inadequate to one that may allow the goal state to be reached. There are several steps in using analogies (Holland, Holyoak, Nisbett, & Thagard, 1986), including detecting similarity between source and target problems, and mapping the corresponding elements of the problems. Humans are good at mapping the problems, but poor at detecting that one problem is an analog of another. An implication for HCI is that potential analogs should be provided to users for situations in which they are confronted by novel problems.

The concept of the mental model, which is closely related to that of the problem space, has become widely used in recent years (see chapter 3, this volume). The general idea of mental models with respect to HCI is that, as the user interacts with the computer, he or she receives feedback from the system that allows him/her to develop a representation of how the system is functioning for a given task. The mental model incorporates the goals of the user, the actions taken to complete the goals, and expectations of the system's output in response to the actions. A designer can increase the usability of an interface by using metaphors that allow transfer of an appropriate mental model (e.g., the desktop metaphor), designing the interface to be consistent with other interfaces with which the user is familiar (e.g., the standard Web interface), and conveying the system's functions to the user in a clear and accurate manner. Feedback to the user is perhaps the most effective way to communicate information to the user and can be used to guide the user's mental model about the system.

Humans often have to make choices for situations in which the outcome depends on events that are outside of their control. According to expected utility theory, a normative theory of decision making under uncertainty, the decision maker should determine the expected utility of a choice by multiplying the subjective utility of each outcome by the outcome's probability and summing the resulting values (see Proctor & Van Zandt, 1994). The expected utility should be computed for each choice, and the optimal decision is the choice with the highest expected utility. It should be clear from this description that, for all but the simplest of problems, a human decision maker cannot operate in this manner. To do so would require attending to multiple cues that exceed attentional capacity, accurate estimates of probabilities of various events, and maintenance of, and operation on, large amounts of information that exceeds STM capacity.

Research of Kahneman and Tversky (2000) and others has shown that what people do when the outcome associated with a choice is uncertain is to rely heavily on decision-making heuristics. These heuristics include representativeness, availability, and anchoring. The representativeness heuristic is that the probability of an instance being a member of a particular category is judged on the basis of how representative the instance is of the category. The major limitation of the representativeness heuristic is that it ignores base rate probabilities for the respective categories. The availability heuristic involves determining the probability of an event based on the ease with which instances of the event can be retrieved. The limitation is that availability is affected not only by relative frequency, but also by other factors. The anchoring heuristic involves making a judgment regarding probabilities of alternative states based on initial information, and then adjusting these probabilities from this initial anchor as additional information is received. The limitation of anchoring is that the initial judgment can produce a bias for the probabilities. Although heuristics are useful, they may not always lead to the most favorable decision. Consequently, designers need to make sure that the choice desired for the user in a particular situation is one that is consistent with the user's heuristic biases.

SUMMARY AND CONCLUSION

The methods, theories, and models in human-information processing are currently well developed. The knowledge in this area, of which we were only able to describe at a surface level in this chapter, pertains to a wide range of concerns in HCI, from visual display design to representation and communication of knowledge. For HCI to be effective, the interaction must be made compatible with the human information processing capabilities. Cognitive architectures that incorporate many of the facts about human information processing have been developed that can be applied to HCI. The Model Human Processor of Card et al. (1983) is the most widely known, but applications of other more recent architectures, including the ACT (Adaptive Control of Thought) model of Anderson and colleagues (Anderson, Matessa, & Lebiere, 1997), the Soar Model of Newell and colleagues (Howes & Young, 1997), and the EPIC Model of Kieras and Meyer (1997), hold considerable promise for the field, as demonstrated in chapter 5 of this volume.

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