

Dimensional Overlap: Cognitive Basis for Stimulus-Response Compatibility— A Model and Taxonomy

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The classic problem of stimulus-response (S-R) compatibility (SRC) is addressed. A cognitive model is proposed that views the stimulus and response sets in S-R ensembles as categories with dimensions that may or may not overlap. If they do overlap, the task may be compatible or incompatible, depending on the assigned S-R mapping. If they do not overlap, the task is noncompatible regardless of the assigned mapping. The overlapping dimensions may be relevant or not. The model provides a systematic account of SRC effects, a taxonomy of simple performance tasks that were hitherto thought to be unrelated, and suggestive parallels between these tasks and the experimental paradigms that have traditionally been used to study attentional, controlled, and automatic processes.

In this article, we address the classic problem of stimulus-response (S-R) compatibility (SRC). A model is proposed that attempts to provide a systematic account of performance in highly compatible, incompatible, and noncompatible tasks. At the core of our model is the idea that when a particular S-R ensemble produces either high or low compatibility effects, it is because the stimulus and response sets in the ensemble have properties in common, and elements in the stimulus set automatically activate corresponding elements in the response set. Noncompatible tasks are those in which the stimulus and response sets have nothing in common. If the activated response is the required one, it will be executed rapidly and correctly; if it is not, then it will be relatively slow and error prone. Whether a particular S-R ensemble will produce compatibility effects is often quite easy to determine because of the relationship between the stimulus and response sets. In the part of the model that treats the representational aspects of the problem, we postulate that this relationship is based on the commonality, simi-

larity, or correspondence of the sets in the ensemble. We call this the *dimensional overlap* of the ensemble. The automatic response activation mechanisms, as well as the response identification processes underlying SRC effects, are the processing aspect of the model. Even though the model is still in its qualitative development phase, it is able to make ordinal predictions concerning several different SRC effects, such as the effects of mapping, irrelevant dimensions, and number of alternatives. These effects had been viewed as unrelated empirical phenomena, and most of the work on SRC has dealt with them as manifestations of unique, nongeneralizable properties of particular dimensions or specific tasks. This approach has led to different accounts being proposed for "spatial," "symbolic," "sensorimotor," and "semantic" tasks. Our model attempts to break with such past approaches in a fundamental way by proposing to account for most major SRC effects in terms of common basic cognitive mechanisms. This unitary approach leads to a taxonomy of SRC tasks that reveals striking similarities between them and suggestive parallels with the experimental paradigms that have traditionally been used to investigate attentional, controlled, and automatic processes.

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Background on SRC

SRC: The Term

Stimulus-response compatibility refers to the fact that some tasks are easier or more difficult than others either because of the particular sets of stimuli and responses that are used or because of the way in which individual stimuli and responses are paired with each other. For example, if a set of digits are used as stimuli, a particular digit generally can be paired more easily with its own name as the response than with the name of a city

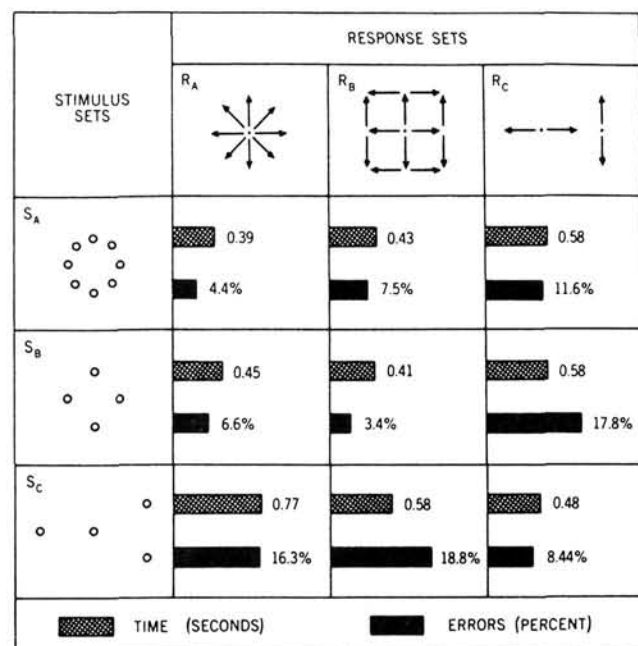


Figure 1. Reaction time and error data for nine different stimulus-response ensembles. (Reprinted from Fitts and Posner, 1967, which was adapted from Fitts and Seeger, 1953, now in the public domain.)

or person. Furthermore, with digit names as the response set, it is generally more difficult to pair a particular digit with another digit's name than with either its own or a city's name. These and other similar effects are among the largest, most reliable, and most robust findings in the laboratory and in everyday life (cf. Fitts, 1959; Norman, 1988). They are also quite general and are not restricted to particular stimuli, tasks, or subject populations. We consider the ubiquity of these effects to be an indication of the fundamental nature of their underlying cognitive mechanisms.

Fitts's Empirical Contributions

SRC as a concept and as a problem owes its existence to Paul Fitts. In summarizing his work on SRC, Fitts (1959) concluded, "we should be very cautious in talking about a 'best type of display code' or about a 'best type of response code'; it is more precise to say that a particular S-R coding *ensemble* [italics added] is better or worse than other ensembles" (p. 7). That is, effective performance depends not on the specific aspects of a particular stimulus or response set but on properties that result from the combination of both sets.

In two classic articles (Fitts & Deininger, 1954; Fitts & Seeger, 1953), Fitts reported evidence for two separate aspects of such combinations. One dealt with properties of the stimulus and response sets themselves; the other dealt with properties of the elements within those sets. The question of set-level compatibility was addressed in an experiment by Fitts and Seeger (1953), in which three different sets of eight spatially arranged stimuli (lights) were combined with three different sets of eight spatially defined responses (movements of a stylus) to generate nine different stimulus-response ensembles (Figure 1). For each en-

semble, the stimulus and response elements were paired to agree most closely with the dominant population stereotype (cf. later). The most significant result was the finding of a strong interaction indicating that for each of the three stimulus sets, a different response set produced the fastest time and the fewest errors. These results were consistent with Fitts's contention that coding efficiency is at least partially determined by the S-R ensemble and not by the properties of isolated stimulus or response sets.¹

Fitts and Deininger (1954) addressed the question of element-level compatibility in a second experiment, in which a set of eight spatially defined responses was combined with three different stimulus sets that varied in their correspondence (cf. below) with the response set. Within each S-R ensemble, they used three S-R pairings: an "optimal" pairing (presumably one that would have corresponded to the highest population stereotype¹), a mirror image of this optimal pairing, and a random pairing (Figure 2). The optimal pairing gave the best performance, and the random pairing gave the worst. However, the most striking result was that the random pairing produced the biggest decrement with S-R ensembles that seemed most compatible at the set level (see the Accounting for the Effect of Mapping section).

With these two studies (Fitts & Deininger, 1954; Fitts & Seeger, 1953) Fitts introduced the concept of SRC into the literature and set the stage for all subsequent studies on SRC, most of which simply capitalized on the extraordinary reliability of SRC effect and merely included SRC as a factor in ongoing experiments. Although the results thus obtained broadened the empirical base of SRC effects, they did not add to the theory to account for them.

Summary of the Experimental Effects of SRC on Reaction Time (RT)

The major empirical findings of SRC are listed in Table 1. A brief selected review of these findings is presented in the framework of a new taxonomy, which is presented later in this article.

The most striking point that these studies bring to light is that SRC effects occur over a wide range of stimulus and response

¹ Even though Fitts (Fitts & Seeger, 1953) did not report having measured the population stereotype for the ensembles in this study, we assume that if he had he would have found that the assigned S-R mappings that he used corresponded to the dominant population stereotype for each ensemble. We further assume that the strength of the population stereotypes for most of these ensembles would have been approximately the same. If Fitts's assertion, that the magnitude of the SRC effect is determined by the strength of the population stereotype, is considered in light of these two assumptions, one would expect the SRC effect for all of these ensembles to be approximately the same. Of course, Fitts did not measure (or define) the SRC effects (i.e., what we call the *mapping effect*) for the ensembles in his study, although he did report the information transmitted. If the latter is considered as an index of SRC effects, we see that performance differs greatly between ensembles. According to the argument that we develop in our model and according to Fitts's implicit position, these differences must therefore be attributed to something other than the population stereotype. This strongly implicates set-level factors, or what we call the *dimensional overlap* in the ensembles.

Correspondence Among the Elements of S-R Ensembles	Stimulus Sets			
	Spatial 2-Dim.	Symbolic 2-Dim.	Spatial 1-Dim.	Symbolic Non-Spatial
Maximum				
Mirrored				
Random				

Figure 2. Reaction time and errors (in parentheses) for four different stimulus-response (S-R) ensembles and the different mapping assignments (from Fitts and Deininger, 1954; in the public domain).

dimensions and encompass many different kinds of tasks. Any model that aims to account for them should therefore be based on broad fundamental principles of information processing rather than rely on special properties of S-R dimensions or peculiarities of selected tasks, as previous theoretical efforts have tended to do (e.g., Duncan, 1977a, 1977b; Simon, 1969; Welford, 1976). We believe that it is precisely because of the restricted and piecemeal approach to the problem during the past 30 years that SRC has remained an atheoretical collection of seemingly unrelated empirical phenomena.

Fitts's Theoretical Contributions

As is true of the two major empirical results, the principal theoretical issues were also first identified by Fitts (Fitts & Deininger, 1954; Fitts & Seeger, 1953). Even though Fitts discovered the experimental basis for the distinction between set- and element-level compatibility, he himself never fully exploited it. In fact, he seems to have been of two minds about it, sometimes blurring the distinction and sometimes sharpening it.

Set-level compatibility. Fitts often described the basis of set-level compatibility in terms of the *congruence* (Fitts & Deininger, 1954, p. 490), *match*, or *correspondence* (Fitts & Seeger, 1953) between "the dimensions employed in forming stimulus sets and response sets" (Fitts & Deininger, 1954, p. 484). He was content to have this match, congruence, or correspondence informally verified by the experimenters "on the basis of the direct similarity of the two [stimulus and response] patterns" (Fitts & Seeger, 1953, p. 201). In a later discussion of the results of his set-level experiment (Fitts & Seeger, 1953), he reaffirmed his belief that the results supported the conclusion that "the

rate at which the perceptual-motor system can process information is a function of . . . the degree to which the sets of stimuli and responses form a congruent match" (Fitts & Deininger, 1954, p. 483). Elsewhere, he stated that "the experiment . . . provides an incidental test of how accurately S-R compatibility can be predicted from a consideration of the correspondence of coding dimensions employed" (Fitts & Seeger, 1953, p. 201).

Clearly, Fitts (Fitts & Deininger, 1954; Fitts & Seeger, 1953) believed that a portion of the SRC effect could be attributed to, and predicted from, a knowledge of the relationship between the set of stimuli and the set of responses (similarity in the case of spatial S-R sets). However, by using the identical terms to talk about set-level and element-level compatibility, that is, *match*, *correspondence*, and *congruence*, and by resorting to haphazard, informal procedures (experimenters' casual judgment of similarity) to determine the degree of set-level compatibility, Fitts minimized the role of the global (set) versus the local (element) factors and, as a result, downplayed the theoretical importance of this distinction.

Element-level compatibility. Fitts (1959) viewed performance in RT tasks as involving the "transformation, translation, and recoding of information, [all of which] are assumed to vary in . . . the time required, and the likelihood of errors, as a function of unlearned and/or highly overlearned behavior patterns" (p. 17). He then goes on: "We shall forego use of the concept of habit strength and shall attempt to predict compatibility effects on the basis of the concept of population stereotype" (Fitts, 1959, p. 19). This concept, as well as the learning principles on which it is based, deals with the relationship be-

Table 1
Six Major Stimulus-Response Compatibility Effects

Effect	Sources
1. Given a stimulus and response set, the fastest reaction time obtainable with optimal mapping is faster if the sets have dimensional overlap than if they do not.	Brainard, Irby, Fitts, & Alluisi, 1962; Brebner, Shepard, & Cairney, 1972; Fitts & Seeger, 1953; Greenwald, 1970; Hawkins & Underhill, 1971; Shulman & McConkie, 1973; Simon, Hinrichs, & Craft, 1970; Stanovich & Pachella, 1977
2. The overall mean reaction time is faster with congruent than with incongruent mapping.	Blackman, 1975; Duncan, 1977a, 1977b; Fitts & Deininger, 1954; Hawkins, MacKay, Holley, Friedin, & Cohen, 1973; Morrin & Grant, 1955; Sanders, 1970; Schwartz, Pomerantz, & Egeth, 1977; Simon, 1967, 1969; Simon & Craft, 1970; Sternberg, 1969
3. The greater the dimensional overlap, the greater the reaction time difference between congruent and incongruent mapping.	Simon & Small, 1969; Wallace, 1971
4. The difference between congruent and incongruent mapping is greater for nonrepetitions than for repetitions.	Bertelson, 1963
5. The increase in mean reaction time when the number of alternatives is increased is greater the less the stimulus-response compatibility, whether it is varied by changing the degree of dimensional overlap or the mapping.	Brainard et al., 1962; Davis, Moray, & Treisman, 1961; Hawkins & Underhill, 1971; Leonard, 1959; Morrin, Konick, Troxell, & McPherson, 1965; Theios, 1975
6. The effects of varying dimensional overlap or mapping with irrelevant dimensions are similar to those with relevant dimensions. (We define a dimension as irrelevant when it has a zero correlation with the required response in the task.)	Broadbent & Gregory, 1965; Costa, Horwitz, & Vaughan, 1966; Kornblum, Hasbroucq, & Osman, 1984; Smith, 1977; Sternberg, 1969; Whitaker, 1979

Note. Our selection and description of stimulus-response compatibility effects was predicated, in part, on the model that is presented later in this article. For definitions of *dimensional overlap* and *congruent and incongruent mapping*, see text.

tween individual stimulus and response elements rather than sets. Fitts (1959) was quite clear about this point: "The degree of population stereotype [is defined as] a function of the uniformity of the responses made by a representative sample of people when they are placed in a standard test situation without any special instruction or training that would bias them in favor of any one of the several responses possible in that situation. Population stereotype is defined such that the larger the proportion of individuals who make identical responses to identical stimuli in such a situation, the stronger is the population stereotype" (p. 19). Population stereotype is designed to assess the degree of element-level compatibility.

Other Theoretical Accounts

Investigators following Fitts did not capitalize on or clarify this distinction any more than Fitts had. For example, in speaking of the interaction between SRC and the number of alternatives, Broadbent (1971) said, "The degree of naturalness or obviousness of the response appropriate to a particular signal alters the effect of the number of alternatives" (p. 282). Theios (1975) said that "if the response code is similar to the name code (or highly practiced) then response time determination is small and relatively independent of . . . the number of alternatives" (p. 424).

A different tack has been taken by other authors, who have

attempted to account for SRC effects by ascribing special properties to certain stimulus or response dimensions. Thus, Welford (1976) made a distinction between "symbolic transformations" and "spatial transpositions" when discussing the "translation mechanisms underlying SRC effects" (p. 71). Other investigators (e.g., Bashore, 1981; Berlucchi, Crea, Di Stefano, & Tassinari, 1977; Poffenberger, 1912) ascribed the effects of *incongruent spatial mapping to hemispheric specialization*. And Simon (1969) attributed them to a "natural tendency" to respond toward the spatial source of stimulation.

The general state of theory concerning SRC has not advanced much since Fitts' (Fitts & Deininger, 1954; Fitts & Seeger, 1953) original account and is probably best summarized by Sanders (1980), who noted that SRC "refers to the degree of natural or overlearned relations between signal and responses. . . . The weakness of the variable is that there is no clear underlying continuum of naturalness. . . . Comparisons between studies on SRC are often difficult since the operational meaning of compatible and incompatible varies across experiments" (p. 339).

The Dimensional Overlap Model

In our model, we retain and sharpen the distinction between set- and element-level determinants of SRC originally drawn by Fitts (Fitts & Deininger, 1954; Fitts & Seeger, 1953) and argue

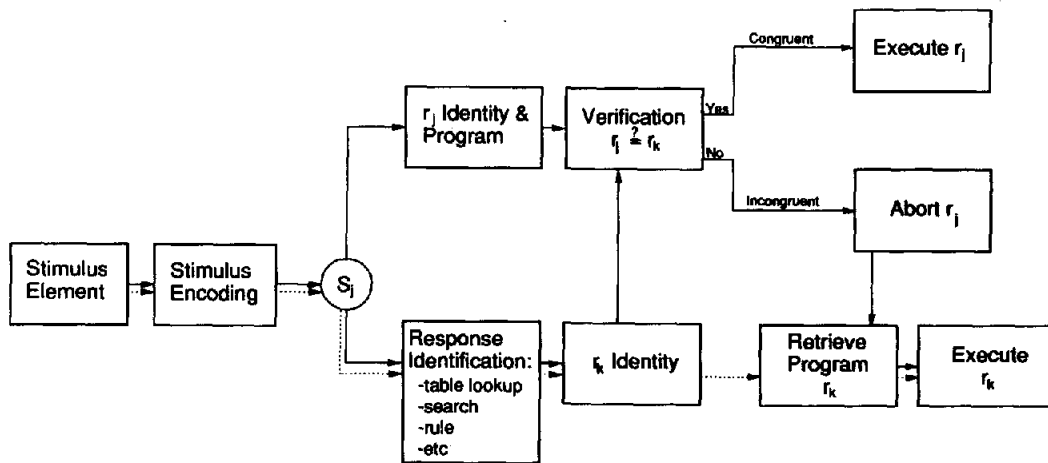


Figure 3. Block diagram of the major information-processing operations in stimulus-response (S-R) compatibility tasks with (solid lines) and with no (dotted lines) dimensional overlap. (The top branch of the solid line path illustrates the operations involved in the automatic activation of the congruent response for S-R ensembles with dimensional overlap. The bottom branch of the solid path illustrates the operations involved in the identification of the correct response.)

that SRC effects are the result of both. We call the set-level determinant the *dimensional overlap* of an ensemble and the element-level determinant the *mapping* between stimulus and response elements. The set-level determinant is the representational aspect of the model; the element-level determinant is its processing aspect. The broad features of the model are illustrated in Figure 3.

Representational Aspect of the Model: Dimensional Overlap

Whenever a normal adult performs any task, the person brings to the task a complex of constraints and riches traceable in part to experience and learning and in part to biological makeup. These are the preexperimental conditions that all subjects participating in psychological experiments bring with them to the laboratory and include the way in which they organize the world along various dimensions and into categories of similar, related, and/or associated objects. As experimenters, we have capitalized on the dimensional repertoire and categorical nature of people's perceptual and cognitive worlds in designing our experiments; however, we have usually ignored this aspect of our subjects in the interpretation of our results and in the formulation of our theories.

By design or by default, most of the stimulus sets that have been used in psychological experiments on SRC have not been haphazard collections of items. Instead, they have consisted of systematic sets of objects that were homogeneous and highly structured with respect to one or more easily identifiable dimensions or attributes. This correlational structure transforms collections of stimuli into classes or categories. The same is true of the responses. For example, the set of digits, whether used as stimuli or responses (digit names), forms a category for literate subjects, as does the set of letters or the subset of vowels. Sets of lights arranged left to right or in another orderly manner form

categories, as does a keyboard with similarly arranged keys, or a set of landing points for a stylus, or a joystick. We know of no experiment in which the set of stimuli consisted of, say, a light flash, the auditory digit six, and a tap to the left heel, with the responses consisting of whistling a middle C, saying one's own name, and blinking. Nor are we proposing such an experiment. What we are proposing, however, is that in the process of selecting and constructing sets of stimuli and responses for their experimental tasks, psychologists have usually ended up not with random sets but with highly structured sets that capitalized on the spatial, semantic, geometric, and other dimensions of the world that subjects brought with them into the experimental situation. The subjects' use of these categorical properties (see Mervis & Rosch, 1981; Rosch, 1978) has therefore been part and parcel of all these experiments, and this factor's very obviousness may have caused it to be overlooked in the analysis and interpretation of the data.

Categories

What do we mean by *category*, and how is the concept related to dimensional overlap? We briefly consider this question from three different but interrelated perspectives: informal, formal, and empirical.

Informally, the term *category* refers to the grouping of a set of items on the basis of one or more shared attributes or properties such that these attributes serve to (a) segregate the items from others with which they may be mixed and (b) distinguish among them. Both criteria are important for the concept of category to be useful in our model. For example, if the stimuli consist of visually presented digits, the sheer detection of digits can be made on the basis of any attribute and/or feature that distinguishes the visually presented digits from nondigits in the visual field (e.g., Jonides & Gleitman, 1976). However, once identified as a digit, the identity of the particular digit may in-

clude its ordinal and cardinal values. Any attributes that satisfied the segregation criterion alone would function well in detection and search tasks but would fail in identification and choice tasks. The same attribute or attributes need not be used for both segregation and identification. However, together, they clearly identify a particular category and discriminate among its individual members.²

Formally, we may speak of a *category* as a relational system (see Roberts, 1979), that is, a set of items together with a set of relations and operations that define the structure of these items with respect to a dimension or attribute. Suppes and Zinnes (1963) distinguished between empirical and numerical relational systems. An empirical relational system's domain "is a set of identifiable entities such as weights, persons, attitude statements, sounds, [and so forth]" (Suppes & Zinnes, 1963, p. 7); a numerical relational system's domain is a set of real numbers. When a mapping exists from one relational system, or category, to another that preserves the relations and operations (i.e., the internal structure) of both, we say that the mapping is *homomorphic*; when the mapping is one-to-one, it is *isomorphic*.³ A homomorphic mapping between stimulus and response sets is a necessary but not a sufficient condition for dimensional overlap in an S-R ensemble. We conjecture that the following relationship may hold between a homomorphism between two sets and the dimensional overlap for those sets: Other things being equal, the greater the number of relations that are preserved by a homomorphic mapping, the greater the degree of dimensional overlap for those two sets. In addition to the homomorphic mapping, the degree of dimensional overlap is also determined by the degree of similarity between the dimensions, or attributes, with respect to which the two sets owe their categorical structure. For example, consider a set *P* of pentagons, and a set *H* of hexagons that vary in size; consider also a set *I* of hexagons that vary in grayness on the scale from white to black. Clearly, a homomorphic mapping may be defined on sets *P* and *H*, and on sets *H* and *I*. Yet, intuitively, the degree of dimensional overlap would seem to be greater for sets *P* and *H* than for sets *H* and *I*. We attribute this difference to a difference in the similarity of the dimension that *P* and *H* have in common (size) in contrast to the dimension that *H* and *I* have in common (size and grayness). Thus, in addition to the homomorphic mapping, dimensional overlap is determined by the similarity of the specific dimensions, or attributes, with respect to which the two sets owe their categorical structure. Because the stimulus and response categories are empirical relational systems, the identification of these categorical attributes and the nature of the mapping are empirical questions (see Palmer, 1978).

Several scaling procedures exist that could be used to identify the dimensions and specify the mapping.⁴ The simplest is to ask subjects to rank a homogeneous set of S-R ensembles (where by *homogeneous* we mean a set of S-R ensembles that all have either the same stimulus set or the same response set) according to how well the stimulus and response sets in each ensemble agree, correspond, or are similar to each other. This procedure would generate an ordinal scale (see Krantz, Luce, Suppes, & Tversky, 1971) for each set of ensembles, where the ensembles in the set are ordered from the most to the least similar or best to worst correspondence. According to the model, this scale is also a measure of the degree of dimensional overlap. A more

informative procedure would be to obtain paired comparison data for the ensembles in a homogeneous set of ensembles. This procedure would not only order the ensembles but would generate an interval scale for each homogeneous set of ensembles. The interesting cases would be ensembles in a homogeneous set for which the population stereotype was the same, and according to Fitts (1959) should therefore produce the same SRC effects, but had in fact produced different SRC effects in performance. We would argue that those are the cases in which the additional information from the dimensional overlap would serve to disambiguate the erroneous predictions of identical performance that were based solely on the population stereotype. Such cases would also provide validation for the measure of dimensional overlap.

Like the population stereotype, and word association norms that are very similar to it, dimensional overlap has predictive but no explanatory power at this time. The existence of dimensional overlap in an ensemble is simply an indication that a set of preconditions have been met for compatibility effects to occur (cf. the Accounting for the Effect of Mapping section that follows). We have been focusing on dimensional overlap in S-R ensembles. However, dimensional overlap may also occur between stimulus sets and between response sets and would form the basis of what Fitts (1959) called *S-S* and *R-R compatibility*.⁵

Dimensional Overlap: Converging, Validating Evidence

Most of the attributes or dimensions in terms of which people categorize the world are learned. It is therefore reasonable to expect that most of the categorical attributes or dimensions on which stimulus and response categories overlap are also learned. For example, Arabic numerals are nonsense figures to

² The distinction between these two types of attributes has an interesting parallel in the attention literature (e.g., Broadbent, 1958; Treisman, 1960), where the control of "stimulus choice" and "response choice" has been attributed to different aspects of the stimulus: stimulus choice being made on the basis of what others called a *channel* and what we call *detection attribute*.

³ An example that makes the idea of homomorphism more precise is the following: Consider a stimulus set *S* consisting of the printed digits and the relation *A* on that set. Together this *n*-tuple $\langle S, A \rangle$ constitutes a relational system in which $s_1 A s_2$ if s_1 is of a lesser numerical value than s_2 . The relation *A* serves to distinguish the elements in *S*. Suppose further that our response set *R* consists of the names of the digits and that the relation *B* is defined on this set such that $r_1 B r_2$ if r_1 is of lesser numerical value than r_2 . With these two categories, it is clear that a mapping, a function *f*, can be defined that will make the set *R* an isomorphic image of the set *S*; that is, for every s_i and s_j in *S*, $s_i A s_j$ if and only if $f(s_i) B f(s_j)$.

⁴ These procedures are based on and would produce measures of similarity or correspondence between sets of items. Previous studies of similarity have addressed the question of similarity between individual items. We know of no work that has explicitly addressed the question of similarity between sets other than those cases where individual items are treated as sets of features (e.g., Tversky, 1977).

⁵ In that case, the homomorphism would be between two stimulus or two response sets. We suspect that dimensional overlap between two stimulus or two response sets plays an increasingly important role in Type 3 and Type 4 ensembles (A Taxonomy of S-R Ensembles and SRC Effects section).

the illiterate but constitute a category of highly meaningful symbols for most adults. Similarly, letters, spatial positions, dozens of object collections, and semantically related words all comprise meaningful categories. We distinguish between such natural categories (Rosch, 1978) acquired as a result of lifelong learning and the categories that are acquired as a result of highly concentrated laboratory training (e.g., Shiffrin & Schneider, 1977). It is quite clear that these two types of categories differ markedly in their processing consequences (e.g., Fisk & Schneider, 1983; Schneider & Fisk, 1984; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

Some studies using natural categories seem to provide particularly good examples of dimensional overlap. One of the most striking involves stimulus and response ensembles where subjects were able to produce a force on a dynamometer that matched the intensity of various perceptual continua ranging from electric shock to white noise and white light (Stevens, Mark, & Stevens, 1960). This is an obvious case of homomorphism between a response and several stimulus categories where the response category easily shared some aspects of its attributes and structure with several stimulus categories. Another, and most compelling study for our purposes, is a recent one in which subjects' discrimination of pitch, brightness, and tactile stimuli was enhanced when the stimuli in one modality were paired with "matching" irrelevant values in another modality (e.g., high pitch paired with bright lights) and was interfered with when paired with the "nonmatching" values (e.g., high pitch paired with dim light; Marks, 1987). That is, discrimination was faster and more accurate when target stimuli were paired with irrelevant matching rather than irrelevant mismatching stimuli from another modality, again strongly suggesting a homomorphic mapping between the modalities (and an example of dimensional overlap between stimulus sets, or S-S compatibility). Marks (1987) concluded that "*correspondences* [italics added] between attributes or dimensions of visual and auditory experiences permeate functional responses to sensory stimulation" (p. 393).

In other purely perceptual tasks, intensity matching has yielded highly consistent results (Stevens, 1959). Length or spatial extent, whether perceived visually, kinesthetically (via active or passive movements), or proprioceptively, was found to be directly proportional and roughly equivalent in all three modalities (Connolly & Jones, 1970; Jones & Connolly, 1970; Stevens & Guirao, 1963; Teghtsoonian & Teghtsoonian, 1970). Auerbach and Sperling (1974) concluded that spatial direction, whether indicated by visual or by auditory signals, was based on a single, common, spatial representation (with which they were homomorphic) rather than on two disjunct representations that then required a comparison process. Modal dominance effects are also in evidence; for example, the dominance of vision over audition in judgments of extent and spatial position is best illustrated by ventriloquism. Even though the dimensional overlap in all these cases appears to involve physically identifiable dimensions (suggesting an unlearned etiology?), the phenomenon is not restricted to them. Roffler and Butler (1968) have shown that sounds differing in pitch are identified as coming from different heights, with high-pitched tones having a perceived source above that of low-pitched tones even though the source of the tones was identical for all tones.

These results were obtained with sighted as well as blind subjects and with adults as well as 4- to 5-year-old children.

The problem of how such cross-modal matching and transfer, or in our terms, dimensional overlap, occurs is an unsolved problem. The fact that it takes place, however, appears to be firmly established. Many attempts have been made to find its basis, and these are well summarized by Marks (1978). However, the problem itself is best summarized by Rudel and Teuber (1964) whom we quote with our own additions, making it pertinent to our problem, in brackets:

The problem of peripheral equivalence across sense modalities [or across stimulus and response categories] does not seem to be too different from the problem of equivalence within a particular modality [or category]. There is some common aspect of perceptual [and/or motor] activity which permits one to utilize information from within a sensory channel [or category], or from several channels [or categories], in such a way that invariant properties of objects [stimulus and response sets] are extracted. (p. 6)

This brief sketch is only the barest outline of the representational aspect of the SRC problem—a problem that has not been explicitly formulated before but for which a solution seems always to have been implicitly assumed by investigators. Our model postulates that stimulus and response sets in SRC tasks are treated as categories, that these categories may or may not share attributes, and to the extent that they do, that they generate varying degrees of dimensional overlap. Dimensional overlap has sometimes been ascribed to the sheer physical similarity between the stimulus and response sets (Fitts & Seeger, 1953; Rosch, 1978), sometimes to features that they have in common (e.g., Gordon & Meyer, 1984; Keele, 1967), sometimes to the fact that the stimuli and responses simply belong to the same class (e.g., Treisman & Fearnley, 1969), and sometimes to the fact that they use the same code (e.g., Hedge & Marsh, 1975; Wallace, 1971). In the model, we do not restrict the notion of dimensional overlap to the physical attributes of stimuli or responses. It is equally, and probably much more, applicable to their mental representations (Wickens, Sandry, & Vidulich, 1983), as would certainly have to be the case when, for example, we speak of dimensional overlap between visual and spoken digits.

Processing Aspects of the Model

When an ensemble consists of an S-R set with a high degree of dimensional overlap, the model postulates that the presentation of a stimulus element triggers two functions, activation and confirmation. The activating function is represented by the upper branch in Figure 3 and is similar to that of an explicit prime in the standard priming (cuing) paradigm with no dimensional overlap between the prime and the stimulus or response.⁶ In

⁶ A trial in a normal, typical RT task consists of the following sequence of events: The trial may, but need not, start with a brief warning signal; after a brief interval of 1 or 2 s, a stimulus is presented to which the subject is required to make a fast and accurate response. The subject then responds. In the standard priming paradigm (e.g., Posner & Snyder, 1975a, 1975b), the typical RT trial is modified by adding a signal between the warning signal and the stimulus. This signal indicates either which stimulus is about to be presented or which response is about to be required or both. This signal is the prime and typically precedes the stimulus by a variable time lag.

SRC tasks where there is dimensional overlap, however, our model postulates that the activation function is automatic.

The confirmation function, illustrated in the lower branch of Figure 3, is similar to that performed by the stimulus in the standard priming paradigm. That is, by identifying the required response, it verifies whether the prime is valid. If the primed and the required responses are the same, then the prime is said to have been *valid*, and the response that is produced will be relatively fast and accurate. The prime is then said to have been *facilitative* and to have provided a *benefit*. If the prime is not valid, then the activated response must be aborted or modified and the correct response put in place. This process will usually cause the new response to be relatively long and error prone, and the prime is then said to have caused *interference* and to have produced a *cost*. In the classic priming paradigm, these two functions are usually separated in time by the sequential presentation of two physically distinct signals, the prime and the stimulus. In the standard SRC paradigm, with S-R ensembles that have dimensional overlap, these two functions are combined in the same physical signal and finish at different times.

The confirmation function consists of a series of steps, including a response identification process that varies in duration depending on the particular S-R mapping assigned by the task. If this mapping permits use of the homomorphism inherent in dimensional overlap to generate a rule to identify the response from the stimulus,⁷ then the response identification process is assumed to be relatively fast. If, on the other hand, the mapping assignment precludes generating such a rule, then the response identification process is assumed to proceed by a search through the table of S-R pairs. This search is assumed to be more time consuming than the execution of a rule. However, the time to execute a rule varies with the complexity of the rule itself, with the identity rule being the simplest, hence the fastest.⁸ We thus end up with two hypothetical boundary values for the duration of the confirmation function: For any S-R ensemble with dimensional overlap, the confirmation function will have its shortest duration when the correct response can be identified by the identity rule and its longest duration when it requires a search procedure through the S-R pairs. Normally, we expect the automatic activation process to finish before confirmation. If it does, the model postulates that both processes, activation and confirmation, need to be completed before the execution of the response.

Accounting for the Effect of Mapping

Mapping is the assignment of a response to a stimulus. If the response that is activated by a particular stimulus is the one that was assigned to that stimulus by the task mapping instructions, then the process is functionally equivalent to a valid prime, and performance will show a benefit. If the activated response differs from the required one, then it is functionally equivalent to an invalid prime, and performance will show a cost. Call the mapping for which the activated and required responses coincide *congruent* and that for which they differ *incongruent*. According to the model, congruent mapping will produce facilitation, and incongruent mapping will produce interference. In the absence of dimensional overlap, any mapping is in principle as good as

any other mapping. Dimensional overlap is therefore a necessary condition for obtaining a mapping effect.^{9,10}

Let us now step the model through its operations for three cases of special interest: a congruent mapping condition, an incongruent mapping condition, and a condition without dimensional overlap.

Both the congruent and the incongruent mapping conditions require that the stimulus and the response sets in the ensemble overlap on one or more dimensions. This requirement implies that in either case, whether in congruent or incongruent mapping, the congruent response is automatically activated when the stimulus is presented, and the results of this activation, including the response program, are stored in a preverification buffer. Simultaneous with this activation is the initiation of the response identification process. In the case of congruent mapping, response identification proceeds by the simplest and fastest rule, the identity rule, and the identity of the correct response is passed on to the verification process with minimal delay. Because the activated and the correct response are one and the same, and this response has been preprogrammed, it can be executed rapidly. In the case of incongruent mapping, response identification may proceed by the application of a rule, or not, depending on the S-R mapping specified by the instructions. If the mapping allows for a rule to be formulated, that rule may be used. If the mapping does not allow for such a rule to be formulated, that is, if the S-R pairing consists of an unsystematic random assignment of stimuli to responses, then response identification will have to proceed by searching through the S-R table (see Footnote 9). In either case, response identification will take longer with incongruent mapping than it did with congruent mapping, thus producing a relative delay in the verification process. Since the activated, preprogrammed, congruent response and the correct response differ, the activated response must be disposed of, lest it conflict with the correct response at the time of execution. The abort process that does this (cf. Figure 2) constitutes a second source of delay. Our model thus predicts that for ensembles with dimensional overlap, the fastest correct response will be the one produced

⁷ Because in the absence of dimensional overlap, the stimulus and response sets in an ensemble share no attributes, strictly speaking, they are not comparable. That is, there is no function or other systematic rule-based way of getting from the stimulus to the required response other than by searching through the table of S-R pairs that was set up by the mapping instructions. In contrast, the homomorphism inherent in dimensional overlap enables, in principle, the formulation of a rule or function (i.e., a transformation of the basic homomorphic mapping) to identify the required response from the stimulus.

⁸ An elaboration of rule-governed behavior for two-choice tasks within the framework of this model may be found in Hasbroucq (1987).

⁹ In principle, once the mapping between a set of stimuli and a set of responses precludes the possibility of the mapping being described as a rule, all the random mappings are equivalent. In some cases, however, particularly with a small number of alternatives made up of combinations of binary dimensions, it is often extremely difficult to come up with a mapping that avoids being formulated as a rule.

¹⁰ It is not possible to distinguish between random and rule-based S-R mapping in tasks of fewer than three choices. A two-choice task can always be reduced to the following rule: If s_1 , then r_1 ; if not s_1 , then the other r .

with congruent mapping assignments, the next fastest will be the one that can be identified by rule in the incongruent mapping condition, and the slowest will be the response identified by search in the incongruent mapping condition (see Footnote 10); Fitts and Deininger's (1954) data are consistent with this prediction.

Ensembles that do not have dimensional overlap do not have automatically activated responses associated with them. Their processes are illustrated by the dotted path in the lower branch of Figure 3. Since there is no dimensional overlap, there is no function or rule in terms of which a response may be identified from the stimulus. The mapping instructions, therefore, set up an S-R table that is then searched regardless of what the mapping instructions may be. Once the correct response has been identified, there is no need, in this class of ensembles, to verify or abort it. Therefore, the process proceeds without interruption to retrieve the appropriate program and to execute the response. According to this argument, ensembles without dimensional overlap can neither benefit from automatic activation of a response or the potential applicability of a rule, nor must they bear the cost of verifying and aborting erroneous responses. One would, therefore, expect the RT for nonoverlapping ensembles to be longer than it would be for congruent mapping conditions, shorter than for incongruent random mapping conditions, and, depending on the complexity of the rule, either longer or shorter than for incongruent rule-governed mapping conditions.

Much of the data in the literature are consistent with these general features of the model and are reviewed in a later section of this article. Of special interest, however, is a recent report by Georgopoulos, Lurito, Petrides, Schwartz, and Massey (1989) that bears on the automatic activation of the congruent response that is postulated in the model. Georgopoulos et al. had a rhesus monkey move a handle either toward (congruent mapping) or in a direction perpendicular to (incongruent mapping) a stimulus light. The RT for the incongruent mapping was 260 ms, which was approximately 80 ms longer than for the congruent mapping. During this test, the experimenters also recorded the activity of cells in the motor cortex and found that the neuronal population vector, which is a weighted sum of contributions of directionally tuned neurons, pointed in the direction of the movement in congruent trials and in the direction of the stimulus (i.e., the congruent movement) at the start of incongruent trials, with a subsequent rotation in the direction of the required movement. We interpret these data as being consistent with the automatic activation-identification-abort mechanism postulated by our model.

Automaticity

We have just explained how the model accounts for the effects of mapping when the dimension is relevant. Before discussing how the model deals with the effects of mapping when the dimension is irrelevant, we need to examine some of the characteristics of automaticity, which is an essential property of the response activation function in the model. Let us first consider the definition of the term.

Several different definitions of *automatic* have been proposed in the literature, each of which has merit and is appropriate for

the context in which it was formulated. For example, Schneider, Dumais, and Shiffrin (1984) asserted that automatic processing "is a fast, parallel, fairly effortless process . . . not limited by [short-term memory] capacity . . . not under direct subject control and . . . responsible for the performance of well developed skilled behaviors" (p. 1). This definition echoes similar proposals from some of their earlier papers (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). At another time, however, Shiffrin, Dumais, and Schneider (1981) proposed a two-rule criterion that was quite different: Rule 1—"any process that does not use general non-specific processing resources and does not decrease the general non-specific processing capacity available for other processes is automatic" (p. 227); Rule 2—"any process that demands resources in response to external stimulus inputs, regardless of the subject's attempts to ignore the distraction, is automatic" (p. 228). This contrast illustrates particularly well how the criteria in the literature have been tied to individual theoretical and experimental contexts. Their first criterion was proposed in the context of this group of experimenters' work on visual search; the two-rule criterion, on the other hand, was proposed in the context of a limited-resource model (Navon & Gopher, 1979; Norman & Bobrow, 1975; Wickens, 1980). Schweickert and Boggs (1984) defined an automatic process as one "not requiring central capacity and executed involuntarily, uninfluenced by strategy" (p. 272). Posner (1978) described automatic processes as those that "may occur without intention, without giving rise to conscious awareness, and without producing interference" (p. 91). Kahneman and Treisman (1984) distinguished among three levels of automaticity: strong, partial, and occasional, where these levels differ in the degree to which whatever process is automatized interacts with attention (*note: attention* and not *capacity* or *resource*). And this definition, of course, is reasonable because attention has been and continues to be these two investigators' principal interest.

The definition that we have adopted in our model is closest to that proposed by Kahneman and Treisman (1984) for dealing with perceptual processes. We have found that it generalizes easily to include S-R processes. The pivotal property that distinguishes automatic from controlled processes is that an automatic process is triggered without the actor's intending to do so and cannot be stopped even when the actor intends to and it is in that actor's best interests to do so. Kahneman and Treisman (1984) differentiated between *strongly automatic* and *partially automatic* processes. A strongly automatic process is one that is "neither facilitated by focussing attention on [its object] nor impaired by diverting attention from [it]" (Kahneman & Treisman, 1984, p. 43). A partially automatic process is one that is normally triggered without attention directed at its object but is facilitated by having attention focused on it. Unlike other definitions of automaticity that treat attention and automaticity as separate and independent entities, we believe, with Kahneman and Treisman (1984), that the two may in fact be closely related. According to this view, an automatic process could under some conditions be attenuated or enhanced. However, under no conditions could it be ignored or bypassed. Subjects in a properly designed experiment, whether instructed to use or to suppress an automatized process would therefore produce evidence of its operation in their performance. SRC

effects may be viewed as reflecting such evidence. We next consider briefly the locus and character of the automatic process itself.

Most investigators working on automaticity seem to agree (e.g., Jonides, Naveh-Benjamin, & Palmer, 1985; Kahneman & Treisman, 1984; Posner, 1978; Shiffrin & Schneider, 1977) that the term *automatic* should be applied to a portion of an act rather than to the whole act. Thus, given two different acts or tasks, both of which exhibit evidence of automaticity, the particular stage, or process, that is automatized may, but need not be, the same. To ignore this point may lead to serious errors. For example, consider two different tasks, say visual search and choice RT; if both show evidence of automaticity, it would be false to conclude, without further evidence, that the identical process was automatized in both. This may, of course, be the case. However, it is a hypothesis at best and is clearly not true in many cases. At some deeper level of analysis, automatized processes undoubtedly have properties in common regardless of the stages or tasks in question. At this point, however, too little is known in sufficient detail with enough confidence about the automatic processes in different tasks to provide much insight at that level.

In our model, we have tentatively identified as automatic the process that leads to the activation of the congruent response. This process consists of several stages, including response identification, selection, and programming. When triggered, this process produces a congruent response that is activated and ready to be executed or aborted by a single command. In a somewhat analogous manner to Miller's (1988) structural analysis of continuous and discrete information-processing models, we envisage automaticity as occurring at two levels: within and between stages. Automaticity within stages means that the recoding or transformations inside any stage occur immediately and in a preset way without any interference or intervention by monitoring or controlling processes. Automaticity between stages means that the output of any one stage is directly transmitted to and received by the subsequent stage without interference or intervention. When there is no dimensional overlap, of course, no congruent response is defined, and the automatic activation process is nonexistent. When there is dimensional overlap, however, the activation process is automatically brought into play with the final level of readiness, or activation, of the congruent response postulated to vary with the degree of dimensional overlap.

The Mapping Effect as a Compatibility Metric

We have argued that performance differences between congruent and incongruent mapping conditions are the result of at least four factors: (a) the degree of dimensional overlap between the stimulus and response sets, (b) the response identification process for the correct response, (c) the automated activation process for the congruent response, and (d) the abort process that this necessitates in incongruent mapping conditions. In the absence of dimensional overlap, the response identification branch (see Figure 3) is the only one involved and, according to the model, provides no basis for giving rise to one performance level with one mapping and a different performance level with another mapping. In the presence of dimensional overlap, how-

ever, the congruent response is automatically activated regardless of the mapping in the task, and the response identification process itself may behave differently, depending on the mapping in the task. The model further postulates that the level of activation for the congruent response is related to the degree of dimensional overlap in the ensemble: That is, the greater the dimensional overlap (as measured by paired comparisons or other techniques for measuring the similarity between sets), the greater the facilitation with congruent mapping and the greater the interference with incongruent mapping.¹¹

From this argument, it follows that the fastest RT for any particular ensemble with dimensional overlap will occur with the congruent mapping condition and that the slowest RT will occur with mapping conditions that preclude the use of a rule and require a search through the S-R pairs for the identification of the response. (In principle, all mapping conditions requiring a search should result in equivalent performances.) The difference in RT between the congruent and the incongruent search-based mapping conditions for an ensemble therefore reflects the extremes of the processes that are postulated by the model and may serve as an appropriate index of the degree of compatibility for that ensemble.

Accounting for the Effects of Irrelevant Dimensions

When a stimulus has more than one dimension that can be varied (e.g., when one can vary both the shape of the stimulus and its location in space, or the letter and its size), then either just one or both dimensions can be correlated with the response. If both dimensions are correlated, then we call them *redundant* in the sense that the response can be identified on the basis of either. If only one dimension is correlated with the response, then we call the correlated one *relevant* and the other *irrelevant*; the uncorrelated dimension is irrelevant in the sense that it cannot be used to identify the response at a better than chance level. Yet, when an irrelevant stimulus dimension overlaps with a response dimension, it produces a mapping effect that is qualitatively similar to that obtained when this dimension is relevant (e.g., Wallace, 1971). In particular, when the S-R mapping is congruent with respect to the irrelevant dimension, the RT is faster than when it is incongruent.

To account for these results, the strong version of the model, based on a strongly automatic activation process (see section on automaticity), would predict identical effects when the dimension is relevant and irrelevant. This would follow because the effect of mapping is based on the automatic activation of a response element by a stimulus. Being strongly automatic, it remains unaffected by having attention directed at it or withdrawn from it. Hence, what would matter is not whether a dimension was relevant, but whether the stimulus and response sets overlapped on it.

The weak version of the model, based on a partially automatic activation process, would predict effects equivalent in kind but reduced in magnitude when the dimension is irrele-

¹¹ This is consistent with the priming literature, which shows that the greater the benefit when the prime is valid, the greater the cost when that prime is invalid (see Kahneman & Treisman, 1984).

vant. That is, both the facilitation and interference effects of congruent and incongruent mappings would occur but would not be as large as when the dimension was relevant. This is because a partially automatic process is facilitated by having attention directed at it and is impaired by having attention withdrawn from it. Clearly, when a dimension is modified from being relevant to being irrelevant, the level of attention directed at this dimension is decreased. If this decrease in attention leads to a corresponding decrease in the level of response activation, the result would be smaller facilitation and interference effects with irrelevant than with relevant dimensions, which, in turn, would lead to a reduced benefit in the case of congruent trials and a reduced cost in the case of incongruent trials.¹²

As was true of the mapping effects with relevant dimensions, the most direct evidence in support of the mechanisms postulated by the model as underlying the mapping effects with irrelevant dimensions comes from a series of psychophysiological studies published by Coles and his colleagues (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). They used a two-choice RT task in which the stimulus for each response was presented flanked by irrelevant noise elements that were either compatible or incompatible with the response.¹³ Previous studies had shown that the RT to stimuli with the incompatible noise was longer than with the compatible noise (Eriksen & Shultz, 1979). By combining the event-related potential and electromyogram measures to construct a composite psychophysiological index of response activation, Coles et al. and Gratton et al. were able to demonstrate that on trials where the stimulus was flanked by compatible noise only one response was activated: the compatible one. On trials where the stimulus was flanked by incompatible noise, both responses were initially activated, with the incompatible response eventually dropping out and the compatible one being left to be executed with a delay. Even though this experimental task differs in important respects from what we have defined as the SRC paradigm and even though the constraints in a two-choice task considerably restrict the generalizability of the results (see Footnote 10), we view the parallel processing structures of the response conflict implied by Coles et al.'s results as consistent with our model's postulates.

Accounting for the Interaction of SRC and the Number of Alternatives

One of the oldest and most solid results in the RT literature is the increase in mean RT as a function of the number of alternatives. An equally solid finding is that the slope of this function decreases with the compatibility of the task.¹⁴ For example, Leonard (1959) found that in making keypress responses to tactile stimuli, there is no measurable increase in RT when going from two to eight alternatives. These two factors, compatibility and number of alternatives, that interact at the level of the overall mean RT also have effects at the level of repetitions and nonrepetitions. In particular, an increase in the number of alternatives increases the RT for nonrepetitions more than it does for repetitions (Kornblum, 1969, 1973); an increase in the incompatibility of a task also increases the RT for nonrepetitions more than for repetitions (Bertelson, 1963). If these two factors, compatibility and number of alternatives, have additive effects at

the level of repetition and nonrepetition, they could still display interactive effects at the level of the overall mean simply as a consequence of the change in the proportion of repetitions and nonrepetitions in changing from an equiprobable, independent, four-choice task (1:3) to an eight-choice (1:7) task (cf. Kornblum, 1969). If, on the other hand, these two factors interact at the level of repetition and nonrepetition, the automatic priming mechanism that is postulated by the model may be the same as is implicated in producing the sequential effects in RT (e.g., Falmagne, 1965).

Training

The question of training is unavoidable in any discussion of automaticity or compatibility. Some studies have linked training to the development of automaticity and others to the elimination of compatibility effects. We have chosen not to make practice a major focus or concern in our model, and we briefly cite and comment on three lines of evidence to support this position.

First, Shiffrin, Schneider, and their colleagues have published an influential series of studies (e.g., Schneider et al., 1984; Schneider & Fisk, 1984; Shiffrin & Schneider, 1977) in which they claim to have demonstrated a strong link between training (with consistent mapping) and automaticity. We do not wish to dispute this claim (but see Cheng, 1985; Ryan, 1983). However, their demonstration does not compel the present model to consider practice as a central issue. Recall that Shiffrin and Schneider's conclusions are based on studies of visual search that used small target sets, with threshold-level stimuli, and binary responses. The same processes that account for automaticity in their tasks are not necessarily the ones that account for automaticity in very different choice tasks with natural categories such as ours. In fact, whereas natural categories have produced automatic performance in some tasks, when Shiffrin and Schneider used target and distractor sets that consisted of natural categories in their task, they had to put these sets through the same

¹² It is interesting to consider information on an irrelevant dimension being processed in a manner equivalent to information on an "unattended channel" (e.g., Moray, 1969), for it reveals a parallel between the prediction of the weak version of the model and the results of, say, dichotic listening tasks, even though our model and the attentional model each start from a different baseline. The strong version of the attentional model (e.g., Broadbent, 1958) predicts that information presented on an unattended channel remains inaccessible and without observable effects on performance. The weaker version (e.g., Treisman, 1960) recognizes that information from the unattended channel often leaks through, thus changing the filter from an all-or-none device to an attenuator. Thus, reduced mapping effects with an irrelevant dimension and the attenuation of information transmission through a leaky filter may reflect similar mechanisms.

¹³ The S-R ensembles in this task did not have dimensional overlap; however, the response conflict triggered by the noise stimuli are sufficiently similar in structure to those postulated by our model to make the results pertinent.

¹⁴ One interesting exception is the study by Schvaneveldt and Staudenmayer (1970), in which additive effects were obtained between mapping and the number of alternatives when mapping was varied by altering the rules for the S-R pairings.

consistent-mapping training procedures as noncategorical items. Thus, because natural categories and those produced with consistent mapping differ in their automatic properties initially, and our model ascribes automatic properties to natural categories, the concerns about automaticity are clearly quite different in search and SRC paradigms.

Second, Mowbray and Rhoades (1959) reported in a well-known study the exploits of a heroic subject who performed 45,000 trials in a choice RT task on which there was an initial difference between two and four choices, the standard finding. After 15,000 trials on the two-choice task and 30,000 trials on the four-choice task, there ceased to be a measurable difference between them. This was a surprising result, going against the classical finding of an increase in choice RT with an increase in the number of alternatives. However, this nondifference had also been observed by Leonard (1959), who used tactile stimuli with keypress responses. But he observed it almost immediately. Can we conclude from this that with enough training all tasks become highly compatible and lose their incompatible performance characteristics? Perhaps. However, as renowned as the Mowbray and Rhoades study is, the differential amount of training given to the two- and four-choice conditions does not make the results unequivocal. Even if they were, the results would not invalidate anything that is either assumed or implied by our model, for it simply asserts that with dimensional overlap between the stimulus and response sets of an ensemble, certain processing consequences follow that lead to certain observable results. This assertion in no way precludes obtaining similar, single, isolated results through different mechanisms or procedures, nor does it necessarily imply that if such results are obtained through different procedures they are mediated by identical mechanisms. At best, therefore, the Mowbray and Rhoades study might provide the empirical grounds for an interesting etiological conjecture.

Finally, given the potential relationships between training, automaticity, and SRC, how concerned should one be about the effects of training when conducting experiments on SRC? The effects of training and the principles of transfer of training were one of Fitts's primary concerns when he began his work on SRC. In his 1953 paper with Seeger, therefore, he included an experiment in which 6 subjects were run for a total of 1,500 trials on three different S-R ensembles with a common response set. The results showed that even though overall RT decreased throughout the training period for all three ensembles, it was not a differential decrease. That is, after the first 200 trials, the difference between the most and the least congruent ensemble remained constant. Thus, even though Fitts's 1,500 trials do not compare with Shiffrin and Schneider's (1977) 20,000 or Mowbray and Rhoades's (1959) 45,000 trials, the stability of the difference between the congruent and incongruent conditions over the 32 sessions and 1,500 trials of Fitts's experiment greatly reduces whatever potential danger there may be of obtaining contaminated or biased data from an experiment in which training is properly balanced over the relevant conditions.

A Taxonomy of S-R Ensembles and SRC Effects

The concept of dimensional overlap that the model uses to account for SRC effects suggests a rational framework for classi-

Table 2
Classification of Stimulus-Response Ensembles by Dimensional Overlap on the Relevant and Irrelevant Dimensions

Ensemble type	Ensemble dimension	
	Relevant	Irrelevant
1	No	No
2	Yes	No
3	No	Yes
4A	Yes	Yes
4B	Yes	Yes

Note. Relevant dimensions refer to ensemble attributes that are systematically and consistently related to the required responses in the task. Irrelevant dimensions are those that bear no systematic or consistent relationship to the required response. The yes and no entries indicate whether the ensemble dimensions that are indicated do or do not have dimensional overlap. The ensemble types 4A and 4B are distinguished according to whether the two dimensions, relevant and irrelevant, are the same or not (see text for further explanation).

fyng S-R ensembles by whether there is dimensional overlap for the relevant and/or irrelevant stimulus and response dimension or dimensions of the task. The four classes of S-R ensembles generated in this way are listed in Table 2.

Type 1 Ensembles

This type of ensemble is characterized by the absence of dimensional overlap in either the relevant or the irrelevant dimensions. According to our model, therefore, any mapping should be as good as any other mapping, and this indeed is what the data show. For example, Fitts and Deininger (1954) included one condition in their experiment in which a set of spatially oriented movements was paired with a set of proper names as stimuli and found that all S-R mappings were equivalent for that ensemble.

Because Type 1 ensembles preclude the presence of automatic response activation processes or response identification by rules, both of which form the basis of SRC effects, such ensembles may be useful as neutral or control conditions in studies that aim at demonstrating effects of dimensional overlap (see Jonides & Mack, 1984).

Type 2 Ensembles

This type of ensemble is characterized by the presence of dimensional overlap, hence of automatic activation processes, in the relevant dimension. According to our model, this type of ensemble satisfies the requirements for obtaining mapping effects. Not surprisingly, most mapping studies are based on this type of ensemble.

Following roughly the same design as that used by Fitts and Deininger (1954), Morrin and Grant (1955) found that performance was best when horizontally aligned stimulus lights were directly mapped onto response keys immediately below them (congruent mapping), worst when the lights were randomly mapped onto the keys (incongruent mapping), and intermediate when the lights were mapped onto the keys in an incongru-

ent but systematic manner. Similar results were obtained by Duncan (1977a, 1977b, 1978) and by Simon and Craft (1970).

Schwartz, Pomerantz, and Egeth (1977) confirmed the superiority of congruent mapping conditions in a task in which subjects were required to press a left or right button in response to a left- or right-pointing arrow. As expected, subjects did better when the side of the button corresponded to the direction indicated by the arrow than when it did not.

In one of his early studies with auditory stimuli, Simon (1967) found that when a monaural tone was presented to the left or to the right ear and subjects were required to press either a left or a right key in response, RT was 89 ms faster with the congruent (i.e., when the tone and the responding key were on the same side) than with the incongruent mapping. In a similar study with monaural tones, when subjects had to move a lever to the left or to the right, depending on whether the tone had been presented in the left or the right ear, Simon (1969) found a 59-ms advantage for the congruent mapping.

Sternberg (1969) and Blackman (1975) conducted studies in which subjects were visually presented with digits to which they had to respond either with the name of the digit (congruent) or with the name of the next digit (incongruent). Both experiments showed a congruent mapping advantage. In a similar study, Sanders (1970) used the visual presentations of vowels as the stimuli and the naming of the presented vowel (congruent) or of the next vowel in the alphabet (incongruent) as the response. As expected, RT for the congruent mapping was faster than for the incongruent mapping.

These studies confirm Fitts's (Fitts & Deininger, 1954) original observations that variations in mapping, that is, variations in element-level compatibility, have a powerful effect on choice RT. Note also that even though most of the studies used spatial S-R dimensions, these effects are also found with nonspatial dimensions.

These results are, of course, consistent with the model's account of mapping effects in terms of the implicit automatic priming of response elements by stimulus elements in ensembles with dimensional overlap. This account is further reinforced by Fitts and Deininger's (1954) striking finding that the most detrimental effect of incongruent (random) mapping was obtained with the ensemble that produced the fastest RT with congruent mapping. Because according to the model, Fitts and Deininger's (1954) random mapping condition is an instance of an invalid prime, it is not surprising that the greatest cost of random mapping should have occurred with an S-R ensemble that also produced the greatest benefit. This assumption of the model has recently been confirmed in a study by Palmer and Jonides (1984) in which they showed that as the benefits of an explicit valid prime increased, so did the costs when that prime was invalid.

Interaction of the Number of Alternatives With SRC: Type 1 and Type 2 Ensembles

The effect of the number of alternatives on RT is one of the earliest and most reliable findings in the literature (cf. an early review by Woodworth, 1938). Because it is thought to reflect the operation of fundamental information-processing mechanisms (e.g., Donders, 1869/1969; Sternberg, 1969), its interaction

with SRC is of great interest. This interaction occurs whether SRC is varied by manipulating set-level or element-level factors (but see Footnote 14). We shall consider each in turn.

Brainard, Irby, Fitts, and Alluisi (1962) compared performance in a keypressing task with that in a naming task when the stimuli in both tasks were either lights or digits. They also varied the number of alternatives. Although RT generally increased with the number of alternatives, this increase was much steeper in the ensembles that did not have dimensional overlap (i.e., where verbal naming responses were made to the lights and keypress responses were made to the digits) than in those that did (i.e., where naming responses were made to digits and keypress responses to lights). In a related study, Morrin, Konick, Troxell, and McPherson (1965) found that the RT for naming visually presented letters showed little increase between two and eight alternatives, whereas the RT for naming animals, colors, faces, or arbitrary symbols produced an increase of more than 150 ms as the number of alternatives increased from two to eight.

In the next three studies that we discuss, dimensional overlap was not varied but was always high for the relevant dimension so that these are all Type 2 ensembles. We include these studies because they illustrate that with high dimensional overlap the effect of the number of alternatives is relatively small. Davis, Moray, and Treisman (1961), using auditory stimuli, presented their subjects with 1 of 10 digit names, 1 of 26 letter names, and one of two, four, or eight nonsense syllables. In all three conditions, subjects simply had to repeat what they had heard. The difference in RT between repeating the 1 of 10 digits and the 1 of 26 letters was only 12 ms; with the nonsense syllables, a small difference between the two- and the eight-choice conditions appeared in the early blocks but disappeared with only a little practice. Theios (1973) reported similar results for a task in which subjects had to name visually presented digits, where the number of alternatives varied between 2 and 10 digits.

In a very different task, Leonard (1959) had subjects press a key to tactile stimuli that consisted of vibrators placed under the responding fingers. Even though he found an increase in RT in switching from one to two alternatives (i.e., between a simple and a choice task), he observed no further increases in RT as the number of alternatives increased to eight.

We now turn to studies on the effect of the number of alternatives that used Type 2 ensembles and varied SRC by varying the mapping.

Shortly after Leonard's (1959) study, Broadbent and Gregory (1965) reported the results of an experiment in which subjects responded with keypresses to tactile stimuli that were applied to the fingertips. There was a two-choice condition and a four-choice condition with mapping that was either congruent or incongruent. With the congruent mapping, they found a slight increase in RT between the two- and four-choice conditions. However, with the incongruent mapping, this increase became much greater. These findings were later confirmed by Smith (1977) in a study that extended the range of the tactile keypressing task to eight alternatives.

We already reported that Sternberg (1969) had found that the RT to name a digit was faster than to name this digit's successor. By presenting the subject one of two or one of eight digits, he was able to observe the effect of the number of alternatives on

this mapping manipulation. The increase in RT with the number of alternatives was greater with the incongruent (i.e., successor) than with the congruent mapping. In a similar experiment, Duncan (1977a, 1977b) and Whitaker (1979) reported that the RT to repeat the name of an auditory digit increased little as the number of alternatives rose from 2 to 10. However, when the mapping was changed from merely repeating the name of the digit to that of a random assignment between the name of the digit and the auditory digit, the RT increased markedly as the number of alternatives increased. Finally, Costa, Horwitz, and Vaughan (1966), again using visually presented digits but using a writing response, found that when the task consisted of simply copying the digit that had been presented, the increase in RT with the number of alternatives was much less than with any other mapping.

Thus, whether SRC is manipulated by varying the dimensional overlap between stimulus and response sets or the mapping between stimulus and response elements, the effect of the number of alternatives on choice RT is greater in incompatible than in compatible tasks.

Type 3 Ensembles

The fact that SRC effects are not confined to manipulations of the relevant dimension but are also obtained by varying either the degree of dimensional overlap or the mapping of irrelevant dimensions is important to the model. It confirms the automatic, involuntary nature of the postulated underlying activation mechanism and may shed light on the nature of the response identification process. In Type 3 ensembles, the relevant stimulus dimension has no overlap with any of the response dimensions, whereas the irrelevant stimulus dimension does.

Wallace (1971) used two visually presented geometric figures and instructed his subjects to press the left key to the square and the right key to the circle. The figures themselves were randomly presented on the left or right side of a display panel. Side was therefore irrelevant. Nevertheless, when the side on which the figure appeared corresponded to the side of the response key, RT was approximately 50 ms faster than when it did not correspond.

Simon and Small (1969) obtained similar results with an auditory task in which they presented subjects with a high-pitched (1000 Hz) or a low-pitched (400 Hz) monaural tone. Subjects were instructed to press the left key to the high tone and the right key to the low tone. The tones themselves were randomly presented to the left or the right ear; the identity of the ear was therefore irrelevant to the task. Nevertheless, when the side of the response key corresponded to the side of the stimulated ear, RT was 65 ms faster than when it did not correspond.

These studies show quite clearly that the difference in RT between congruent and incongruent mapping is not restricted to relevant stimulus dimensions but extends to irrelevant dimensions as well.

Simon and his colleagues (e.g., Simon, Craft, & Webster, 1973) have performed many experiments over the years in which either visual or auditory stimuli, or both, were presented to the left or the right of the body midline and have shown that

this irrelevant positional aspect of the stimulus strongly affected lateralized responses in those tasks.

Role of Anatomical Factors in Performance With Spatial S-R Sets: Type 2 and Type 3 Ensembles

On the basis of his own results and those of others, Simon was led to conclude that SRC effects were the result of "a strong natural tendency to react toward the *major* source of stimulation" (e.g., Simon, Craft, and Small, 1970, p. 67). This view raises the question of whether the crucial spatial correspondence is the one between the stimulus and the effector or between the stimulus and the manipulandum.

Simon (1969) had already provided a partial answer to this question when he showed that spatial congruence and incongruence affected the performance of a leftward or rightward movement performed by a single limb. However, he provided a more direct answer to the question in a later experiment. Simon, Hinrichs, and Craft (1970) presented subjects with a tone in either the left or the right ear. In the congruent condition, a tone in the left ear was responded to with the left key, and a tone in the right ear was responded to with the right key. In the incongruent condition, this mapping was reversed. The subjects performed the congruent and incongruent mapping conditions with their hands crossed and uncrossed (in the hands-crossed condition, the left key was pressed with the right hand, and the right key was pressed with the left hand). We have recalculated the results and summarized them in Table 3. The data in the uncrossed-hands condition replicate the mapping effects that Simon (1967) had previously observed. Crossing the hands does increase the RT; however, the magnitude of the mapping effect in the crossed-hands and uncrossed-hands conditions was approximately the same.

Almost identical results were obtained with visual stimuli by Brebner, Shepard, and Cairney (1972). The stimuli consisted of a left and a right light to which subjects either pressed a left and a right key, respectively, in the congruent condition and a right and a left key in the incongruent condition. Subjects performed both the congruent and incongruent tasks with hands crossed and uncrossed. The results are summarized in Table 3. There is the expected mapping effect of roughly the same magnitude in both the uncrossed- and the crossed-hands conditions. Thus, even though the general level of RT was approximately 50 ms faster in this task than in the Simon et al. (1970) study, the pattern of results is remarkably similar.

We have already reviewed part of Wallace's results (1971) in discussing Type 3 ensembles. Recall that he mapped a circle or a square onto a left and right key and presented these geometric figures on the left or right side of a display panel. Subjects also performed his task with either uncrossed or crossed hands, and the results are summarized in Table 3. Even though the side on which the figure appeared was irrelevant, there was an effect of the congruence between the side on which the figure was displayed and the side of the responding key, as previously noted. Now, in addition, the results show that the magnitude of this effect was roughly the same for the uncrossed- and the crossed-hands conditions. These three studies suggest that the mapping factor and the anatomical factor have roughly additive effects whether the stimuli are auditory or visual.

Table 3
Effects of Stimulus-Response Mapping of an Irrelevant Dimension and the Anatomical Factor in Two-Choice Reaction Time Tasks (in Milliseconds)

Hands	Mapping		Difference
	Congruent	Incongruent	
Ear to key ^a			
Uncrossed	386	451	-65
Crossed	419	474	-55
Difference	-33	-23	—
Lights to key ^b			
Uncrossed	250	293	-43
Crossed	287	319	-32
Difference	-37	-26	—
Figure to side ^c			
Uncrossed	360	413	-53
Crossed	406	456	-50
Difference	-46	-43	—
Fingers to key ^d			
Different	337	379	-42
Same	379	430	-51
Difference	-42	-51	—

^a Simon, Hinrichs, and Craft (1970). ^b Brebner, Shepard, and Cairney (1972). ^c Wallace (1971). When the geometrical figures were presented either above or below the fixation point, thus precluding a "congruent" or "incongruent" mapping condition with left and right responses, the reaction times for the uncrossed- and crossed-hands conditions were 383 and 435 ms, respectively, which is between the congruent and incongruent mapping conditions. The difference of 52 ms is close to the crossed-uncrossed differences obtained with the congruent and the incongruent mapping conditions. ^d Shulman and McConkie (1973).

One last experiment is included here to show that the anatomical factor can be varied in a different way than by crossing and uncrossing the hands. Shulman and McConkie (1973) presented subjects with a visual stimulus to the left or right of a fixation point. In the congruent mapping condition, the left stimulus was responded to with the left key, and the right stimulus with the right key. In the incongruent condition, this mapping was reversed. Subjects performed these two tasks by pressing the left and the right keys with their left and right index fingers, respectively, or by pressing these keys with the index and middle fingers of their right hands. The two alternative responses were, therefore, both on the same hand or on different hands. The results are shown in Table 3. Mapping has the expected effect of producing a difference of 40–50 ms between the congruent and incongruent conditions. The response factor also had an effect that is comparable in size with that found in other studies.

The additivity (in the additive-factors sense) of the effects of SRC and the effect of the anatomical factor indicates that neither can be reduced to the other but that each has an independent effect on the information-processing sequence between a stimulus and a response. This, of course, has extremely interesting implications for a general stage analysis of RT, which is beyond the scope of this article.

Type 4 Ensembles

In this last type of ensemble, the stimulus and response sets overlap on both a relevant and an irrelevant dimension. These two dimensions may be the same or different. If they are different, we label the ensemble 4A; if they are the same we label it 4B. Whether the dimensions are the same or different, the factors considered by the model thus far may interact with each other and with new factors in ways not dealt with before in Type 4 ensembles. In particular, the relative perceptual dominance and degree of overlap of the relevant and irrelevant dimensions (i.e., S-S compatibility) in 4A and the relative degree of dimensional overlap of the two S-R sets in 4B may give rise to complex patterns of interaction in the data.

For example, consider a study by Hedge and Marsh (1975), which is the only study that we know of that approximates the conditions of a Type 4A ensemble. Their subjects performed a choice RT task in which the stimuli consisted of a red or green light going on to the left or right of a fixation point. The responses consisted of pressing a green key on the right or a red key on the left. Color was relevant, side was irrelevant, and mapping was the major experimental variable. The experimenters reported strong interactions between the mapping conditions for relevant and irrelevant dimensions. These results were replicated by Simon and Sudalaimuthu (1979). Brebner (1979), on the other hand, replicated the original Hedge and Marsh study with only one condition altered: He reversed the relevant and irrelevant dimensions so that side was relevant and color irrelevant. With this one modification, all the interactions disappeared, the relevant dimension behaved "normally," and the irrelevant dimension appeared to have had no effect, although the appropriate controls for drawing this conclusion are missing from the study. Other things being equal, that is, in principle precluding any interactions, the model's predictions for the Hedge and Marsh or Type 4A ensembles were no different from what they would be for the Type 2 ensemble for the relevant dimension and for Type 3 for the irrelevant dimension. Brebner's results suggest that the other-things-being-equal condition was not met in the study by Hedge and Marsh and that dimensional dominance or differential degrees of overlap or both may have played a significant role in their experiment. Much more work with this type of ensemble is obviously needed.

Subtype 4B comprises ensembles in which there is overlap on the relevant and irrelevant dimensions and in which the two dimensions are either identical or at least very similar. These ensembles characterize the Stroop-type tasks (Stroop, 1935), which have generated a vast literature (for reviews, see Dyer, 1973; Jensen & Rohwer, 1966). Most of the more recent studies on the Stroop effect deal with issues such as the degree of similarity between the relevant and irrelevant dimensions (Flowers & Dutch, 1976; Green & Barber, 1981; Harrison & Boese, 1976; Kahneman, 1973; Naish, 1980; Seymour, 1977; Smith & Kirsher, 1982), the degree of automaticity (or dimensional overlap) associated with the relevant and irrelevant dimensions (this issue is closely related to the similarity question; Green & Barber, 1983; Logan, 1980; Magiste, 1984; Regan, 1978; Warren, 1974), and the time course for processing the one dimension as against the other (Glaser & Glaser, 1982; Neill, 1978; Paley & Olson, 1975; Posner, 1978; Ray, 1979; Schweickert,

1983; Williams, 1977). These are all complex issues that require much more research before being resolved.

Summary and Conclusions

We have outlined a conceptual framework for the analysis of the classic problem of SRC. On the basis of this framework, we have developed a taxonomy for simple performance tasks that were hitherto viewed as unrelated but can now be seen as variants of the basic SRC paradigm. The resulting family of tasks allows some of the fundamental questions in cognitive psychology to be probed with relatively simple experimental procedures, the results of which have been made comparable. This article marks a beginning and clearly poses many more questions than it answers. However, implicit in these new questions is a research agenda that includes quantifying the model, spelling out how the various factors interact in complex tasks, and extending the dimensional overlap framework to encompass the higher level cognitive processes.

References

- Auerbach, G., & Sperling, P. (1974). A common auditory-visual space: Evidence for its reality. *Perception & Psychophysics*, *16*, 129-135.
- Bashore, T. R. (1981). Vocal and manual reaction time estimates of interhemispheric transmission time. *Psychological Bulletin*, *89*, 352-368.
- Berlucchi, G., Crea, F., Di Stefano, M., & Tassinari, G. (1977). Influence of spatial stimulus-response compatibility on reaction time of ipsilateral and contralateral hand to lateralized light stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, *3*, 505-517.
- Bertelson, P. (1963). S-R relationships and reaction times to new versus repeated signals in a serial task. *Journal of Experimental Psychology*, *65*, 478-484.
- Blackman, A. R. (1975). Test of additive factors method of choice reaction time analysis. *Perceptual and Motor Skills*, *41*, 607-613.
- Brainard, R. W., Irby, T. S., Fitts, P. M., & Alluisi, E. A. (1962). Some variables influencing the rate of gain of information. *Journal of Experimental Psychology*, *63*, 105-110.
- Brebner, J. (1979). The compatibility of spatial and nonspatial relationships. *Acta Psychologica*, *43*, 23-32.
- Brebner, J., Shepard, M., & Cairney, P. (1972). Spatial relationships and S-R compatibility. *Acta Psychologica*, *36*, 1-15.
- Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon Press.
- Broadbent, D. E. (1971). *Decision and stress*. London: Academic Press.
- Broadbent, D. E., & Gregory, M. (1965). On the interaction of S-R compatibility with other variables affecting reaction time. *British Journal of Psychology*, *56*, 61-67.
- Cheng, P. W. (1985). Restructuring versus automaticity: Alternative accounts of skill acquisition. *Psychological Review*, *92*, 414-423.
- Coles, M. G. H., Gratton, G., Bashore, T. R., Eriksen, C. W., & Donchin, E. A. (1985). Psychophysiological investigation of the continuous flow model of human information processing. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 529-553.
- Connolly, K., & Jones, B. (1970). A development study of afferent-efferent integration. *British Journal of Psychology*, *61*, 259-266.
- Costa, L. D., Horwitz, M., & Vaughan, H. G., Jr. (1966). Effects of stimulus uncertainty and S-R compatibility on speed of digit coding. *Journal of Experimental Psychology*, *72*, 895-900.
- Davis, R., Moray, N., & Treisman, A. (1961). Imitating responses and the rate of gain of information. *Quarterly Journal of Experimental Psychology*, *13*, 78-89.
- Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica*, *30*, 412-431. (Original work published 1869)
- Duncan, J. (1977a). Response selection errors in spatial choice reaction tasks. *Quarterly Journal of Experimental Psychology*, *29*, 415-423.
- Duncan, J. (1977b). Response selection rules in spatial choice reaction tasks. In S. Dornic (Ed.), *Attention and performance VI* (pp. 49-71). Hillsdale, NJ: Erlbaum.
- Duncan, J. (1978). Response selection in spatial choice reaction: Further evidence against associative models. *Quarterly Journal of Experimental Psychology*, *30*, 429-440.
- Dyer, F. N. (1973). The Stroop phenomenon and its use in the study of perceptual, cognitive and response processes. *Memory & Cognition*, *1*, 106-120.
- Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics*, *25*, 249-263.
- Falmagne, J.-C. (1965). Stochastic models for choice reaction time with applications to experimental results. *Journal of Mathematical Psychology*, *2*, 77-124.
- Fisk, D., & Schneider, W. (1983). Category and word search: Generalizing search principles to complex processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*, 177-195.
- Fitts, P. M. (1959, June). *Human information handling in speeded tasks* (Report No. RC-109). Yorktown Heights, NY: IBM Research Center.
- Fitts, P. M., & Deiningner, R. L. (1954). S-R compatibility: Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology*, *48*, 483-492.
- Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont, CA: Brooks/Cde.
- Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*, 199-210.
- Flowers, J. N., & Dutch, S. (1976). The use of visual and name codes in scanning and classifying colors. *Memory & Cognition*, *4*, 384-390.
- Georgopoulos, A. P., Lurito, J. T., Petrides, M., Schwartz, A. B., & Massey, J. T. (1989). Mental rotation of the neuronal population vector. *Science*, *243*, 234-236.
- Glaser, M. O., & Glaser, W. R. (1982). Time course analysis of the Stroop phenomenon. *Journal of Experimental Psychology*, *8*, 875-894.
- Gordon, P., & Meyer, D. E. (1984). Perceptual-motor processing of phonetic features in speech. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 153-178.
- Gratton, G., Coles, M. G. H., Sirevaag, E. J., Eriksen, C. W., & Donchin, E. (1988). Pre- and post stimulus activation of response channels: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 331-344.
- Green, E. J., & Barber, P. J. (1981). An auditory Stroop effect with judgments of speaker gender. *Perception & Psychophysics*, *30*, 459-466.
- Green, E. J., & Barber, P. J. (1983). Interference effects in an auditory Stroop task: Congruence and correspondence. *Acta Psychologica*, *53*, 183-194.
- Greenwald, A. G. (1970). A choice reaction time test of ideomotor theory. *Journal of Experimental Psychology*, *86*, 20-25.
- Harrison, N. S., & Boese, E. (1976). The locus of semantic interference in the Stroop color naming task. *Perception & Psychophysics*, *20*, 408-412.
- Hasbroucq, T. (1987). *Contributions à l'étude de la compatibilité stimulus-réponse: Essai de formalisation théorique, résultats expérimentaux* [Contributions to the study of stimulus-response compatibility: Attempt at formalizing the theory with experimental results]. Unpublished doctoral dissertation, Université de Provence, France.
- Hawkins, H. L., MacKay, S. L., Holley, S. I., Friedin, B. D., & Cohen,

- S. L. (1973). Locus of the relative frequency effect in choice reaction time. *Journal of Experimental Psychology*, 101, 90-99.
- Hawkins, H. L., & Underhill, J. R. (1971). S-R compatibility and the relative frequency effect in choice reaction time. *Journal of Experimental Psychology*, 91, 280-286.
- Hedge, A., & Marsh, N. W. A. (1975). The effect of irrelevant spatial correspondence on two-choice response-time. *Acta Psychologica*, 39, 427-439.
- Jensen, A. R., & Rohwer, W. D. (1966). The Stroop color word test; a review. *Acta Psychologica*, 25, 36-93.
- Jones, B., & Connolly, K. (1970). Memory effects in cross modal matching. *British Journal of Psychology*, 61, 267-270.
- Jonides, J., & Gleitman, H. (1976). The benefit of categorization in visual search: Target location without identification. *Perception & Psychophysics*, 20, 289-298.
- Jonides, J., & Mack, R. (1984). On the cost and benefit of cost and benefit. *Psychological Bulletin*, 96, 29-44.
- Jonides, J., Naveh-Benjamin, M., & Palmer, J. (1985). Assessing automaticity. *Acta Psychologica*, 60, 157-171.
- Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.
- Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 29-61). Orlando, FL: Academic Press.
- Keele, S. W. (1967). Compatibility and time sharing in serial reaction time. *Journal of Experimental Psychology*, 75, 529-539.
- Kornblum, S. (1969). Sequential determinants of information processing in serial and discrete choice reaction time. *Psychological Review*, 76, 113-131.
- Kornblum, S. (1973). Sequential effects in choice reaction times: A tutorial review. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 259-288). New York: Academic Press.
- Kornblum, S., Hasbroucq, T., & Osman, A. (1984, November). *The dimensional overlap model of stimulus-response compatibility*. Paper presented at the meeting of the Psychonomic Society, St. Antonio, TX.
- Krantz, D. H., Luce, R. D., Suppes, P., & Tversky, A. (1971). *Foundations of measurement*. New York: Academic Press.
- Leonard, J. A. (1959). Tactual choice reaction time: I. *Quarterly Journal of Experimental Psychology*, 11, 76-83.
- Logan, G. C. (1980). Attention and automaticity in Stroop and primary tasks: Theory and data. *Cognitive Psychology*, 12, 523-553.
- Magiste, E. (1984). Stroop tasks and dichotic translation: The development of interference patterns in bilinguals. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 10, 304-315.
- Marks, L. E. (1978). *The unity of the senses*. New York: Academic Press.
- Marks, L. E. (1987). On cross-modal similarity: Auditory-visual interactions in speeded discrimination. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 384-394.
- Mervis, C. L., & Rosch, E. (1981). Categorization of natural objects. *Annual Review of Psychology*, 32, 89-115.
- Miller, J. (1988). Discrete and continuous models of human information processing: Theoretical distinctions and empirical results. *Acta Psychologica*, 67, 191-257.
- Moray, N. (1969). *Attention*. London: Hutchinson Educational.
- Morrin, R. E., & Grant, D. A. (1955). Learning and performance of a key-pressing task as a function of the degree of spatial stimulus-response correspondence. *Journal of Experimental Psychology*, 49, 39-47.
- Morrin, R. E., Konick, A., Troxell, N., & McPherson, S. (1965). Information and reaction time for "naming" responses. *Journal of Experimental Psychology*, 70, 309-314.
- Mowbray, G. H., & Rhoades, M. U. (1959). On the reduction of choice-reaction times with practice. *Quarterly Journal of Experimental Psychology*, 1, 16-23.
- Naish, P. (1980). Phonological recording and the Stroop effect. *British Journal of Psychology*, 71, 395-400.
- Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review*, 86, 214-255.
- Neill, T. W. (1978). Decision processes in selective attention: Response priming in the Stroop color-word task. *Perception & Psychophysics*, 23, 80-84.
- Norman, D. A. (1988). *The psychology of everyday things*. New York: Basic Books.
- Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, 7, 44-64.
- Palef, S. R., & Olson, D. R. (1975). Spatial and verbal rivalry in Stroop-like tasks. *Canadian Journal of Psychology*, 29, 201-209.
- Palmer, E. (1978). *Fundamental aspects of cognitive representations*. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 259-303). Hillsdale, NJ: Erlbaum.
- Palmer, J., & Jonides, J. (1984). *Automatic categorization and the mechanism underlying effects of information load and irrelevant foils*. Unpublished manuscript.
- Poffenberger, A. T. (1912). Reaction time to retinal stimulation with special reference to the time lost in conduction through nerve centers. *Archives of Psychology*, 23, 1-73.
- Posner, M. I. (1978). *Chronometric explorations of mind*. Hillsdale, NJ: Erlbaum.
- Posner, M. I., & Snyder, C. R. R. (1975a). Attention and cognitive control. In R. L. Solso (Ed.), *Information Processing and Cognition. The Loyola Symposium*: (pp. 55-85). Hillsdale, NJ: Erlbaum.
- Posner, M. I., & Snyder, C. (1975b). Facilitation and inhibition in the processing of signals. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V* (pp. 669-682). London: Academic Press.
- Ray, C. (1979). Some components of colour-word interference and their relationship with field dependence. *Acta Psychologica*, 38, 32-33.
- Regan, J. (1978). Involuntary automatic processing in color naming tasks. *Perception & Psychophysics*, 24, 130-136.
- Roberts, F. S. (1979). Measurement theory with applications to decision-making, utility, and the social sciences. In *Encyclopedia of mathematics and its applications* (Vol. 7). Reading, MA: Addison-Wesley.
- Roffler, S. K., & Butler, R. A. (1968). Localization of tonal stimuli in the vertical plane. *Journal of the Acoustical Society of America*, 43, 1260-1266.
- Rosch, E. (1978). Principles of categorization. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 27-48). Hillsdale, NJ: Erlbaum.
- Rudel, R. G., & Teuber, H.-L. (1964). Cross modal transfer of shape discrimination by children. *Neuropsychologia*, 2, 1-8.
- Ryan, C. (1983). Reassessing the automaticity-control distinction: Item recognition as a paradigm case. *Psychological Review*, 90, 171-178.
- Sanders, A. F. (1970). Some variables affecting the relation between relative signal frequency and choice reaction time. In A. F. Sanders (Ed.), *Attention and performance III: Proceedings of a symposium on attention and performance* [Special issue]. *Acta Psychologica*, 33, 45-55.
- Sanders, A. F. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 331-354). Amsterdam: North-Holland.
- Schneider, W., Dumais, S. T., & Shiffrin, R. M. (1984). Automatic and control processing and attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 1-27). Orlando, FL: Academic Press.
- Schneider, W., & Fisk, D. (1984). Automatic category search and its transfer. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 10, 1-15.
- Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic hu-

- man information processing: I. Detection, search, and attention. *Psychological Review*, 84, 1-66.
- Schvaneveldt, R. W., & Staudenmayer, H. (1970). Mental arithmetic and the uncertainty effect in choice reaction time. *Journal of Experimental Psychology*, 85, 111-117.
- Schwartz, S. P., Pomerantz, J. R., & Eggeth, H. E. (1977). State and process limitations in information processing: An additive factors analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 3, 402-410.
- Schweickert, R. (1983). Latent network theory: Scheduling of processes in sentence verification and the Stroop effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 9, 353-383.
- Schweickert, R., & Boggs, G. J. (1984). Models of central capacity and concurrency. *Journal of Mathematical Psychology*, 28, 223-281.
- Seymour, P. N. R. (1977). Conceptual encoding and locus of the Stroop effect. *Quarterly Journal of Experimental Psychology*, 29, 245-265.
- Shiffrin, R. M., Dumais, S. T., & Schneider, W. (1981). Characteristics of automatism. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 223-238). Hillsdale, NJ: Erlbaum.
- Shiffrin, R., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review*, 84, 127-190.
- Shulman, H. G., & McConkie, A. (1973). S-R compatibility, response discriminability, and response codes in choice reaction time. *Journal of Experimental Psychology*, 98, 375-378.
- Simon, J. R. (1967). Choice reaction time as a function of auditory S-R correspondence, age and sex. *Ergonomics*, 10, 659-664.
- Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*, 81, 174-176.
- Simon, J. R., & Craft, J. L. (1970). Effects of altered display-control relationships on information processing from a visual display. *Journal of Applied Psychology*, 54, 253-257.
- Simon, J. R., Craft, J. L., & Small, Q. M., Jr. (1970). Manipulating the strength of a stereotype: Interference effects in an auditory information-processing task. *Journal of Experimental Psychology*, 86, 63-68.
- Simon, J. R., Craft, J. L., & Webster, J. B. (1973). Reactions toward the stimulus source: Analysis of correct responses and errors over a five-day period. *Journal of Experimental Psychology*, 101, 175-178.
- Simon, J. R., Hinrichs, J. V., & Craft, J. L. (1970). Auditory S-R compatibility: Reaction time as a function of ear-hand correspondence and ear-response-location correspondence. *Journal of Experimental Psychology*, 86, 97-102.
- Simon, J. R., & Small, A. M. (1969). Processing auditory information: Interference from an irrelevant cue. *Journal of Applied Psychology*, 53, 433-435.
- Simon, J. R., & Sudalaimuthu, P. (1979). Effects of S-R mapping and response modality on performance in a Stroop task. *Journal of Experimental Psychology: Human Perception and Performance*, 5, 176-187.
- Smith, G. A. (1977). Studies of compatibility and a new model of choice reaction time. In S. Dornic (Ed.), *Attention and performance VI* (pp. 27-48). Hillsdale, NJ: Erlbaum.
- Smith, M. C., & Kirsher, K. (1982). Language and orthography as irrelevant features in colour-word and picture-word Stroop interference. *Quarterly Journal of Experimental Psychology*, 39A, 153-170.
- Stanovich, K. E., & Pachella, R. G. (1977). Encoding, stimulus-response compatibility, and stages of processing. *Journal of Experimental Psychology: Human Perception and Performance*, 3, 411-421.
- Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (Ed.), *Attention and performance II: Proceedings from a symposium on attention and performance* [Special issue]. *Acta Psychologica*, 30, 276-315.
- Stevens, S. S. (1959). Cross modality validation of subjective scales for loudness vibration and electric shock. *Journal of Experimental Psychology*, 57, 201-209.
- Stevens, S. S., & Guirao, M. (1963). Subjective scaling of length and the matching of length to loudness and brightness. *Journal of Experimental Psychology*, 66, 177-186.
- Stevens, J. C., Mark, J. D., & Stevens, S. S. (1960). Growth of sensation on seven continua as measured by force of handgrip. *Journal of Experimental Psychology*, 59, 60-67.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18, 643-662.
- Suppes, P., & Zinnes, J. L. (1963). Basic measurement theory. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of mathematical psychology* (pp. 1-76). New York: Wiley.
- Teghtsoonian, R., & Teghtsoonian, M. (1970). Two varieties of perceived length. *Perception & Psychophysics*, 8, 389-392.
- Theios, J. (1973). Reaction time measurements in the study of memory processes: Theory and data. In G. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 7, pp. 43-85). New York: Academic Press.
- Theios, J. (1975). The components of response latency in simple human information processing tasks. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V* (pp. 418-440). London: Academic Press.
- Treisman, A. M. (1960). Contextual cues in selective listening. *Quarterly Journal of Experimental Psychology*, 12, 292-298.
- Treisman, A., & Fearnley, S. (1969). The Stroop test: Selective attention to colors and words. *Nature*, 222, 437-439.
- Tversky, A. (1977). Features of similarity. *Psychological Review*, 84, 327-352.
- Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology*, 88, 354-360.
- Warren, R. E. (1974). Association, directionality, and stimulus encoding. *Journal of Experimental Psychology*, 102, 151-158.
- Welford, A. T. (1976). *Skilled performance: Perceptual and motor skills*. Glenview, IL: Foreman.
- Whitaker, L. A. (1979). Dual task interference as a function of cognition processing load. *Acta Psychologica*, 43, 71-84.
- Wickens, C. (1980). The structure of attentional resources. In R. S. Nickerson (Ed.), *Attention and performance VIII* (pp. 239-257). Hillsdale, NJ: Erlbaum.
- Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input, central processing and output. *Human Factors*, 25, 227-248.
- Williams, E. (1977). The effects of amount of information in the Stroop color-word test. *Perception & Psychophysics*, 22, 463-470.
- Woodworth, R. (1938). *Experimental psychology*. New York: Holt.

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