An Information-Processing Analysis of Perception and Action

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Metatheory for the Study of Perception and Action

How much behavior can psychological theory be expected to predict or fully explain? A recent New Realist theory of philosophy of science allows for predictability in the laboratory, but not in the naturally varying environment (Manicas & Secord, 1983). Complexity of the natural setting far exceeds what any scientific theory could hope to accommodate. Theories will have predictive power only in the laboratory in which the complexity of everyday life can be simplified, measured, and controlled. Our point of departure is even more pessimistic in that the complexity of the prototypical psychology experiment might exceed any theory's predictive power. Revising the dictum that "data without theory are meaningless" (Coombs, unpublished), laboratory data might exceed the constraints demanded by theory (even reasonably correct theory).

There is considerable basis for the above conjecture in the study of perception and the study of action. My contention is that our experiments in these domains too infrequently have the constraints to inform theoretical alternatives (Massaro,

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1975a, 1987). The relationship between perception and action is a question, at least, a log unit more complex than questions concerning their separate functions. Theoretical enlightenment in this arena will be slow in coming, if it is achieved at all. The behaviorists failed: the stimulus does not enable us to predict the response (or even to postdict it). Other more creative efforts are equally unsatisfactory. An influential example is Gibson's (1979) ingenious development of the concept of affordance to explicate the relation between perception and action. The visual world has meaning for behavior, we detect its invariants and we perceive affordance or the actions that the objects or events make available to the perceiver. Affordance is used to explain why apples tend to be seen and eaten rather than seen and kicked. As observed by Cutting (1982), however, the affordance of a stimulus does not constrain behavior sufficiently. There are simply too many possibilities. (In a later section the neo-Gibsonian dichotomy that the perception of stimuli either specifies or simply indicates action proves somewhat helpful in elucidating some perception-action relationships).

The variety of variables influencing the observed relationships between perception and action precludes any hope for a simple solution. Jenkins (1979) has given a similar view of memory research, because of the context sensitivity of any finding. The "law" of memory that is observed depends on subjects, acquisition conditions, memory materials, and memory tasks. The law will differ under different choices of these four classes of variables. Jenkins catalogued these four classes of variables in a Problem Pyramid or Theorist's Tetrahedron. We might expect that laws relating perception to action will have an analogous context sensitivity, depending on subjects, performance history, stimulus situation, and response requirements. Notwithstanding this complexity, the useful heuristic of information-processing models offers the potential for some progress, and this is the tack taken in this chapter. Analogous to Winston Churchill's view of democracy, information processing is not perfect but it is the best that is currently available.

William James (1890) sets the stage for our inquiry, as he does for most inquiries in psychology. "The question is this: 'Is the bare idea of a movement's sensible effects its sufficient mental cue, or must there be an additional mental antecedent, in the shape of a fiat, decision, consent, volitional mandate, or other synonymous phenomenon of consciousness, before the movement can follow?' I answer: sometimes ..." (p. 522). In an information-processing approach, James' question is addressed in the general concern for how input processing relates to output processing. James used the term "ideomotor action" to describe the situation of movement following unhesitatingly and immediately the notion of it in the mind, without awareness. As James said, "We think the act and it is done" (p. 522). Almost a century later, we realize how inadequate this introspective analysis is, but it sets the stage for the study of the relationship between perception and action. Without a doubt, there is a continuum of perception-action relations, from the automatic and fast striking out at the mosquito that has landed on my arm during a walk in the woods, to the deliberate and slow rising from a warm bed onto a cold floor in a cold room.

The preceding statement of the perception-action problem illuminates for me how much of the problem is empirical and not simply theoretical. It is necessary to measure this perception-action relation across the spectrum of human behavior to provide the constraints on potential theory. Without a systematic measurement of the range of phenomena, we are no better off than was James with his introspective method. Luckily, psychologists have been busy since the time of James and have provided useful results on the relation between perception and action. Interestingly, several results were not acquired in the direct search for perception-action relations. Given that even the simplest behavior is assembled from both perception and action, the purest perception experiment has some action, as the purest motor experiment has some perception. As in other domains of psychological inquiry, experimental and theoretical progress are mutually tied to one another.

An Information-Processing Model

We present a stage model to organize the multiplicity of variables influencing perception, action, and the relation between the two. A stage model operates on the assumption of relative independence in that some stages are hypothesized to be influenced by only some variables. Evidence consistent with this hypothesis allows a more parsimonious description of behavior than highly interactive or nonindependence models. In addition, this independence is what makes a theoretical description possible in that the functioning of some stages can be described relatively independently of others. The model is a useful heuristic and is presented in the spirit of falsification and strong inference strategies of scientific inquiry (Massaro, 1979). Specific alternatives or contrasts, not otherwise transparent, can be formulated within the context of the model.

The serial stage model has come under heavy fire in recent years and some defense is warranted even before we begin. The serial nature of the model is assumed because it is the most parsimonious, in many instances, mathematically equivalent to the nonserial models (McClelland, 1979; Townsend & Ashby, 1983; Schweickert, 1978, 1983; Theios & Amrhein, 1989). In these parallel, cascade, or PERT (critical path) networks, stages are somewhat autonomous subprocesses, each with a unique starting time and a unique finishing time. Although the subprocesses can overlap in time, they each contribute to or affect performance time. As stressed by Theios and Amrhein (1989), our prototypical experiments using mean reaction time (RT) as a dependent measure cannot address the issue of serial versus parallel stages. Luckily, the research is still informative regardless of the eventual outcome of the serial/nonserial questions (Townsend & Ashby, 1983). In both instances, performance can be broken down into its component parts, and a theory must describe the parts and how each part is influenced by the multiplicity of variables available to nature and the experimenter. The current effort builds on the foundation assembled by the thorough reviews of Theios (1975), Teichner and Krebs (1974), Sanders (1980), and Keele (1986). The current goal is to confront more directly the relation between perception and action, something not previously explored within the information-processing framework. The information-processing analysis will prove valuable only if it provides a reasonable conceptual framework for the research on perception and action, particularly for those studies previously believed to be exceptions to typical information-processing explanations.

Six Stages of Processing

Following Sanders (1980), it is necessary to distinguish among six stages of processing, as illustrated in Table 1. Sanders distinguishes between perceptual and motor stages but does not make explicit a stage of processing responsible for the translation of perception into action. Our percept-act translation stage replaces his response-choice stage to make the process of translation more apparent. Sanders assumes that stimulus-response compatibility is the critical variable at this stage. Percept-act compatibility is a better descriptor of this variable, however, because it is the relationship between the percept and act that is critical, not simply the relationship between stimulus and response. For example, the overt naming of a Chinese ideogram would be difficult for English but not Chinese readers. The stimulus and response are equivalent for the two groups of subjects, but the translation of the percept (perceptual recognition) into an act (spoken articulation) differs in difficulty for the two groups. Percept-act compatibility better represents the relation between perception and action than does stimulus-response compatibility.

Table 1. Six stages of processing and the variables influencing each stage.

Stages	Variables
1. Sensory transduction	1. Signal intensity, duration
2. Featural registration, evaluation, and integration	2. Clarity of features: spatial frequency of visual sine wave gratings ambiguity of acoustic features in speech
3. Pattern classification	3. Similarity of stimulus alternatives
4. Percept-act translation	4. Percept-act compatibility, associative strength between perceptual code and action code
5. Motor programming	5. Complexity of movement, specificity of percept
6. Motor execution	6. Physical components of movement, muscle involved

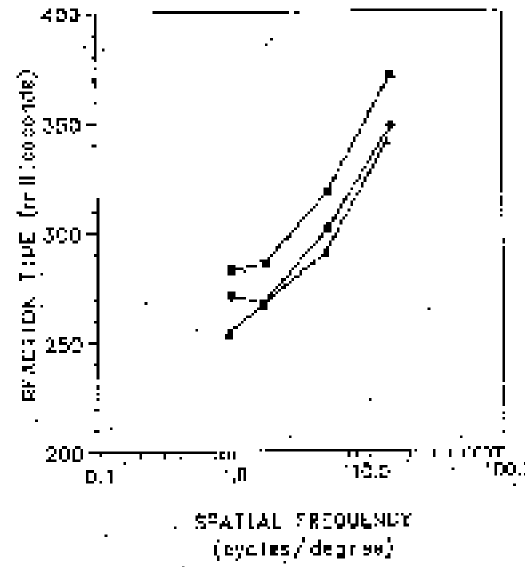

Fig. 1. Simple reaction time to vertical bar gratings of differing spatial frequency and contrast. Patterns of vertical stripes subtending a visual angle of 3.8° by 5.3° were presented to the fovea for 100 ms. The spatial frequency varies from 1.0 to 16.0 cycles per degree (higher frequencies involve more stripes). The contrast between light and dark portions was set 3.0 (squares), 1.5 (circles), or 6.0 (triangles) times greater than the just detectable (threshold) contrast for each spatial frequency. Reaction time is greater for higher frequency gratings but tends to decrease with contrast. (Lupp et al., 1976)

It should be noted that there is a transition from physiological terms to psychological terms between stages 1 and 2 and back to physiological terms at stage 6. This terminology is as it should be in that the algorithmic mental level has proven more appropriate for more central functions and the neural/physiological level more appropriate for more peripheral functions.

Sensory transduction is the first measurable stage and is influenced by signal intensity. As an example, simple RT to detect a stimulus decreases with the intensity of the auditory test signals (McGill, 1961, 1963). Increasing the amplitude of a 1000-Hz test tone from 30 to 100 dB decreases RT by about 100 ms. Analogously, Fig. 1 shows that simple RT to detect visual sine wave gratings decreases with increases in the contrast between the light and dark portions of the pattern (Lupp, Hauske, & Wolf, 1976).

Featural registration, evaluation, and integration is the second stage, which is influenced by the quality of the featural information, the nature of the evaluation, and the type of integration that is required. Our visual acuity varies with detail (spatial frequency) of the pattern, and we might expect spatial frequency also to influence simple RT. As illustrated in Fig. 1, RT changes systematically with spatial frequency, and this change is roughly additive with changes in the contrast between the light and dark portions. This additivity supports the distinction between a sensory-transduction stage and a featural-registration-evaluation stage of processing. In the auditory domain, the second stage will consume more time in speech perception to the extent the featural information is ambiguous, but this effect should be roughly additive with the intensity of the speech signal. Identification RTs increase with increases in the ambiguity of the speech syllable along a synthetic speech continuum (Massaro & Cohen, 1983; Repp, 1981), but the possible interaction between ambiguity and intensity has *not* been evaluated.

The third stage is pattern classification or the perceptual encoding of a stimulus event relative to various alternatives in memory. If the output of this stage were discrete rather than continuous, we would say that the pattern is categorized as a given alternative. However, this stage of processing makes available the degree to which the signal represents one pattern relative to the degree to which it matches all other patterns. This stage is influenced by the family of alternatives that are relevant to the task at hand. Thus, identification RTs should be shorter to auditory speech syllables if subjects are discriminating between the alternatives /ba/ and /da/ than the alternatives /va/ and /tha/. The latter two are psychophysically much more similar to one another than are the former two. Similarly, time for pattern classification will usually increase with increases in the number of alternatives because of a natural confounding between this variable and similarity among the alternatives. To use another example, literate drivers find it easier to react to the word in the traffic sign "HILL" than to the picture of the international sign depicting a hill. The ambiguity at this stage of pattern classification is greater in the second case relative to the first.

The fourth stage is referred to as "percept-action translation" (more traditionally known as "response selection"). This stage, in many respects the focus of the current chapter, is influenced primarily by what has been covered by the blanket term "stimulus-response compatibility." A more realistic description would be "percept-act compatibility." An important contribution to performance is how readily perception maps into action. Reacting in the direction of a signal is usually easier than reacting away from a signal. It would be a feat of effort to look away from rather than toward someone speaking your name at a cocktail party. Consider the task of identifying pictures of objects by pronouncing either their names or their superordinate categories. A picture of a sparrow would be named as *bird* more quickly than it would be called *sparrow*, whereas the opposite might occur for a picture of a parrot. Given the similarity of sparrow to the prototypical bird and the uniqueness of parrot with respect to the category "bird," we have learned to call sparrows birds and parrots parrots (Rosch, 1978).

The fifth stage is motor programming. Once the action is selected, it has to be programmed before it can be executed. An obvious variable influencing motor programming is complexity of the action that is required. Complexity should increase with the number of discrete actions, and thus this variable should influence programming time. Figure 2 shows that the RT to initiate a response sequence increases with increases in the number of key presses required (Inhoff, Rosenbaum, Gordon, & Campbell, 1984). In addition, the effect of this variable is additive with whether subjects responded in the direction of or away from the test signal. Given that the direction of the response relative to the stimulus has already been described as a percept-act compatibility variable, we have some evidence for distinguish-

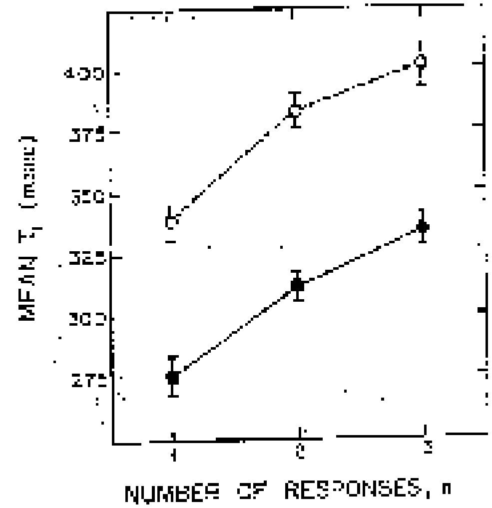

Fig. 2. Mean choice reaction time for response 1 (T_1) of sequences consisting of n = 1, 2, or 3 responses tested in compatible (*solid circles*) or incompatible (*open circles*) stimulus-response translation conditions. (About 300 observations contribute to each point.) Estimates of SE are based on between-subjects differences. (Data from Inhoff et al., 1984, experiment 1)

ing between the fourth and fifth stages. The specificity of the percept also appears to be important for motor programming. In some cases, the percept underspecifies the action, whereas, in other cases, the action is inherently specified by the percept. Programming time is longer when preparation and the percept do not specify the required action. Thus, for literate adults, the RT of a naming response to pictures will be longer than the same response to words (all other things being constant; Theios & Amrhein, 1989).

The motor execution stage involves moving the appropriate effectors for the desired action. Needless to say, the physical requirement of the action will influence this stage of processing. It will obviously take longer to move a lever with your foot to one of four locations than to hit one of four buttons with a finger. Muscle tension can also influence execution time of a given response (Sanders, 1980). As noted by Sanders, the motor stages have not been studied as extensively as the perceptual stages. The relation between the two types of stages has been studied even less, but the few dozen studies in this domain are surprisingly informative (Annett, 1983; Keele, 1986; Sanders, 1980).

Accuracy and RT Measures of Performance

An experimenter is fairly limited in dependent measures of performance. A subject's behavior can be described by classification judgements across a set of alternatives in terms of accuracy and/or reaction time. One important recommendation of the current approach is that information-processing models should be developed and tested using both accuracy and RT as dependent measures of performance. Specific theories have been developed too often handle one dependent measure or the other but not both. One working hypothesis explored in this section is that accuracy and RT provide converging measures of human performance.

Santee and Egeth (1982), on the other hand, challenge the idea that RT and accuracy measure the same aspects of human performance. The task they use is letter recognition of one of two alternative letters. Subjects were shown letters presented on opposite sides of a fixation point. Sometime after the onset of the test display, subjects were cued to report one of two letters. The independent variables were (a) the psychophysical similarity between the cued letter and the noncued letter, and (b) whether the noncued letter was identical to the cued letter, was the alternative target letter, or was a nontarget letter. Short durations of the test letters were used to produce errors in the accuracy condition, and we refer to this condition as a "data-limited condition." A long display duration was used to produce essentially perfect performance in the RT condition, but subjects were instructed to respond as rapidly as possible without errors. We therefore call this condition a "time-limited condition."

The process involved are (a) lateral interference of similar letters on letter recognition; and (b) response interference between target and noise items at response selection. Lateral interference occurred in the data-limited task and response interference in the time-limited task. If the noncued letter was identical to the cued letter, accuracy was lower than the in case of different noncued letters in the data-limited task. In the time-limited task, RTs were longer when the noncued test letter was the alternative target. Thus, the results reveal lateral interference in the data-limited task and response interference in the time-limited task. Santee and Egeth used these results to challenge the notion that RT and accuracy are assumed to be converging measures of performance.

However, these results can be explained within a model of information processing. Finding no effect of response interference in the data-limited task is reasonable. These subjects take their time in responding and simply optimize the accuracy of their choice. The stage of *response* selection should not be influenced by the similarity of the target and background items, and neither accuracy nor RT (which Santee and Egeth do not report) should be influenced by the similarity manipulation in the data-limited task. In the time-limited task, subjects respond as quickly as possible without too many errors. Response interference is reasonable; presentation of the alternative target as the noncued test letter produces response interference analogously to the Stroop color word situation.

One might ask additionally, however, why an effect of similarity of the two test letters on RT is not observed. That is, subjects should be somewhat slower when the noncued letter is identical to the cued letter relative to the case in which the two letters differ. To address the question, however, it is necessary to have a quantitative model of the contribution of lateral interference and response interference. It could be the case that the disadvantage of identical letters in perception is outweighed by an advantage in response selection. For example, the identical background could have slowed down perceptual processing of the target item by 100 ms, but having the background identical to the target could have speeded up response selection by 300 ms. Supporting this interpretation, Shapiro and Krueger

(1983) revealed significant but opposing effects of discriminability and bias due to the similarity of context letters to the test letter.

Given an information-processing description, the Santee and Egeth (1982) experiment does not challenge the common assumption that accuracy and RT are converging measures of human performance. Although it is easy to overlook the differences in the stimulus conditions in the accuracy and RT tasks, these differences could contribute to any differences that are observed. What the results make apparent is that data are meaningless without some kind of model analysis. One needs both information-processing models and fine-grained analyses of performance in the study of perception and action. A good theory will accommodate both accuracy and RT measures of performance.

Our rejection of the Santee and Egeth (1982) conclusion is also supported by Salthouse's (1981) converging evidence for the stage model by comparing accuracy and RT paradigms. Visual information processing in a tachistoscopic task was contrasted with performance in a speed-accuracy RT task. The test stimuli were digits or symbols, and the responses were key presses. In one experiment, for example, the odd integers 1 to 9 were responded to with the right index finger on one key, and the even digits 0 to 8 were responded to with the left index finger on another key. A short stimulus presentation was used to produce errors in the tachistoscopic task, but the stimulus remained in view until the subject responded in the speed-accuracy task. The size of the effect of an independent variable in the two tasks was used to assess whether its influence was at an early stage or a late stage of information processing. As an example, manipulating the number of stimulus alternatives while holding the number of response alternatives constant produced a smaller effect in the tachistoscopic task than in the RT task. This result agrees with earlier research in the RT domain showing that perceptual processing is less influenced by the number of alternatives than is response processing. Another reasonable finding was no effect of stimulus-response compatibility in the tachistoscopic task, but a large effect in the RT task.

An important result for the study of perception and action was finding no significant effect of stimulus quality in the tachistoscopic task along with a small effect of this variable in a speed-accuracy task. A stronger manipulation of stimulus quality would have produced a large effect of this variable in the tachistoscopic task. If the size of the effect remains larger in the speed accuracy task than in the tachistoscopic task, it would provide some evidence that quality influences both perceptual and motor stages of processing. Given the more prominent role of a stage of perception-action translation in the current model, this result is more easily accommodated. Quality of the perceptual code could influence the time needed to translate it into an action code and possibly even the time needed to program the action. Salthouse's comparative-influence method is a promising paradigm for the study of perception and action and should be explored in more detail.

Perception-Action Translation

We have neglected a significant stage of processing in the two decades of information-processing research since Neisser's (1967) book. The stage of processing seldom addressed in inquiry is the translation between perception and action. We have studied one or the other or both but have tended to ignore the translation process. More recently, several researchers have recognized the problem, and their studies will contribute significantly to the present review. Our bias is that the translation between perception and action can be studied and analyzed within the same framework used for study of these two general classes of processing. The assumption is that complex performance can be described in terms of its component parts and the relationship among the components.

Consider the task of naming a picture or naming a written word describing the same object. Identification would involve making contact with some knowledge about the object on the basis of its pictorial or written representation. Response selection might be said to involve a selection of the appropriate action such as programming the articulators to utter the appropriate word. These two stages of processing do not capture an important process between identification and response selection referred to as "perception-action translation" in the present development (see also Vinzi & Egeth, 1985). In this case translation involves a transformation of information about the object made available by identification to information about some code that is meaningful to the response-selection stage. This perception-action translation process would differ significantly for the picture - and word-naming tasks. The translation between the identified word and naming is more direct than the translation between the identified picture and naming because the former carries information about what is to be articulated. (Even Chinese ideographs have a phonetic component that provides information about the sound of the word.) The word specifies for the skilled reader its pronunciation (to some extent), whereas the picture does not. Unfortunately, previous studies had overestimated the case of processing pictures relative to words because of comparing large pictures to small words. Theios and Amrhein (1989), using an ingenious control for the visual properties of picture and words, found that the translation process was 154 ms longer for naming pictures than for naming words.

Hick's Law

An independent variable receiving much attention and presenting a challenge to interpretation within the information-processing framework is the number of stimulus-response alternatives in the task. Shannon's (1948) information measure was tested for psychological validity by assessing whether RT would be linear with information transmitted when measured in bits. As formulated in Hick's law, doubling of the number of alternatives should add a constant to RT. After some initial support (Hick, 1952), several studies reported a number of limiting conditions. These limiting conditions have been reviewed and interpreted by Teichner

and Krebs (1974). Stimulus-response compatibility and practice were discovered to be important variables. Hick's law failed for cases of high stimulus-response compatibility, such as pressing a key with the finger stimulated by vibration (Leonard, 1959). In the prototypical task with test digits and key presses, practice effects can also drive the RT function to a zero slope as in the heroic performance for 39 000 trials by the single subject in Mowbray and Rhoades (1959). A lifetime of practice can be observed in the laboratory by having subjects simply pronounce written numbers or letters of the alphabet (Fraisse, 1967; Hellyer, 1963; Morin, Konick, Troxell, & McPherson, 1965; Mowbray, 1960).

Broadbent and Gregory (1962) even eliminated the robust difference between the Donders B and C conditions with highly practiced or compatible responses. The B condition requires differential responding to different stimuli, whereas the C condition requires a response to only one of the stimuli. With practiced or compatible stimulus-response (verbal naming and tactile key pressing) pairings, RT in the B condition was as short as it was in the C condition. This result was not found for unpracticed pairings (saying a word other than the verbal stimulus or incompatible responses - hitting a key with a different finger than the one stimulated).

Another important variable noted in the early work (Morin et al., 1965) and studied intensively in the last decade is stimulus-response consistency. Morin et al. (1965) found that RTs increased with increases in the numbers of stimulus-response alternatives when drawings of animals were used as test stimuli that were pronounced in a naming task. On the other hand, we would expect little, if any, increase in RT with increases in the number of alternatives if the alternatives are presented as written or spoken words (Theios, 1973). Given the same names in both conditions, response familiarity is an inadequate explanation of the differences between the picture and word conditions. The rather mundane but all too real variable of association provides a handle on these observations. What seems critical is the relative associative strength between the stimulus and response. A picture of a dog might be associated with other responses such as collie, pooch or Lassie, whereas the word "dog" is associated first and foremost with the name dog.

The notion of associative strength between stimulus and response is translated easily into stimulus-response consistency. Using a Sternberg (1975) memory search task, Schneider and Shiffrin (1977) asked subjects to indicate whether or not a test item is a member of a memory set of items. A test item identical to an item in the memory set is a target item and requires a positive response, whereas a test item not in the memory set is a nontarget and requires a negative response. The makeup and the number of items in the memory set are varied systematically. With consistent mapping, the memory items are always chosen from the same superset of items, and these items are never presented as nontargets. In the varied mapping condition, the memory items are not constrained in this way, and a target item on one trial can be a nontarget on another trial. The results showed that memory search with arbitrary stimulus-response pairings is influenced by the consistency of the pairings throughout the experiment (Kristofferson, 1975). If the pairings change randomly, RTs will increase with increases in memory set size. If the memory set items are never presented as nontargets, however, a relatively small number of trials (2100) is sufficient for the subjects to produce RTs independent of memory set size. In addition, reversal of the target and nontarget sets produced a huge negative transfer. Subjects were asked to search for items that were previously nontargets in displays with nontargets that were previously targets. This task was found to be more difficult and time consuming than the original task without practice.

Longstreth, El-Zahhar, and Alcorn (1985) illuminate the importance of the percept-act translation stage in perception-action tasks. Subjects were visually presented with any one of a number of digits and had to press a corresponding key, as in the typical task, or hold a single key down for a duration given by the value of the test digit. The digit 2, for example, would require the duration of the key press to be two time units (usually about 30 ms per time unit), and so on for other test digits. Unpracticed subjects were fairly accurate in this task, but their RTs did not increase much with the number of test alternatives. The large difference in the RT functions from the two tasks is impressive (see Fig. 3). In the traditional task with a unique key for each alternative, RTs increased by 150 ms with a doubling of alternative between 2 and 4. The increase was only about one-tenth of this value, however, in the novel duration task using a single key. A number of obvious explanations, such as much of the processing occurring after the response was initiated, were eliminated.

Differences in memory requirements appear to be sufficient to account for the flattening of the RT function in the novel task of Longstreth et al. (1985) relative to the prototypical task. As explained in formal detail by the authors, a single stimulus-response code can be used by the subjects in the duration task: press the key for the duration specified by the test digit. The recognition of the test digit provides the numerical code needed for the duration task but does not describe the key to be pushed in the traditional multiple-key task. The efficient responding in the duration task was eliminated by changing the test items to letters and having the subject treat the letters ordinally. In this case, the letter had to be recognized and then transformed into a numerical code before response selection could occur. With few alternatives, subjects could hold these translations in memory and access them fairly quickly. Increasing the number of alternatives will make this process more difficult and, accordingly, lead to an increase in RT.

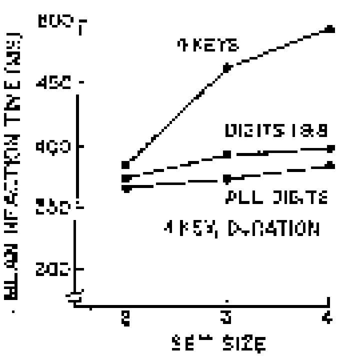

Fig. 3. Reaction time as a function of the number of alternatives in the typical task with a response key for each unique alternative (*4 KEYS*) and in the novel task of holding a single key down for the duration specified by the value of test digit (*1 KEY, DURATION*). (Longstreth et al., 1985)

A stage analysis illuminates the variables of stimulus-response compatibility, number of alternatives, practice, stimulus-response consistency, and memory requirements in the prototypical information-processing task. The number of stimulus-response alternatives interacts with stimulus-response compatibility, practice, consistency, and memory requirements. Stimulus-response compatibility refers to the ease with which a given response can be made to a given stimulus, everything else being constant. Young soccer players find it easier to approach the ball rather than to approach the goal to receive a pass. We find it easier look to the location of a sound or light, rather than to look away from these events. Orienting responses to stimuli might offer some a priori specification of stimulus-response compatibility. Responses similar to the natural orienting response to a stimulus might well predict stimulus-response compatibility. Practice and stimulus-response consistency represent the number of times and the consistency with which the stimulus is responded to in a given manner, and they might be interpreted as the relative association strength between some stimulus and some response. Neisser (1964) described how efficiently employees in news-clipping services could spot their clients' names in newspaper articles. These agents have both a consistent history of clients and practice on their side. Memory requirements are related to the complexity of the translation between the stimulus and the response. To the extent that each additional alternative requires a unique translation into a response, we can expect some increase in RT.

No single variable or process will account for the range of performance that is observed. Analogous to the observations made by Ryan (1983), no single factor can explain whether controlled or automatic processing will emerge in search tasks. Performance is influenced by multiple factors as revealed, for example, by the range of variables influencing trial-to-trial effects in choice RT tasks (Soetens, Deboeck, & Hueting, 1984). A similar conclusion can be reached about the multiple contributions to context effects (Taylor, 1977). An information processing framework, although usually utilized to isolate cognitive processes (analysis), also provides a framework for the integrative functioning of the processes (synthesis).

Spelling-to-Sound Translation

Brooks (1977) translated real English words into an artificial alphabet and asked subjects to learn the original pronunciation of the words presented in the artificial alphabet. The same subjects were also asked to learn stimuli that had the stimuli and responses re-paired so that the new alphabet was no longer a useful guide to pronunciation. Figure 4 lists an example of the alphabets, and the stimuli and responses used in the experiment. In the orthographic condition, each of the artificial letters corresponds to an English letter. In the paired-associate condition, the stimuli are re-paired with the responses so the regularity between spelling and sound is lost.

Subjects were asked to read aloud lists of six items as fast as possible without error. Although the paired-associate list was initially read faster than the ortho-

Stimuli	Responses	
	Paired Associate	Orthographic
[illegible]	TANS	PENT
[illegible]	SANE	PEAT
[illegible]	PEAT	SANE
[illegible]	SAPS	TAPE
[illegible]	PENT	TANS
[illegible]	TAPE	SAPS

Fig. 4. Illustration of an experiment to test the importance of an alphabet on fluency. For each subject, one list has a functional alphabet and one does not. Each subject is given 400 trials of practice naming the words in each of the two lists. Which list is orthographic (has a functional alphabet) is counterbalanced across even- and odd-numbered subjects. (After Brooks, 1977)

graphic list, the asymptotic reading times of highly practiced subjects were significantly faster for the orthographic than the paired-associate condition. In the second experiment, the component letters were concatenated to form glyphic patterns, making it difficult to recognize the component letters. Even though the glyphic calligraphy was read faster than the words made up of discrete letters, the orthographic patterns were still read faster than the paired-associate patterns at asymptote. In the Brooks study (1977), words that looked similar were pronounced similarly in the orthographic condition but not in the paired-associate condition. Therefore, the advantage of the orthographic condition over the paired-associate condition could reflect the correspondence between spelling and pronunciation in the former but not the latter condition. This facilitation with the orthographic patterns would be located in the percept-act translation stage in our information-processing model.

Singer (1980) replicated the findings in a lexical decision task, even when the subject did not learn the pronunciations of the test words. Not surprisingly, the constraints built into the test words influence other stages in addition to percept-act translation. In this case, the orthographic redundancy is effective in facilitating perceptual recognition of the test words (Massaro, 1979). Letter and word recognition is easier to the extent that the letters conform to the spelling constraints in the language. Partial information about a string of letters, when combined with knowledge about spelling, can lead to correct recognition - even though each of these is insufficient taken alone (Massaro, 1975b).

Sound-to-Movement Translation

Simon (1969) presented a test tone to the right or left side of subjects, and their task was to move control handle toward or away from the side of the test tone presentation. Subjects were significantly faster in responding toward the test tone than away from the test tone. This result was described in terms of a natural tendency to react toward the source of stimulation (see also Simon, Small, Ziglar, & Craft, 1970).

Simon et al. (1970) extended the Simon (1969) study in the following manner. Two test tones differing in frequency were used. The test tone frequencies were 200 and 500 Hz, respectively. Half of the subjects were instructed to press a right

key to the low tone and to press a left key to the high tone. The other half of the subjects were given the opposite tone-key rule. The tones were presented to either the left or right side of the subject. The RTs between the tone presentation and the onset of a key press were significantly longer when the ear of the test tone presentation conflicted with the meaning of the tone command. That is, longer RTs were observed when subjects had to hit a key on the opposite side of the tone presentation.

Logically, we might interpret the results of Simon et al. (1970) in terms of the perception-action stage of processing. Given recognition of the pitch of the test tone, subjects must select the appropriate response given the tone-key press rule. The rule states which key should be pressed to each of the two possible pitches of the test tone. Evidently, it takes subjects longer to select the response to the appropriate key when the location of the test tone conflicts with the location of the key to be pressed. Hearing the test tone at a particular location might produce a natural tendency to respond to that location. This would interfere with selecting the key in the opposite location and, therefore, would be longer in this condition.

However, the single-factor experiment of Simon et al. (1970) does not unambiguously locate the stage of processing responsible for the results. One might also argue that recognition time is responsible for the observed differences. Subjects might have more difficulty recognizing the pitch of the test tone when its location of presentation conflicts with the key-press location required by that test tone. Consider the situation in which the subject is instructed to respond with the right key when the high tone is presented. Given this rule, the subject might be biased to hear any tone on the right side as high. This bias would tend to increase the recognition time when the location of the test tone conflicts with the location of the response.

As can be seen by the above analysis, the stage of processing responsible for the effect of stimulus-response compatibility is not known. The additive-factor method can be used to locate the stage or stages of processing responsible for a particular experimental finding. The key feature of this method is to manipulate two or more variables in the experiment, and to observe the pattern of results. To disambiguate the issue, it is possible to manipulate a variable that is expected to influence the recognition stage of processing. The frequency difference between the two test tones can be assumed to influence recognition time. To the extent that there is a large difference between the tones, we can expect recognition time to be short. Decreasing the frequency difference can be expected to increase recognition time. The critical result of interest is whether this variable adds with or interacts with the stimulus-compatibility variable. If the latter variable influences only perception-action translation, then the effects of the two variables should be additive. If stimulus-response compatibility also influences recognition time, then the two variables should interact.

In an unpublished study, we manipulated the frequency difference between the two test tones. In the easy recognition condition, the test tones were 600 and 1400 Hz. In the difficult recognition condition, the test tones were 800 and 1200 Hz. Depending on the location of the test tone, the response will be either compatible or incompatible. If the tone and key are on the same side, the response is compatible. When the tone and key are on opposite sides, the response is incompatible. The results shown in Fig. 5 revealed the main effects of stimulus discriminability and stimulus-response compatibility but no interaction between the two factors.

We have interpreted the Simon effect terms of stimulus-response compatibility. Additional support for this interpretation has come from recent experiments by Inhoff et al. (1984) and Nicoletti and Umiltà (1984). Inhoff et al. showed additivity between the Simon stimulus-response compatibility manipulation and number of discrete responses in the judgment (see Fig. 2). Subjects were required to make one, or three responses to compatible or incompatible locations specified by the stimulus cue. Figure 2 shows that RTs of the first response were longer in the incompatible relative to the compatible condition and increased systematically with increases in the number of required responses. The joint effects of these variables was additive. Nicoletti and Umiltà showed that the Simon effect was equivalent to a spatial compatibility effect in which a subject is required to encode relative positions of the stimuli.

Dual-Task Performance

Results from dual-task experiments also support the important role of stimulus-response compatibility in human performance. McLeod and Posner (1984) had subjects perform the Posner Letter Match Task on every trial, producing a same-different response to two visually and sequentially presented letters. In half the trials, the subjects received one of two possible auditory probes. In one condition, the probes could be the word "high" requiring the subjects to say the word "high,"

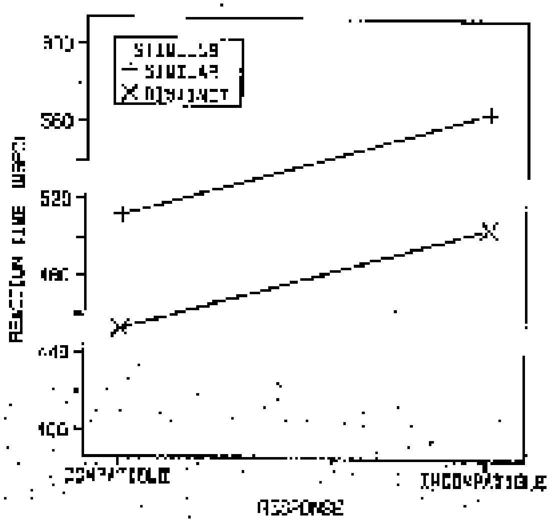

Fig. 5. Reaction times as a function of stimulus discriminability and stimulus-response compatibility (Massaro, unpublished results)

or a 400-Hz square wave tone requiring the subjects to say "low." RT to the probe tone varied systematically with the temporal location of the probe during the letter-matching task. On the other hand, the RT to the word "high" was independent of its temporal occurrence during the letter-matching task. The letter-match same-different RT was influenced by both types of probes so that the independence was not symmetrical.

McLeod and Posner (1984) propose that auditory-vocal (actually speech-vocal) tasks function as a privileged loop which is a special class of input-output transformation that are separate from the general information-processing network. This property allows these privileged loop operations to be performed with relatively little interference from other cognitive activities. However, Pasp and Ogden's (1981) point about the appropriate control for the probe RT may be important here. The RT to naming the word "high" was significantly longer in the dual-task than in the single-task condition, and therefore we cannot say that the privileged loop task occurred independently of the same-different letter-matching task. In addition, we might expect that visual information with the same stimulus-response compatibility would be equally easy. For the primary task in this situation, we could present the auditory letters *a* and *b* or *a* and *a* and have the subject move a lever left and right to indicate whether the letters match or mismatch. The probe task would be either the reading of a word "up" and the reading of a nonsense symbol presented in a particular spatial location as "down". My proposal is that the probe RT task with reading the written word "up" will show very little interference from the same-different matching task analogous to the auditory word "high" in the probe task during the visual matching task. If this result obtains, there is not necessarily an auditory-vocal privileged loop. Both results would simply reflect high stimulus-response compatibility conditions in which information about the response is specified in the stimulus (see Greenwald, 1972; Greenwald & Shulman, 1973).

Perception-Action Compatibility

"Stimulus-response compatibility" is a misnomer in that perception-action compatibility is the predictive variable. Usually, stimulus-response compatibility maintains its predictive value because of its close correspondence with perception-action compatibility. A recent study pulled apart these two descriptions of compatibility in a serendipitous way (ten Hoopen, Akerboom, & Raaymakers, 1982). The authors failed to replicate Leonard's (1959) classic study showing that high stimulus-response compatibility can lead to a violation of Hick's law. Leonard stimulated the fingertips with a 50-Hz vibration, and the task of the subject was to press the key of the finger that had been stimulated. Ten Hoopen et al. (1982) observed an increase in RT between four and eight choices, and they realized that the vibrations in their experiment were relatively weak.

To assess whether the amplitude and frequency of the vibrations might be important, they systematically varied the frequency and amplitude of the vibrations along with the number of alternatives in the task. They found a systematic effect of both frequency and amplitude of the vibration. With high frequencies and high amplitude, a relatively flat RT function like that observed by Leonard (1959) was obtained. On the other hand, with a low-frequency, low-amplitude vibration, RTs increased systematically with increases in the number of choices. An analysis of the error rates revealed a systematic increase in errors with increases in the number of choices for the low-frequency, low-amplitude condition. The ten Hoopen et al. results replicate previous experiments showing that stimulus discriminability interacts with number of choices (Sternberg, 1969; Sanders, 1980). Given highly confusable percepts, the translation process going from perception to action becomes more difficult, and thus one observes an increase in RT. With highly discriminable stimuli, as in the high-frequency, high-amplitude vibrations, the high percept-act compatibility produces very little increase in RT with increase in the number of alternatives.

Ten Hoopen et al. (1982) used the concept "ideomotor compatibility" to explain the results. Their assumption is that an ideomotor action gives feedback resembling the activity of the stimulus. The argument is that the low-frequency, low-amplitude vibration is not ideomotoric in that the weakly vibrating button activates only Meissner corpuscles, but that the pressing of the button activates both Meissner and Pacinian corpuscles. Thus, the feedback of the button pressing does not totally resemble that of the vibration. On the other hand, the high-frequency, high-amplitude vibration stimulates both types of corpuscles which would then also be simulated with the appropriate action. However, this explanation seems to require some kind of advanced processing, in that feedback of the response must further activate the response to speed it up. A test of this idea would be to measure the dynamics of the movement, so that the onset of the movement could be measured, as well as the movement time itself. My prediction would be that the onset of the movement would show the same results as the key press observed by ten Hoopen et al., making their version of the ideomotor compatibility explanation unreasonable. This conclusion follows because the onset of the movement should not be influenced by feedback from the touch receptors, and, therefore, no increase in RT with the number of alternatives should be observed. It is not necessary to postulate separate systems since percept-act compatibility is sufficient to explain the results.

Percept-act compatibility will, in many cases, be an empirical question. Consider an impressive finding by Rosenbaum, Gordon, Stillings, and Feinstein (1987). Subjects were presented with a tone that was high or low in pitch and had to respond with a spoken syllable /gi/ or /gu/. The vowel /i/ is high in subjective pitch, whereas the vowel /u/ is low in subjective pitch. An intriguing possibility is that responding /gi/ to the high tone and /gu/ to the low tone would have more percept-act compatibility than the opposite pairing. Indeed, the reaction times for the onset of the spoken response in the compatible condition averaged 88 ms faster than the incompatible condition. In addition, this compatibility effect was additive with a motor-programming effect involving the number of syllables in the spoken response "Spelling-to-Sound Translation," (see Fig. 2). Given a percept-act compatibility effect with a pure tone and a spoken response, we might expect that there are a multitude of similar effects yet to be discovered. What seems problematic is the development of theoretical framework that would predict these effects a priori.

Communication Between Perception and Action

Miller (1982) has accumulated important relationships between perception and action. Although his work is formalized within testing the distinction between discrete and continuous stage models, it is relevant to the relationship between perception and action. If perception and action are considered as two stages of processing, an important question is whether these stages of processing can overlap in time. In Miller's terms, the question is whether response preparation can begin before stimulus identification is complete, or whether the stimulus must be completely identified prior to any response preparation or activation. Miller's novel technique is to control the information available at various times during stimulus identification by making some relevant stimulus characteristics easy to discriminate and some difficult to discriminate. The question is whether the stimulus characteristics which are easy to discriminate could be used for response preparation before the stimulus was completely identified, i.e., before the stimulus characteristics which are difficult to discriminate were also resolved.

Consider an experiment with four letters created by independently varying the size and identity of the letters. Two stimulus sets were used; there were large and small S's and T's in one condition, and capital and lower-case I's and T's in the other condition. Pilot results indicated that letter discrimination could be made about 85 ms faster than the size discrimination in the first stimulus set (sSiT), whereas the size discrimination could be made about 72 ms faster than the letter discrimination in the second stimulus set (iIiT).

The utilization of partial information about the stimulus could be observed by the response requirements in the task. The usefulness of partial information was varied by manipulating the assignments of particular stimuli to responses. On each trial, subjects responded to one of the four stimuli with one of four fingers, two on each hand. Two responses made by the same hand can be prepared together more efficiently than two responses made by different hands. The preparation of two response fingers on the same hand has been shown to be more effective than preparation of two response fingers on different hands (Rosenbaum, 1980).

Subjects responded more quickly if the large and small versions of a given letter were assigned to the same hand for both stimulus sets. Subjects also responded more quickly if the two large letters were assigned to one hand and the two small letters were assigned to the other hand, but only when the size discrimination was very easy relative to the letter discrimination, that is, in the letter set (iIiT). Thus, separate or discrete attributes of the stimulus could be encoded before the stimulus was completely identified, and this information could be passed on and influence response preparation. The idea is that determining that the letter is a large letter even though the letter has not yet been identified can tell the subject which hand is relevant and thus decrease RT relative to the case in which the two letters of the same size are not assigned to the same hand. Analogously, and much more intuitively, if the letter name is assigned to a given hand so that both the large and small versions of a given letter are responded to on the same hand, then determination of the letter name can aid response selection even though the size of the letter has not been completely determined to identify uniquely the alternative as one of four alternatives.

However, now consider the stimulus set with the capital letters M, N, U, and V. Information obtained early in processing can constrain the stimulus to be one of the two letters M or N versus one of two letters U or V. Thus, this information derived before the letter was completely identified could inform the subject about which pair of letters was present in the display. If subjects are able to utilize this information for response preparation, then the subjects should be faster in responding when the letters M and N are assigned to one hand and U and V are assigned to the other relative to the case in which these letters are assigned to different hands. This was not the case, however, in that no facilitation was observed. The explanation is that the information could not be encoded in terms of a discrete code to pass on to response preparation. In these simple information-processing tasks, information appears to be transmitted discretely from perception to action in terms of stimulus codes. Information that is not encoded discretely does not constrain response preparation.

Meyer, Yantis, Osman, and Smith (1984) found similar results in a priming task. Subjects performed a choice RT task to a test stimulus preceded by a priming stimulus. The priming stimulus completely predicted the test stimulus and, therefore, the response that would be required. The test stimulus followed the prime after a short, medium, or long delay interval. A discrete stage model predicts, according to the authors, that the RT to the test will be determined by either the prime or the test. That is, there must be no interaction between these two horses in the race. A cascade model, on the other hand, predicts an interaction between the horses in the race. In fact, no interaction was found in a two-choice task with compatible stimulus-response mappings. Although these results can be taken as evidence for a discrete stage model, the opposite results would not necessarily disprove a discrete stage model. It is possible that there are successive evaluation and integration process leading to a response. Although the evaluation process might function in a manner that treats the two stimuli as independent horses in a race, the information from the prime and test stimuli could be integrated by the integration process (Massaro, 1987). This integration could provide more information than provided by either one of the two stimuli at the evaluation stage. The integration would lead to response facilitation not predicted by two independent horses in a race. In principle, a discrete stage could still be consistent with the results. Some results with four alternative responses and incompatible stimulus-response mappings, in fact, were inconsistent with their version of the discrete model (Meyer, Yantis, Osman, & Smith, 1985). However, it remains a possibility that the discrete stage model is valid, but that the information is integrated and the response is selected on the basis of the integrated information (Massaro, 1987).

The role of categorization in perception and action is apparent in studies of the relationship between speech perception and production (Pickett, 1985; Repp & Williams, 1985). A classic study of speech perception and naming was carried out by Chistovich, Fant, Serpa-Leitao, and Tjernland (1966). A speech continuum between adjacent vowel categories was synthesized, and subjects were required to echo each vowel as it was presented in random order. There was no one-to-one relationship between the formants of the stimulus and the formants of the response; subjects achieved a good imitation for only the three canonical vowels. Repp and Williams (1985) found similar results for synthetic vowels between /i/ and /u/ when the authors imitated the vowels as much as possible. Given that it is well known that the vowels along the continuum could be differentiated, the observations reject a direct link between perception and action. Categorization intervenes between the two, and action is controlled by this categorization rather than the perceptual processing that led to the categorization. This mediation is not surprising for the discrete messages of language. Morton (1979) found it necessary to distinguish between input and output logogens in his model of language processing, for example, and it should be worthwhile to evaluate the relationship in other domains that are less discrete.

Categorization of Natural Objects

Attention to perception and action relationships illuminates research findings in the categorization literature. It is now well known that typicality predicts the facility with which subjects categorize instances as belonging to different categories (Rosch, 1978). Asked to categorize instances as members of categories such as bird, dog, car, and boat, subjects responded much more quickly to typical than atypical instances. The explanation of these results could be in terms of the "entry point" concept (Jolicoeur, Gluck, & Kosslyn, 1984) or the level of abstraction first identified by the observer. The time for categorization can be considered to be a function of the degree of association between the entry point of an object and the category name. Viewing a picture of a sparrow, the entry point level is bird, and categorization in the category bird is very easy. Viewing a picture of a duck, however, the entry point level is duck, and more time is needed to access the appropriate superordinate category. Supporting evidence also comes from neurological patients who succeed in reading aloud many more object names (banana and chair) than superordinate nouns (fruit and furniture) (Funnell & Allport, 1987). This explanation is at the level of percept-act translation in our six-stage model. Objects differing in typicality differ from one another in terms of the time needed to translate between their perceptual code and superordinate category code. We expect that similar results would occur if words rather than pictures were presented. In fact, Jolicoeur et al. (1984) found a positive correlation between words and picture in this task.

Spatial Linguistic Processing

Brooks (1968) offered a dramatic demonstration of the importance of the relationship between perception and action (i.e., between stimulus-processing and response-processing requirements in the task). Subjects performed some task with two different types of stimulus material and three different types of response. In the visual-spatial task, subjects imagined blocked letters such as the F shown in Fig. 6. They were required to scan the image from a particular starting position and in a given direction and to indicate at each corner "yes" when the point was at the extreme top or the extreme bottom of the letter, and "no" otherwise. For the example in Fig. 6, the answers would be "yes, yes, yes, no, no, no, no, no, no, yes". In the linguistic task, subjects were given a sentence to remember such as, "A bird in the hand is worth two in the bush." Their task was to indicate "yes" or "no" whether each successive word was a noun. Subjects made their responses for both tasks in one of three ways, by saying "yes" or "no", by tapping with their left and right hands, and pointing to Y's and N's arranged randomly on a sheet.

Table 2 gives the mean performance times to complete the six different tasks. Given that the two tasks differ in difficulty, the absolute times are not at issue but rather the interactions between stimulus material and response output. For the pointing and tapping responses, the visual spatial task is three and two times more difficult than the sentence task. For the vocal response, on the other hand, the sentence task is 20% more difficult than the visual task. Contrary to what might be expected from stimulus-response compatibility, subjects find it more difficult to act spatially to spatial perceptual processing and to act linguistically to linguistic input. These results occurred because of the relatively arbitrary relationship between the perception and action tasks. In this case, both perception and action required relatively unique operations, and it was more optimal for the systems to divide perception and action across spatial and linguistic processing rather than to utilize just one of these for both the perception and action tasks. In this situation, perception and action are two tasks, and there is more conflict between the two tasks when they are both carried out spatially than when the two tasks are performed spatially and linguistically, respectively.

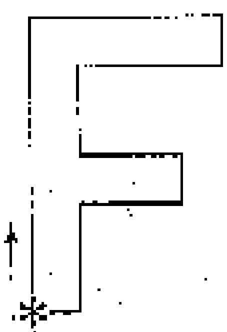

Fig. 6. An example of a simple block diagram used by Brooks (1968) to study the scanning of mental images. The asterisk and arrow showed the subject the starting point and the direction for scanning the image.

Table 2. Mean performance times in seconds for the visual-spatial and the memory-linguistic task.

	pointing	tapping	vocal
visual-spatial	28.2	14.1	11.3
memory-linguistic	9.8	7.3	13.8

Specificational Versus Indicational Information

Pattee (1974) has developed the distinction between *specificational* and *indicational/injunctional* types of information, and this distinction has been important in recent neo-Gibsonian theories (Kelso & Kay, 1987; Turvey & Kugler, 1984). Specificational information implies that the environment constrains or specifies the appropriate action, whereas indicational information only indicates what actions are appropriate. The former supposedly specifies how the action is to be performed, whereas the latter indicates only that a given action should be performed. This distinction seems to illuminate to some extent the nature of the perception-action interactions that are observed. Consider the results of our extension of the Simon et al. (1970) study, however (Fig. 5). Can we claim that the tone in the compatible response situation specified the response, whereas it only indicated the response in the incompatible condition? No, because the influence of stimulus-response compatibility is a continuous variable and cannot be captured by a qualitative distinction. That is, it would be easy to create a situation between the two levels of compatibility such as presenting the tone at the middle of the subject's head. The results would resemble neither of the previous two conditions, but would fall somewhere between them. The qualitative distinction would fail to explain the three different results.

The specificational mode of information description can, on the other hand, illuminate some other perception-action relationships, however. Expansion of the retinal image of a surface can provide reliable information about the time to contact that particular surface (Lee & Reddish, 1981). How does this information specify some action, however? A gannet, a large seabird, diving for its prey, must retract its wings before hitting the water's surface. Although time to contact can not specify wing retraction to the gannet, it can provide continuous information about rate of contraction. Time to contact indicates wing retraction and specifies perhaps the time course of retracting its wings. Is the gannet behaving qualitatively differently from a teenager approaching a stop sign with her mother's new car? The stop sign indicates one must stop (or at least slow down) at the impending intersection, while, supposedly, the rate of expansion of the retinal image specifies how to slow down. Admittedly, the latter information provides the detail about the visual world needed to stop the car at the appropriate place and time, whereas this detail is not provided by the word *STOP*. The rate of expansion does not specify the action, however. The action must still be selected from a repertoire of actions; the driver could release the gas pedal, shift into a lower gear, apply the brakes, begin looking both ways to run the stop sign if nobody is coming, or engage in some subset or all of these actions. Gibson's concept of affordance notwithstanding, I remain to be convinced that the rules of perception will disambiguate rules of action and the relationship between the two. We will need rules of perception, action, and of the translation between the two.

Similarly, reference to different modes of description of information (Pattee, 1974) - the discrete, symbolic rate-independent mode and the continuous, dynamic, rate-dependent mode - will not predict perception-action interactions. The hope for the neo-Gibsonians might be that, although the former is not sufficient to control action, the latter is. We might expect that much less translation between perception and action would be needed for dynamic relative to symbolic information. A counter example to this expectation might be the vocal articulation of the word *bird* to either the object or to the written word. Reaction time is faster to the word than to a picture of the object (Lupker, 1979; Lupker & Katz, 1982; Theios & Amrhein, 1989), and yet the written word fits the symbolic mode to a greater degree than does the object. Although this counterexample should not be taken to preclude further study of these two different modes of description, it indicates to this observer that perception-action interactions will not be totally explained by the mode of information description.

Stimulus-Response Compatibility Versus Separate Cognitive Systems

We have used the notion of stimulus-response compatibility to clarify perception-action relations. An alternative view is to postulate separate cognitive systems such that performance is efficient if perception and action occur within a system and difficult if they occur between systems. [The Brooks (1968) study discussed in the section "Categorization of Natural Objects" above, would be a counterexample.] We address these contrasting interpretations in an old and venerable task which is as challenging today as it was at the time of its introduction (Stroop, 1935).

Stroop Color-Word Findings

The role of stimulus-response compatibility has been used to explain Stroop color-word interference first reported by Stroop in 1935. Subjects are asked to name as rapidly as possible the color of various stimuli, such as the print of a color name. A color word that specifies a different name than the color of its print can produce large interference and increase the naming time of the color. McClain (1983) modified the Stroop color-word situation to demonstrate the contribution of stimulus-response compatibility. An auditory analog of the Stroop task was developed

with the words "high" and "low" sung in high and low pitches. Each stimulus had two dimensions, word and pitch, and the two dimensions could be either congruent or incongruent.

Subjects were asked to respond to either the pitch or the word dimension with either a high or low verbal response or a high or low humming response. When the word was the relevant dimension, there was no difference between incongruent and congruent test stimuli. That is, subjects could verbally name the appropriate word regardless of the pitch that the word was sung in. On the other hand, when subjects were required to hum the word, the incongruent stimulus gave significantly slower responses than the congruent stimulus. The analogous results occurred when the relevant dimension was pitch. No difference between the congruent and incongruent test stimuli was observed when subjects were required to hum the pitch dimension. On the other hand, large differences were observed between the congruent and incongruent test stimuli when subjects were required to name verbally the pitch dimension. Thus, subjects were able to ignore the irrelevant dimension when the response that was required was compatible with the relevant dimension. When the response was incompatible with the relevant dimension, and therefore compatible with the irrelevant dimension, significant interference effects were observed. Although these results might not account for all versions of the Stroop interference and facilitation, they point to the important role of stimulus-response compatibility in the task.

Virzi and Egeth (1985) replicated and extended these findings in both the color-word situation and a new situation. Subjects are presented with the word "left" or "right" presented in a spatial location to the left or right of fixation. The subjects respond to either the spatial location of the stimulus or its meaning. The response is either hitting a left or right button or responding with the words "left" or "right". This factorial design combines two modes of presentation with two modes of response. Half of the trials are congruent (e.g., word "left" presented on the left side) and half are incongruent (e.g., word "right" presented to the left of fixation), as in the Stroop Color-Word Task. Subjects make the appropriate decision, and reaction times are recorded. In the compatible situation, subjects are responding to spatial location with the button pushing, and, in the incompatible situation, subjects are responding to the word with a button push. If subjects are asked to respond to the meaning of the word, the vocal response RTs show no difference between the congruent and incongruent situations. However, there is a large difference if subjects are asked to make a manual response to the meaning of the word. Analogously, if subjects are asked to respond manually to the location of the word, there is no difference between the congruent and the incongruent situation but a large difference if subjects have to name or use linguistic output with respect to the location of the word in the display.

According to Virzi and Egeth (1985), these results cannot be explained by simple stimulus-response compatibility, but must be explained in terms of having two cognitive systems. The idea is that each cognitive system codes and processes information in a way that is specific to that system. Some systems have a response stage perfectly suited to the information that that system processes. This model is reminiscent of McLeod, McLaughlin, and Nimmo-Smith's (1985) idea of information encapsulation. A particular perceptual system can resolve and transmit information very quickly to a particular motor system. In their study, information about time to contact of an object approaching could be transmitted very quickly to a motor response of hitting the approaching object with a bat but could not be translated into a judgement about when the object would arrive at a given location in space. The idea of different systems is also reminiscent of the concept of modularity as articulated by Fodor (1983).

With respect to the Stroop task, translation between the two systems is required when the stimulus and response come from two different systems. For example, responding with the word "left" to the word "left" can be carried out within a single linguistic system. Responding with a button push, however, would require a translation between two systems. Although information may be translated from one system into the code of another system, the translation process takes time. Rather than postulating separate systems, however, it seems that the concept of stimulus-response compatibility might be capable of handling the results. Some translation is always required from a perceptual code into an action code. The nature of the translation will influence the time for this stage of processing.

A third condition of the McClain (1983) study might distinguish between the translation model of Virzi and Egeth (1985) and the present interpretation in terms of stimulus-response compatibility. In this condition, subjects had to respond by hitting a button, with the two buttons labeled "high" and "low." In this case, no difference between the congruent and incongruent conditions occurred when the relevant dimension was the word, whereas significant differences occurred between these two conditions when the relevant dimension was the pitch. According to the translation model, it seems that a translation would be necessary to go from the word dimension to the button push, because these would not be capable of being emitted by the same system, yet no interference was observed. The results indicate instead that encoding pitches into verbal labels is not necessary, and therefore no difference between the incongruent and congruent stimulus conditions is observed. Thus, in addition to stimulus-response compatibility, we have the factor of whether or not a stimulus dimension must be encoded. Perhaps if the subjects were taught that the buttons correspond to high and low pitches or if the buttons were placed high and low on a response panel, then differences would be observed between the congruent and incongruent conditions when the relevant dimension was a word, but not when the relevant dimension was the pitch. Thus, it would not be whether or not the response followed within a system without any translation, but rather the stimulus-response compatibility between the perceptual code and the action code.

Virzi and Egeth (1985) state, "The main conclusion reached is that the translational model provides a useful model of dual attribute processing" (p. 316). This conclusion must be considered an overgeneralization because the authors in no way provide a complete model of dual-attribute processing. The authors' work, like much of the previous work on Stroop, is aimed at discovering a single explanatory principle of the Stroop phenomenon. The literature reveals multiple influences and determinants of Stroop interference (e.g., Regan, 1978) analogous to other domains such as context effects and priming (La Heij, van der Heijden, & Schreuder, 1985). In addition to the focus on a single explanatory principle, the research is carried out in terms of a confirmation bias, in that research is developed only to confirm rather than to falsify the explanation. The Stroop phenomenon is a complicated piece of performance and will not be explained in terms of a single variable or process. It engages most of the stages of processing developed in our prototypical information-processing model and will thus be affected by variables that affect each of these processing stages. An explanation of the Stroop phenomenon will involve the contribution of several stages in the information-processing model.

The translation mechanism proposed by Virzi and Egeth (1985) also reflects the bias of investigators to assume qualitative mechanisms to explain experimental results. Thus, a Stroop effect occurs when a code must be translated from one system to another, whereas no Stroop effect occurs when no translation is necessary. However, one can expect that such an all-or-nothing process does not exist. In all cases, a translation is necessary between a perception code and an action code, and the translation process will depend on stimulus-response compatibility. Thus, translation requires time, and the amount of time will be directly related to the incompatibility between the perception and action codes. Also, there is no reason to assume different cognitive systems to explain the results. It is only necessary to assume, as in fuzzy logical model of perception (Massaro, 1987), that attributes are processed in parallel and independently of one other at the feature evaluation stage of processing. These attributes are usually integrated to provide perceptual identification, and a pattern is classified. The unique feature of the Stroop task, as in other attention experiments (Treisman, 1969), is that subjects are required to report a given attribute and ignore some other attribute (see van der Heijden, this volume). Given this type of task, we should ask the following kinds of questions: (a) are the two dimensions processed independently of one other (see Ashby and Townsend, 1986); (b) is one dimension processed more quickly than the other; (c) to what extent can a response be selected on the basis of only the relevant dimensions? The similarity between the Stroop situation and other tasks is reinforced by the observations of La Heij et al. (1985). They uncovered common processes in the priming task in which an irrelevant stimulus facilitates performance and the Stroop task in which interference is observed. Semantic facilitation and response competition occur in both types of tasks, but to different degrees depending on the number of semantic domains/response alternatives in the task.

The idea of different cognitive systems also loses its explanatory force, as anticipated by Virzi and Egeth (1985), when empirical results require postulation of a plethora of cognitive systems. The authors acknowledge that one will have to assume separate cognitive systems for colors, written words, positions, auditorily presented words, pitch, numerosity, and digit identity. Given the ease with which it is possible to construct analogs of the Stroop Color-Word Task, the number of cognitive systems will have to grow with the number of independent attributes in our perceptual world. Thus, we can imagine Stroop results in situations in which subjects have to process the size, shape, depth, brightness of a word independently of its meaning. Similarly, several attributes could be varied in the auditory domain and even the tactile domain, and so on. One critical distinction, however, might be that linguistic and nonlinguistic codes are responsible for the Stroop effect. The two attributes, linguistic and nonlinguistic, are not usually integrated in our perceptual world, whereas other attributes within each of these two dimensions are usually integrated for decision and action.

One critical component of the Stroop Color-Word Task seems to be that one of the two dimensions be represented in a way that the surface structure stimulus specifies a given response, as in a written word specifying the name of the word. Interference occurs when the name of the word conflicts with the required response to the relevant dimension. In McClain's (1983) experiment, subjects required to hum the meaning of the word showed interference when the word was sung in a high or low pitch. In this case, it is necessary to assume that singing the word in a high or low pitch specified humming high or low which then interfered with humming the relevant word dimension. Consistent with previous interpretations of the Stroop task, it appears that the Stroop phenomenon requires that the response mode be primed in the Stroop task which is then easily captured by the irrelevant dimension. In McClain's experiment, subjects were primed to hum high or low, and the singing of a high or low pitch captured the response mechanism and therefore interfered with humming the meaning of the word.

One test between the two viewpoints might involve manipulating the stimulus-response compatibility in the Stroop task by re-pairing the stimuli and responses within a "cognitive system." In one condition, the word would be the relevant dimension but it would be pronounced by another color name. The word red would be called blue, for example, and so on. If the linguistic system could function independently of the color system, then no difference should be found between this condition and (a) a control condition with the words printed in a neutral color; or (b) a facilitation condition with the words printed in the color appropriate for the response. Although a translation between the color and the verbal label might not be mandatory (Dunbar & MacLeod, 1984) we expect effects of stimulus-response compatibility to interact with Stroop interference even when separate cognitive systems are not a viable explanation. Analogously, colors could be paired with colored patches pressed manually and the stimulus-response within the "color system" varied by repairing stimulus colors and response presses. Once again, stimulus-response compatibility should interact with Stroop interference even though the stimuli and responses are within the same color system.

Two Visual Systems

There has been much interest in the idea of two visual systems in vision, one serving cognitive function and one serving motor function. These systems have also been referred to as serving the functions of object recognition and object location. Consider the evidence that is normally used to support the idea of two visual systems. Subjects are given some visual display and asked to make some

judgment about the display. The judgment consists of a verbal report or a motor response. For example, a target might be moved in a visual field, and the subject is asked either to report verbally whether the target moved or to point at the new location of the target. Results have shown that subjects are able to point accurately at the location of the dot even though they fail to report verbally a displacement in the target. This result has been taken to mean that the motor system has access to information that is unavailable to the verbal cognitive system (Bridgeman, Lewis, Heit, & Nagle, 1979). Similarly, the target could be induced to appear to move by movement of a background even though it did not (Bridgeman, Kirch, & Sperling, 1981). The background position did not influence pointing to the target, however. This double dissociation between the verbal report and pointing responses does not necessitate two visual systems. Both judgments could be mediated by the same visual information, but with the function relating the judgment to the visual information differing for pointing and verbalization. Birnbaum (1981) has given an analogous interpretation of the differences observed between cognitive and affective reports of experience (Zajonc, 1980). In this case, it is not necessary to assume separate affective and cognitive systems. Similarly, Roediger (1984) points out that a dissociation might reflect different processes rather than different systems.

More parsimoniously, consider relative movement with respect to a frame and absolute movement with respect to oneself as two forms of information. The first might be given the most emphasis in the verbal judgment and the latter given the most emphasis in the pointing judgment. The functions relating these two sources of information to the verbal and pointing judgments might differ from one another, as illustrated in Fig. 7. Both judgments are influenced by both forms of information, and there is no need to postulate two visual systems. Another interpretation of these phenomenon is to postulate not two visual systems, but a translation stage

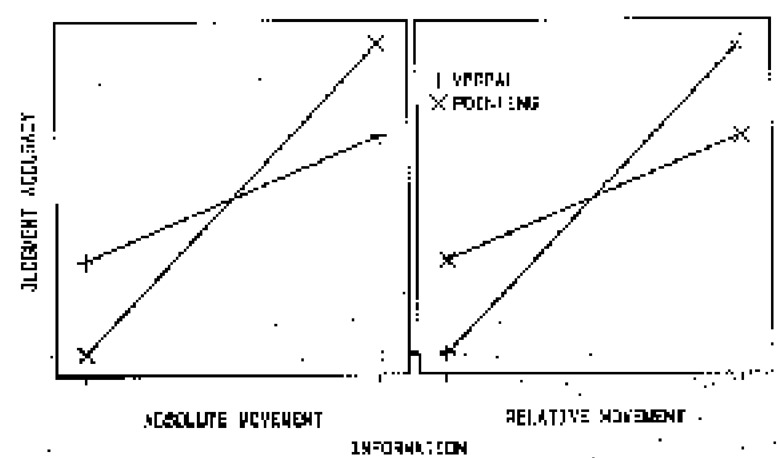

Fig. 7. Hypothetical functions relating judgment accuracy of the two types of judgment as a function of the two types of stimulus information

between perception and action. In this case, the same perceptual information would be available to verbal and motor processes, but the translation might work differently for the two modes of action. Stimulus-response compatibility might account for some of the differences that are found for these two modes of action. For example, pointing to target is more compatible than verbally reporting the location of the target changed, because the latter requires a more elaborate translation between a perceptual dimension and a verbal dimension.

The reluctance to propose two different systems is based on the eventual need for a plethora of cognitive systems. One might ask whether analogous phenomena in related domains demand separate systems. For example, does the visual information that support pointing come from different systems depending on the distance of the object from the observer? Do we have a different system handling information within our reach as opposed to outside our reach? Similarly, we can view the visual world in two different modes, the standard three-dimensional mode, and also in what might be considered to be a two-dimensional mode as viewing two-dimensional works of art. Thus, we can respond differently to the same display depending on the mode of responding. Different sources of information may be utilized within the two modes of responding, and, therefore, a double association could be established in this domain as in the cognitive-motor domain. There would also be cross-talk between the two domains, again analogous to more recent results in the cognitive-motor domain. One can see that the number of systems can grow considerably, and one must be cautious about contributing to such growth. If a cognitive report can be found to indicate better sensitivity to location information than a motor action, it would seem to weaken the case for two visual systems.

Conclusion

Survivors of a voyage through this article have experienced a somewhat involved treatment of information processing and how perception relates to action. One guiding principle has been that of parsimony. I have tried to build onto the simplest explanation of relatively complex interactions. Stages of processing and information-processing principles provide a useful heuristic to impose some order on what might appear to be somewhat disorderly results. Most environment-behavior relationships are too complex to be predicted from simple information-processing principles. This failure does not reflect the limitations of the principles, as much as the complexity of the natural world and most experiments. There are no easy solutions; science of the mind and behavior is difficult work. Given the growing number of scientists resonating to the challenges of explaining our behavior, we can expect significant, although slow and gradual, progress in this enterprise.

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