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Stimulus–Response Compatibility With Relevant and Irrelevant Stimulus Dimensions That Do and Do Not Overlap With the Response

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Five experiments were conducted using 4- and 6-choice stimulus–response compatibility tasks with graphic and alphabetic stimuli, and keypress and verbal responses. A comparison of performance with compatible, incompatible, and neutral conditions shows that when a stimulus set is perceptually, conceptually, or structurally similar to a response set, (a) mean reaction times (RTs) are faster when individual stimuli and responses match than when they do not match, (b) this is true whether the stimulus and response sets are similar on relevant or irrelevant dimensions, (c) this "compatibility effect" is greater when the dimensions are relevant than when they are irrelevant, and (d) whether the dimensions are relevant or irrelevant, the faster RTs are due to a facilitative process and the slower RTs to an interfering process. These results are accounted for by the dimensional overlap model.

It is almost universally true that performance is easier and better (i.e., faster and more accurate) with what are called *compatible* tasks than with *incompatible* tasks.[1] This observation was first reported by Paul Fitts (Fitts & Deininger, 1954; Fitts & Seeger, 1953) and has been confirmed in a variety of settings many times since then (for recent reviews, see Alluisi & Warm, 1990; Kornblum, 1992; Norman, 1988; Proctor & Reeve, 1990). From the very outset (Fitts, 1959), it was clear that this effect—the stimulus–response compatibility (SRC) effect—was not determined by either stimulus or response properties acting independently, but was the result of the interaction between them. The principal theoretical problem posed by these results has been the clarification of the nature of this interaction, thus making SRC a classic problem touching on fundamental issues in cognition.

We have recently presented a model, the dimensional overlap model (Kornblum, 1992; Kornblum, Hasbroucq, & Osman, 1990), in which we propose that SRC is the direct consequence of the degree to which the stimulus and response sets of a *stimulus–response (S-R) ensemble* (see Appendix) are perceptually, conceptually, or structurally similar. We call this relationship *dimensional overlap* (see Appendix).

In this article we summarize and update selected, relevant aspects of the dimensional overlap model. We then present the results of three experiments (Experiments 1, 2, and 3) that were designed to test various implications of the model. The results of two more experiments (Experiments 4 and 5) follow up on some of the observations made in the first three experiments that are pertinent to extensions of the model.

The Dimensional Overlap Model

Similarity is a property usually associated with individual items like words, shapes, faces, countries, and so forth. Rarely is similarity thought of as a property of sets. However, there is no reason why sets of items, such as categories (see Kornblum et al., 1990; Oliver & Kornblum, 1991), cannot also be scaled in terms of similarity. For example, consider the set of digits, the set of digit names, and a set of nonsense syllables. To the extent that the set of digits and

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[1] The terms *compatible* and *incompatible* are widely used in the literature; however, they are not very precise terms. Even though we do not use these terms in the development of our model, we do occasionally use them, and when we do, they refer to the fact that some tasks are easier to perform than others either because of the particular sets of stimuli and responses that are used, or because of the way individual stimuli and responses are paired with each other (see also *compatibility* in the Appendix).

the set of digit names each consists of different representations of the same concept, namely numerosity, they are more similar to each other than either is to the set of nonsense syllables. We use the term *dimensional overlap* to refer to similarity when it occurs at the set level. Dimensional overlap is thus a property of the mental representation of sets and is also heir to all the strengths and weaknesses inherent in the concept of similarity[2] (see Kornblum et al., 1990, for a slightly more formal discussion of similarity at the set level).

When an S-R ensemble has overlapping S-R dimensions, individual S-R pairs will either match or mismatch. For example, consider the set of digits and the set of digit names as the set of stimuli and responses, respectively. If the *mapping instructions* (see *stimulus–response mapping* in the Appendix) call for the digits 1, 2, 3, and 4 to be responded to with their own names, then the individual stimuli and responses in the pairs so formed will match. This is a match at the element level. If, on the other hand, the mapping instructions call for the digits 1, 2, 3, and 4 to be responded to with the digit names *two*, *three*, *four*, and *one*, respectively, then at the element level, the pairs so formed will mismatch. Note that in the absence of dimensional overlap, that is, a nonmatch at the set level, matches and mismatches at the element level are undefined. Mapping instructions with nonoverlapping sets result in nonmatches.

The Taxonomy

It is widely recognized that overlapping S-R or S-S dimensions have profound consequences on performance, whether these dimensions are *relevant* or *irrelevant* (see *dimensional relevance* in the Appendix; e.g., Proctor & Reeve, 1990). By combining the concepts of dimensional overlap and dimensional relevance, we have constructed a taxonomy of compatibility tasks that ranges from the simple (e.g., Fitts & Deininger, 1954) to the complex (e.g., Stroop, 1935) and encompasses eight different types of S-R ensembles (Kornblum, 1992). These are listed and illustrated in Table 1. The first four ensembles overlap on a single dimension, and the last four overlap on two or more dimensions. In the present study we consider the first three of the four unidimensional ensembles.

Type 1 ensembles are characterized by the absence of dimensional overlap in either the relevant or the irrelevant dimensions. Examples of Type 1 ensembles are ubiquitous in the choice reaction time (RT) literature (e.g., Luce, 1986; Welford, 1980). If, as the dimensional overlap model asserts, compatibility requires dimensional overlap, it follows that Type 1 ensembles do not produce compatibility effects. However, such ensembles have been quite useful in constructing neutral, baseline, control conditions for the study of such effects.

Type 2 ensembles are characterized by overlap between the response and the relevant stimulus dimensions of the S-R ensemble. These are the classical ensembles that are ordinarily used in the study of S-R compatibility (see, for example, Fitts & Deininger, 1954; see also Sanders, 1980, for a review).

Type 3 ensembles are characterized by having the only overlap occurring between the response set and the irrelevant stimulus dimension. This is the type of ensemble that produces the so-called "Simon effect" (e.g., Simon & Small, 1969; see also Umilta, 1994, and Kornblum, 1992).

Type 4 ensembles have the only overlap occurring between the relevant and an irrelevant stimulus dimension. This type of ensemble includes all the Stroop-like tasks in which researchers have tried to preserve Stroop-like stimulus characteristics (e.g., Keele, 1972) in order to dissociate their effects from those of the response. (The Stroop task itself uses a Type 8 ensemble.)

The Processing Model

The full processing model consists of two modules with stagelike characteristics (cf. Sternberg, 1969) separated by a cutpoint (cf. Schweickert, Fisher, & Goldstein, 1991). The first module, the stimulus identification module, is not involved in the present study and is described elsewhere (Kornblum, 1994). This module generates a stimulus vector that is passed on to the second module, the response production module. The stimulus vector consists of all the stimulus attributes or features encoded by the stimulus identification module, including the relevant and the irrelevant attributes. The relevant stimulus attribute is identified in the vector by a tag.

The response production module has two principal processing paths: automatic response activation and response identification. The model postulates that when the *stimulus sets* and the *response sets* (see Appendix) of an S-R ensemble have overlapping dimensions, presentation of a *stimulus element* (see Appendix) automatically activates its corresponding *response element* (see Appendix).[3] For example, if the stimulus set consists of the digits 1, 2, 3, and 4 and the response set consists of the digit names *one*, *two*, *three*, and *four*, then presenting the stimulus digit 1 automatically activates the response *one*. This process is similar to that

[2] Because dimensional overlap is based on similarity, which varies continuously, dimensional overlap, in principle, varies continuously as well. However, for purposes of exposition in this article, we treat dimensional overlap as a dichotomous variable.

[3] The functionally significant automatic response activation process described in the model refers to activation increments that are added to a baseline level. When a set of stimuli and responses are identified as components of a particular task, the model postulates that the base activation level for these stimulus sets and response sets is increased by the very instructions. The automatic response activation that produces the effects described in the model is the sum of the raised baseline level plus the automatic activation increment. It is quite likely that particular stimulus codes (e.g., the digit 1 or the color red) always produce activation increments of their corresponding response codes (e.g., the digit name *one* or the word *red*). However, as long as this increment is added to a normal resting baseline, it has no functional consequences.

Table 1
A Taxomony of Stimulus–Response (S-R) Ensembles According to the Dimensional Overlap Model (Kornblum, 1992; Kornblum et al., 1990)

	Overlapping ensemble dimensions			Illustrative stimulus and response sets			
	S-R dimensions		S-S Dimensions	Illustrative stimulus sets			
Ensemble type	Relevant (S_r)	Irrelevant (S_i)	(S_r-S_i)	Relevant (S_r)	Irrelevant (S_i)	Illustrative response sets	Representative studies
1	no	no	no	colors	geometric shapes	digit names	Many choice RT tasks that have no dimensional overlap
2	yes	no	no	digits	colors	digit names	Fitts & Deininger, 1954; Fitts & Seeger, 1953
3	no	yes	no	colors	digits	digit names	Simon, 1969; Wallace, 1971
4	no	no	yes	colors	color words	digit names	Ericksen & Ericksen, 1974; Kahneman & Henick, 1981; Keele, 1972
5	yes	yes	no	colors	position (left or right)	keypresses (left or right) on colored keys	Hedge & Marsh, 1975
6	yes	no	yes	position (left or right)	colors and color words	keypress (left or right)	none
7	no	yes	yes	colors	color words/ position (left or right)	keypress (left or right)	Kornblum, 1994
8	yes	yes	yes	colors	color words	color names	Simon & Rudell, 1967; Stroop, 1935

Note. RT = reaction time.

triggered by an explicit prime or precue[4] (see Posner & Snyder, 1975) and is represented by the upper branch of the response production module in Figure 1. Whether or not there is dimensional overlap between the stimulus and the response sets, the relevant attribute in the stimulus vector triggers the response identification process, represented by the lower branch of the response production module in Figure 1. The response identification process identifies the correct response, that is, the response that the mapping instructions require given the stimulus that was just presented. Even though the response identification process is involved in response production regardless of whether S-R dimensions overlap, it is very much influenced by the presence or absence of overlap between the stimulus and the response sets. When there is no overlap (e.g., Ensemble Type 1), response identification proceeds by search, or table look-up, which by assumption is the longest and most time-consuming identification procedure. When there is overlap between the stimulus and the response dimensions (e.g., Ensemble Type 2), it introduces the potential of using a rule to get from the stimulus to the correct response. The simplest and fastest rule is the identity rule. For example, if the stimulus set consists of the digits 1, 2, 3, and 4 and the response set consists of the digit names *one*, *two*, *three*, and *four*, and the mapping instructions assign the stimulus digits to their own names as responses, the identity rule is the quickest way to select the correct response. There are other rules, of course, that are more complex and, by assumption, more time consuming.[5] For example, if the stimulus set is viewed as a loop, then the mapping instructions could be given as correct response = stimulus + 2, which would define the digit names *three*, *four*, *one*, and *two* as the correct responses for the stimuli 1, 2, 3, and 4, respectively. Note that the use of a rule requires dimensional overlap between the stimulus and the response sets (see Kornblum et al., 1990, p. 260, Footnote 7); however, the existence of such overlap does not necessarily force the use of a rule or exclude the use of a search procedure. In fact, as is illus-

[4] A typical trial in a priming paradigm consists of the following sequence of events: The trial starts with a warning signal; this is followed by a signal, the prime, that usually gives some advance information about which stimulus is about to be presented, which response is about to be required, or both; this, in turn, is followed by the stimulus to which the response is then made. Typically, one of the variables of interest is the time lag between the presentation of the prime and the presentation of the stimulus; this is called the *stimulus onset asynchrony* (SOA). In the standard SRC paradigm, with dimensional overlap between the stimulus and response sets, the "prime" and "stimulus" are combined into a single physical event.

[5] The order assumption—that the identity rule is fastest, other rules are intermediate, and search is slowest—is supported by a number of studies (Costa, Horwitz, & Vaughan, 1966; Everett, Hochhaus, & Brown, 1985; Fitts & Deininger, 1954; Schvaneveldt & Staudenmayer, 1970; Smith, 1977).

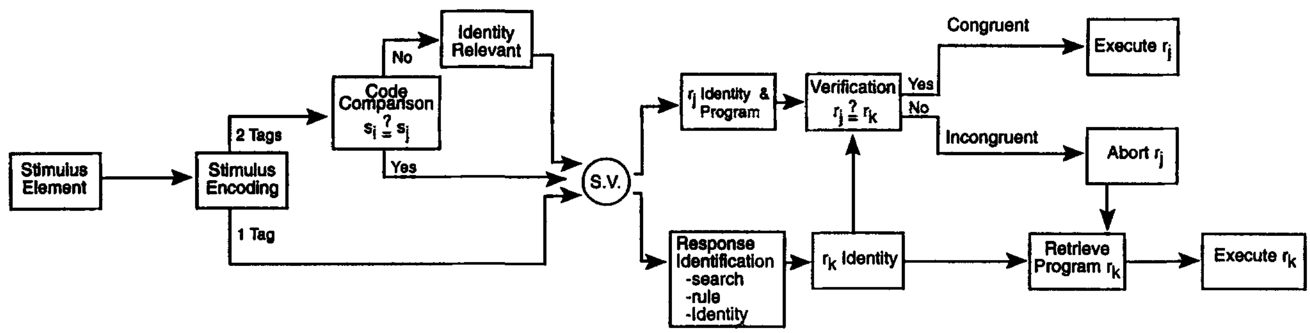

Figure 1. The dimensional overlap processing model. The stimulus vector (S.V.) marks the cutpoint in the network. To the left of the cutpoint is the stimulus identification stage; to the right is the response production stage. s_i = a stimulus attribute that overlaps with another stimulus attribute; s_j = a stimulus attribute that overlaps with a response attribute; r_j = an automatically activated response; r_k = the correct response.

trated in the present study, in order to compare experimental conditions, it is often important, albeit difficult, to formulate mapping instructions for overlapping S-R ensembles that force response identification into a search procedure.

Thus, the duration of the response identification process may, but need not, be affected by the presence of dimensional overlap between the stimulus and response sets. Response identification is clearly longest for S-R ensembles that have nonoverlapping S-R dimensions. Here, search is necessarily the procedure used. Response identification is fastest for S-R ensembles with overlap in which the mapping instructions permit the use of the identity rule, and it is of intermediate duration for S-R ensembles with overlap in which the mapping instructions permit the use of another, nonidentity rule. In the last two instances, the response identification process is facilitated by the presence of overlapping S-R dimensions, when compared with the search procedure. If, despite dimensional overlap, the mapping instructions require the use of search, then the overlapping S-R ensemble accrues no time advantage in response identification over the nonoverlapping ensemble.

To summarize the response production process thus far: (a) When the stimulus and the response sets in an S-R ensemble have overlapping dimensions, presenting a stimulus element automatically activates its corresponding response element (upper branch, right-most module in Figure 1), whether or not the overlapping dimension is relevant. (b) Irrespective of whether the stimulus and response sets overlap, the relevant attribute of a stimulus triggers the response identification process. (c) Response identification may occur in one of three ways (ordered from fastest to slowest): identity rule, nonidentity rule, and search. The first two procedures require overlap; the last procedure is applicable with or without overlap.

Next we examine when and how the automatic response activation and the response identification processes interact. We consider three cases: (a) when there is no S-R overlap (e.g., ensemble Type 1), (b) when the S-R overlap is on a relevant stimulus dimension (e.g., ensemble Type 2), and (c) when the S-R overlap is on an irrelevant stimulus dimension (e.g., ensemble Type 3).

Ensemble Type 1

When there is no S-R overlap in an ensemble, we have just seen that presentation of a stimulus element has no effect on the automatic response activation process. The only process triggered is response identification, which is activated by the relevant, tagged attribute. In the absence of dimensional overlap, response identification proceeds by search. After identification of the correct response, the appropriate motor program is retrieved, and the response is then executed.

Ensemble Type 2

With dimensional overlap between the stimulus and the response sets, we have just seen that presentation of a stimulus element triggers the automatic response activation process as well as the response identification process. Note that these two processes are triggered by one and the same feature, or attribute, in the stimulus vector. Whether response identification uses the identity rule, another rule, or search depends, of course, on the particular mapping instructions for the task. Thus, the duration of the identification process in Type 2 ensembles is determined by the mapping instructions. Whatever the mapping, however, the automatically activated response and the response identified as correct must now be compared before the correct response can be executed (see the verification box in Figure 1). If the two are the same (e.g., if the stimulus is the digit 1 and the correct response is the digit name *one* and was so identified), that response is executed without further ado. Note that with this mapping, the duration of the entire response production process is shortened in two places: First, response identification uses the identity rule, which is the fastest response identification procedure in the repertoire, and second, once verified, this response is executed without further processing, that is, without abort or further program retrieval. If the two responses are not the same, then the automatically activated response together with its program are aborted, the program for the correct response is retrieved, and the response is then executed. Note that compared with the case in which the automatically activated response and the correct response are the same, in the case in which they are different, the process is lengthened in two places: First, response identification is done either by a nonidentity rule or by search, either of which takes longer than the identity rule. Second, instead of being executed without further processing right after verification, a response must be aborted and the appropriate motor program retrieved, both of which are time-consuming operations. Call the mapping instructions that assign stimulus elements to the response elements that they automatically activate *congruent mapping* and the other mapping instructions in an overlapping S-R ensemble *incongruent mapping* (see *stimulus–response mapping* in the Appendix). With nonoverlapping S-R dimensions, all S-R mappings are called *noncongruent.*

The model can now generate a number of hypotheses concerning the effects of relevant stimulus dimensions when they do and do not overlap with the response, and when they are and are not relevant. Some of these hypotheses are consistent with experimental findings in the literature; others embody generally held beliefs in the field for which, up until now, the empirical evidence was lacking; others still are new.

Hypothesis 1: The mapping hypothesis. Given an ensemble with S-R overlap on the relevant dimension, the RT for congruent mapping will be faster than for incongruent mapping (Experiments 1 and 2. This hypothesis is consistent with results reported by Blackman, 1975; Broadbent & Gregory, 1962, 1965; Fitts & Deininger, 1954; and Whitaker, 1979. See, however, the section entitled A Prototypical Experimental Design and Rules of Inference below.)

Hypothesis 2: The facilitation/interference hypothesis. The RT for the congruent mapping will be faster than, and the RT for the incongruent mapping will be slower than, the appropriate neutral condition (the "appropriate" neutral condition is defined below in the section on A Prototypical Experimental Design and Rules of Inference).

Hypothesis 3: The nonoverlap hypothesis. Given an ensemble without S-R overlap, the RT for any one S-R mapping will not differ significantly from that of any other S-R mapping (Experiments 1 and 5).[6]

Ensemble Type 3

When the overlap is between an irrelevant stimulus dimension and the response (e.g., a stimulus set consisting of the digits 1, 2, 3, and 4 written in red, blue, green, and yellow, together with a response set consisting of the digit names *one, two, three,* and *four,* and color is the relevant stimulus dimension and digit is the irrelevant dimension), presentation of the stimulus element will again trigger the automatic response activation and the response identification processes. However, instead of having these processes triggered by the same feature or attribute in the stimulus vector, they will each be triggered by a different feature. Automatic response activation will be triggered by the stimulus feature that represents a value on the irrelevant stimulus dimension (in our example, the digit), which overlaps with the response (in our example, the digit name). The response identification process will be triggered by the tagged, relevant feature that does not overlap with the response (in our example, the color) and will therefore necessarily use search in identifying the correct response. This, of course, precludes Type 3 ensembles from displaying any of the time advantages that accrue from using rule-based response identification procedures which, by assumption, are faster than search—which leads to the next hypothesis.[7]

Hypothesis 4: Mapping and S-R consistency effects. Given a stimulus dimension that overlaps with the response, the mapping effect with this dimension will be larger than the *consistency effect* (see Appendix; also Experiments 1 and 2).

As was true of the Type 2 ensemble, given a correct response as the output of the identification process and an automatically activated response as the output of the automatic process, a decision must be made about which response to execute. If the two are the same (the *S-R consistent* case), this response is executed without further ado. If they are different (the *S-R inconsistent* case; see *consistency/inconsistency* in the Appendix), the automatically activated response is aborted, the program for the correct response is retrieved, and the response is then executed.

Hypothesis 5: The S-R consistency hypothesis. Given an

[6] To the extent that dimensional overlap is defined in terms of the degree of similarity between sets and that "respects for similarity" (see Medin et al., 1993, and the General Discussion section) implies that similarity may be an emergent property, it may be quite difficult to obtain ensembles with zero dimensional overlap. For example, suppose one were to ask which of the items in the following two pairs are more similar to each other: (a) a tire and a tree or (b) a tire and a doughnut. If the question is one of similarity with respect to shape, then the tire and the doughnut are clearly the more similar pair. If the question is one of similarity with respect to ability to float, then the tire and the tree are the more similar pair. People are very good at picking out these relationships, and they use them very effectively. Our theories of human performance have to take this into account. This, however, does not invalidate the hypothesis.

[7] Most previous studies of Type 3 ensembles have used two-choice tasks in which the irrelevant dimension is spatial (Stoffels, van der Mollen, & Keuss, 1989, used a four-choice task). The results from such studies have been called the *Simon effect* (Hedge & Marsh, 1975; for a review, see Lu & Proctor, in press; Simon, 1990; Umilta & Nicoletti, 1990). Despite its deserved eponymous origins, this term is ambiguous, for it has been used to refer to two distinct and separate phenomena. The first is the effect of an irrelevant spatial, stimulus dimension when it overlaps with the response, as in Type 3 ensembles; the second is the effect of an irrelevant spatial, stimulus dimension when it overlaps not only with the response but also with the relevant stimulus dimension. We call the latter *Type 8 ensembles* (see Table 1 and Kornblum, 1992). Consider a task in which the response consists of a left or a right keypress to a monaural, auditory stimulus, in which the ear to which the stimulus is being delivered is irrelevant. If the relevant stimuli are high- and low-pitched tones (Type 3), then the effects of relevant and irrelevant stimuli are relatively easy to isolate. If the relevant stimuli are the words *left* and *right* (Type 8), the effects of the relevant and irrelevant stimuli are confounded and difficult to disentangle. To call the results from both tasks the Simon effect is therefore potentially confusing.

ensemble with overlap on the irrelevant stimulus dimension and the response, the RT for S-R consistent trials will be faster than that for S-R inconsistent trials (Experiments 2 and 3).

Hypothesis 6: The neutral, irrelevant S-R hypothesis. Assuming that the verification process is faster than response programming or retrieval, the RT for S-R consistent trials will be faster than that for appropriate neutral trials (Experiment 3).

A Prototypical Experimental Design and Rules of Inference

Because S-R compatibility is determined by the interaction and not by the independent effects of stimulus and response properties, tests of S-R compatibility require "the use of more than one set of stimuli, more than one set of responses, and more than one way of combining each set of stimuli and responses" (Fitts, 1959, p. 6). Fitts continues with the observation that "few experiments of this sort have been carried out" (Fitts, 1959, p. 6), and this state of affairs has not changed since Fitts wrote these words. Illustrated in Figure 2 is the minimal experimental design that permits the isolation and identification of such interactions. Here, one stimulus set (S_1) is combined with two response sets: one with which it has dimensional overlap (R_1) and one with which it does not (R_2). A second stimulus set is now introduced that does not overlap with the first and for which the overlap relationships with the two response sets are reversed. This results in four S-R ensembles: two with dimensional overlap (Ensembles A and C) and two without (Ensembles B and D). When the data along each diagonal of this 2×2 design are appropriately combined (i.e., congruent with congruent and incongruent with incongruent), any observed differences between them cannot be attributed to the effects of isolated stimulus or response properties, because both stimulus and response sets are represented along both diagonals. Such differences must therefore be the result of the interactions between the stimulus and the response sets. By the same argument, the mean of the BD diagonal is an appropriate neutral reference value for the *mapping effects* (see Appendix) of the AC diagonal. This is the basic design used in Experiments 1 and 2 of this study.

Brief Overview

Experiment 1 tests the first three hypotheses concerning the effects of dimensional overlap when it occurs on relevant S-R dimensions (Hypotheses 1, 2, and 3). Experiments 2 and 3 test the model's hypotheses concerning the effects of dimensional overlap when it occurs on irrelevant S-R dimensions (Hypotheses 5 and 6). Because Experiments 1 and 2 use the identical stimulus and response dimensions, we are able to compare the "compatibility effects" of identical dimensions when they are relevant and irrelevant (Hypothesis 4). Experiment 4 explores the model's assertion concerning the relation between the size of the mapping effect and the degree of dimensional overlap. Experiment 5 tests the model's prediction concerning the absence of a mapping effect in the absence of dimensional overlap (see Hypothesis 3).

Experiment 1

In the first experiment we examined the effects of relevant S-R dimensions when they do and do not overlap. In particular, according to the model, if the relevant stimulus and response dimensions of an S-R ensemble overlap, then the mean RT for congruent mapping will be faster than for incongruent mapping. If the relevant stimulus and response dimensions do not overlap, then in principle, all mappings will yield identical RTs. Furthermore, all other things being equal, the RT for the S-R ensemble with nonoverlapping dimensions will be faster than the RT for incongruent mapping (search based) and slower than the RT for congruent mapping.

Finally, the model asserts that the mapping effect is a measure of the degree of dimensional overlap (Kornblum et al., 1990), so that two S-R ensembles with the same degree of dimensional overlap should produce mapping effects of equal magnitude, provided response identification is done by search in both cases.

Method

Stimuli and responses. There were two stimulus sets and two response sets. Each set contained four elements. The task was therefore a four-choice task.

The two stimulus sets were letters and hand icons. The individual letters in the set of letters were B, J, Q, and Y. The set of hand icons consisted of an outline drawing of the left and right hands, side by side, with the index and middle fingers of each hand extended (see Figure 3). Both sets of stimuli were visually presented.

The two response sets were keypresses and letter names. The keypresses were made by the index and middle fingers of the left and right hands. The set of letter names consisted of the verbally spoken English names of the letters B, J, Q, and Y.

Design. The design of this experiment follows the logic and structure of the prototypical design described previously. The two stimulus sets were factorially combined with the two response sets to form four S-R ensembles: two with overlapping S-R dimensions (Ensemble A: hand icons–keypresses; Ensemble C: letters–letter names) and two without (Ensemble B: hand icons–letter names; Ensemble D: letters–keypresses). These are illustrated in Figure 2B.

We assumed that there was maximal dimensional overlap between the sets of hand icons and keypresses (Ensemble A) and between the sets of letters and letter names (Ensemble C), and that there was zero dimensional overlap between the sets of hand icons and letter names (Ensemble B) and between the sets of letters and keypresses (Ensemble D).[8] Two S-R mappings were constructed

[8] As already indicated, dimensional overlap is treated in this study as a discrete, dichotomous variable: present versus absent. We felt that with the stimulus and response sets that we had selected, the determination of presence or absence was obvious. Well—as is evident from some of the results—we were wrong. However, this error in judgment also led to some interesting results (see particularly Experiment 5).

A.

STIMULUS SET / RESPONSE SET

	R1	R2
S1	**Dimensional Overlap (D.O.)** Congruent Mapping Incongruent Mapping A	**No D.O.** Mapping 1 Mapping 2 B
S2	**No D.O.** D Mapping 1 Mapping 2	**Dimensional Overlap (D.O.)** C Congruent Mapping Incongruent Mapping

B.

RESPONSE SET / STIMULUS SET

	Key Presses	Letter Names
Hand Icons	**Ensemble A** **(D.O.)**	**Ensemble B** **(no D.O.)**
Letters	**Ensemble D** **(no D.O.)**	**Ensemble C** **(D.O.)**

Figure 2. Illustration of (A) a prototypical stimulus–response compatibility design and (B) its implementation, which illustrates the stimulus–response ensembles and full experimental design of Experiment 1; it is also the reference framework for the stimulus–response ensembles used in Experiments 2–5 of this study.

for each ensemble (see Figure 3). For Ensembles A and C, with dimensional overlap, one of the mappings was congruent and the other incongruent. The incongruent mapping was an arbitrary assignment of the stimulus to the response elements from which we attempted to exclude any systematicity that could have made the response identification process rule based. For Ensembles B and D, two arbitrary S-R mappings were defined that avoided as much as possible preexisting associations between individual stimuli and responses. The combination of two S-R mappings for each of four S-R ensembles yielded a total of eight experimental conditions.

Subjects were run for 3 days with all eight experimental conditions presented on each day. Day 1 was used for training. On that day, all eight experimental conditions were run in the same order for all subjects. The order of ensembles was A, C, B, and D. The order of the mapping conditions within each ensemble was congruent followed by incongruent for Ensembles A and C, and Mapping 1 followed by Mapping 2 for Ensembles B and D. Days 2 and 3 were the experimental days. On those days, two orders of presentation were used: clockwise (e.g., Ensembles A, B, C, and D) and counterclockwise (e.g., Ensembles D, C, B, and A). Similarly, there were two orders for the S-R mappings within an ensemble: congruent (or Mapping 1) followed by incongruent (or Mapping 2) and incongruent (or Mapping 2) followed by congruent (or Mapping 1). For a particular subject if the ensembles were presented in a clockwise order on Day 2, they were presented in a counterclockwise order on Day 3. Similarly, whatever the order in which the mapping conditions were presented on Day 2, the opposite order was used on Day 3. Finally, regardless of the order in which the S-R ensembles were presented, different subjects began the clockwise or counterclockwise series with a different ensemble as the starting point. This yielded two different 4 × 4 Latin squares of ensembles by subjects on each of the two experimental days.

Subjects. Eight right-handed male students at the University of Michigan with no visual, auditory, or other detectable defects volunteered to participate in this experiment. They were paid $4.50 per hour, plus a bonus that was determined by their performance.

Stimulus presentation and response recording. Stimulus presentation and response recordings were computer controlled. The stimuli were presented on a Fairchild 737A vector oscilloscope (25 × 28 cm) controlled by a Hewlett Packard (Palo Alto, Cali-

Ensemble A			Ensemble B		
Stimulus	**R(C)**	**R(I)**	**Stimulus**	**R(1)**	**R(2)**
L_m	L_m	R_i	L_m	"Y"	"B"
L_i	L_i	L_m	L_i	"Q"	"Y"
R_i	R_i	R_m	R_i	"J"	"Q"
R_m	R_m	L_i	R_m	"B"	"J"

Ensemble D			Ensemble C		
Stimulus	**R(1)**	**R(2)**	**Stimulus**	**R(C)**	**R(I)**
B	R_m	L_m	B	"B"	"Y"
J	R_i	R_m	J	"J"	"B"
Q	L_i	R_i	Q	"Q"	"J"
Y	L_m	L_i	Y	"Y"	"Q"

Figure 3. Stimulus–response mapping instructions for Experiments 1 and 2. The R(C) and R(I) columns indicate the correct responses for the congruent and incongruent mapping conditions, respectively. The R(1) and R(2) columns indicate the correct responses for Mappings 1 and 2, respectively. R and L indicate the right and left hand index (i) and middle (m) fingers, respectively.

fornia) Model 1350 graphics controller. The hand icons occupied a total area of 17 × 12 cm on the screen; the fingertip area of the hand icons occupied a smaller area of 3 × 6.5 cm. The letters were 1 cm high and 1 cm wide. The subject was seated approximately 65 cm from the screen. The visual angle subtended by the hand icons was thus 14.90° and by the letters was 0.88°.

The keypress responses were made on a keyboard consisting of four round buttons approximately 1 in. (2.5 cm) in diameter, so placed as to enable subjects to rest their fingers comfortably on them. The microswitches to which the buttons were attached required a force of 50 g and 1 mm of travel to be depressed. Latency and accuracy of the keypress responses were recorded and monitored by the computer.

The verbal responses were fed into a Grason-Stadler (West Concord, Massachusetts) voice-operated relay (Model E7300A-1) that was tripped by the subjects' utterances. These utterances were also routed to the experimenter, who monitored their accuracy, as well as to a two-channel storage oscilloscope (Tektronix Type RM564; Beaverton, Oregon) that displayed the subjects' utterances in one channel and the voice key in the other, thus making it possible to detect any spuriously triggered voice key responses.

Procedure. Subjects sat in a dimly lit experimental chamber and wore earphones with a boom microphone at all times. The earphones and microphone were used to communicate with the experimenter as well as to receive the auditory warning and error signals and to make the verbal responses.

A trial began with a warning signal consisting of a 1-kHz tone that lasted 100 ms. Simultaneously with the onset of the warning signal, a fixation pattern appeared on the screen. When the stimulus was hand icons, the fixation pattern consisted of the outline drawing of the hands with the index and middle fingers of the left and right hands extended. When the stimulus was letters, the fixation pattern consisted of the four corners of the virtual rectangle within which the letter would subsequently be presented. Seven hundred milliseconds after the onset of the warning signal/fixation pattern, the stimulus was presented. In the case of hand icons, the stimulus consisted of an asterisk appearing in the fingertip region of one of the four fingers (left or right index or middle finger). In the case of letters, the stimulus consisted of presentation of a capital letter B, J, Q, or Y in the rectangle delineated by the four corners of the fixation pattern. Subjects then made their response, which removed the fixation pattern and the stimulus from the screen.

Each trial was followed by feedback. When the subject's response was correct and within the time window that the computer would accept (i.e., 1,400 ms following the onset of the stimulus), the word "good" appeared on the screen; when the response was either incorrect or unintelligible (as sometimes occurred with verbal responses), there was a brief burst of white noise in the earphones and the word "incorrect" appeared on the screen. When the response latency was longer than the time window (1,400 ms), the message "too late" appeared on the screen; and when the subject made a response before the stimulus had been presented, the words "wait for the signal" appeared on the screen. All feedback messages lasted 1 s and were followed by a 500-ms pause, after which the warning signal for the next trial was presented.

Feedback was also presented at the end of a block of trials that summarized the subject's performance for that block and consisted of the mean RT for correct responses in the block, the total number of errors in the block, and the score for the block. The score was calculated on the basis of a payoff matrix that rewarded speed and accuracy and penalized errors and slow responses.

There were 48 trials per block, and two blocks per condition, for a total of 16 blocks per day. Prior to each block, subjects could practice the conditions for the upcoming block until they felt ready. When they felt ready to go on, they pressed a foot switch that started the block. Stimuli were equiprobable and randomized in each block.

Results

Only the data from Days 2 and 3 were analyzed. Practice trials that had been given before the beginning of a block were not included in the analysis. For purposes of analysis a correct response was defined as a correct response preceded by a correct response; correct responses following errors were thus excluded. Again for purposes of analysis, an error was defined as an erroneous response preceded by a correct response; multiple errors were therefore excluded. Median RTs were calculated for each block in each condition and session for each subject. These data were then subjected to different analyses of variance (ANOVAs) that looked at the effects of different factors. All the ANOVAs included day and blocking addition to other experimental factors. The results collapsed over blocks are shown in Figure 4.

The first ANOVA tested for the overall effects of Dimensional Overlap and included Mapping, Stimulus Set, and Response Set as factors. The factor Dimensional Overlap was formed by combining the data of Ensembles A and C (with dimensional overlap) and comparing them with the combined data of Ensembles B and D (without dimensional overlap), as prescribed in the prototypical design. The Dimensional Overlap × Mapping interaction was highly significant, $F(1, 7) = 631.27$, $p < .00001$. These data are illustrated in Figure 5. Dimensional overlap also interacted with stimulus set,[9] $F(1, 7) = 81.13$, $p < .00001$. This interaction is readily apparent by comparing the RTs for the two overlapping and the two nonoverlapping ensembles. The overall difference between the two overlapping ensembles (A and C) is 166 ms, whereas the overall difference between the two nonoverlapping ensembles (B and D) is only 41 ms. Note that the same two stimulus sets (and the same two response sets) are involved in the overlapping and nonoverlapping ensembles: hence, this interaction. Dimensional overlap had a significant main effect, $F(1, 7) = 15.83$, $p < .005$, and a triple interaction with mapping and stimulus set, $F(1, 7) = 56.23$, $p < .0001$. This interaction is evident from the data in Figure 4 and is examined in more detail in the next two ANOVAs in which data of the overlapping (A and C) and nonoverlapping (B and D) ensembles are analyzed separately.

For the overlapping ensembles (A and C), mapping had a highly significant effect, $F(1, 7) = 270.08$, $p < .00001$, with congruent mapping being 203 ms faster than incongruent mapping (see Figure 5). For nonoverlapping ensembles (B and D), a mapping effect of 15 ms was obtained that is barely significant, $F(1, 7) = 6.56$, $p < .0375$. Ensemble A (hand icons and keypresses) was significantly faster (166 ms) than Ensemble C (letters and letter names), $F(1, 7) = 149.87$, $p < .0001$, and the mapping effect for Ensemble A (143 ms) was significantly smaller than for Ensemble C (263 ms), $F(1, 7) = 41.59$, $p < .0004$. Finally, the Mapping × Day interaction was significant for the overlapping (A and C) ensembles, $F(1, 7) = 8.17$, $p < .0244$, with more improvement occurring with the incongruent than with the congruent mapping.

An overall ANOVA also yielded the following results: RT for hand icons (502 ms) was significantly faster than for letters (564 ms), $F(1, 7) = 33.81$, $p < .0007$; keypress responses were faster (481 ms) than verbal responses (584 ms), $F(1, 7) = 91.13$, $p < .00001$; the effect of day was significant, $F(1, 7) = 8.27$, $p < .02$, as was the effect of block, $F(1, 7) = 5.99$, $p < .0442$.

Discussion

Recall that the rationale behind the prototypical SRC design was twofold: First, we wanted to examine the effects of dimensional overlap and mapping without having these effects confounded with stimulus or response factors or both, and second, we wanted to have an appropriate neutral condition against which to compare these effects (note that by satisfying the first, we satisfy the second). The design of this experiment meets both of these requirements.

By combining the data of Ensembles A and C for congruent and incongruent mapping separately, and comparing them with the combined data of Ensembles B and D, the results are quite clear (see Figure 5). First, a highly significant mapping effect of 203 ms was obtained for the ensembles with dimensional overlap (Ensembles A and C). This contrasts sharply with the barely significant mapping effect of only 15 ms that was found for the ensembles that did not have dimensional overlap (Ensembles B and D). Even though this 15-ms effect is statistically significant, it is minuscule when compared with the 203-ms effect for dimensional overlap (see Footnote 8, Experiment 5, and the General Discussion section for further discussion of this 15-ms effect). The general RT pattern is that predicted by the model. Second, according to the model, the RTs for congruent and incongruent mappings should be faster and slower, respectively, than an appropriate neutral condition. The logic of the prototypical design makes the mean RT for Ensembles B and D (555 ms) the appropriate neutral condition for this comparison, and the RT for the congruent mapping conditions shows a facilitation effect of 147 ms, $F(1, 7) = 154.04$, $p < .0001$, whereas the RT for the incongruent mapping conditions shows an interference effect of 56 ms, $F(1, 7) = 13.44$, $p < .008$.

We now turn to an examination of the individual S-R ensembles in which the difference in the mapping effect for Ensemble A (143 ms) and Ensemble C (263 ms) was unexpected. According to the model, two processes contribute to the mapping effect. The first is response identification, where the correct response is identified by the identity rule when the mapping is congruent and by a slower,

[9] Because the factor "Dimensional Overlap" is defined interactively as a particular combination of stimulus and response sets, the factor "Stimulus" is completely redundant with "Response" in any analysis that includes dimensional overlap as a factor. Whether one selects "Stimulus" or "Response" as the label for this other factor is therefore arbitrary. In this article we have chosen to use "Stimulus" for this purpose.

Ensemble A			Ensemble B		
	Day 2	Day 3		Day 2	Day 3
Congruent			**Mapping 1**		
RT	354	357	RT	578	561
SD	34	48	SD	67	43
%E	-0-	.26	%E	1.17	.91
Incongruent			**Mapping 2**		
RT	506	490	RT	604	560
SD	61	65	SD	77	59
%E	2.01	1.3	%E	1.95	1.43

Ensemble D			Ensemble C		
	Day 2	Day 3		Day 2	Day 3
Mapping 1			**Congruent**		
RT	521	533	RT	460	462
SD	43	55	SD	23	33
%E	1.19	1.62	%E	.15	.19
Mapping 2			**Incongruent**		
RT	550	535	RT	746	703
SD	32	44	SD	71	64
%E	2.71	1.69	%E	2.08	1.69

Figure 4. Mean reaction times (RTs), standard deviations (SDs), and errors rates (%Es) for Experiment 1. RTs and SDs are given in milliseconds.

nonidentity rule-based or search procedure when the mapping is incongruent. The second is what occurs immediately following verification. If the verification process determines that the automatically activated and the correct responses are one and the same, that response is immediately executed. If it determines that the automatically activated and correct responses differ, then the former needs to be aborted and the latter programmed before execution can take place.

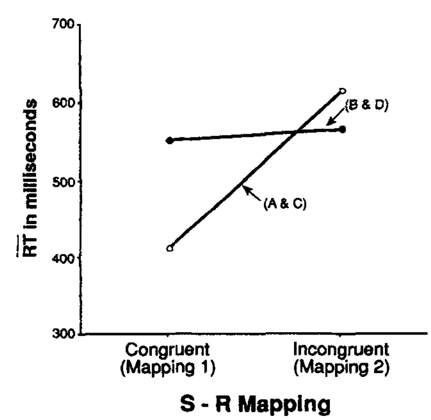

Figure 5. The data for Experiment 1 for the overlapping (A and C) and nonoverlapping (B and D) ensembles. $\overline{RT}$ = mean reaction time; S-R = stimulus–response.

If the model is correct, then given that Ensembles A and C have the same degree of dimensional overlap, we should have obtained mapping effects of equal magnitude for the two ensembles. Yet, the mapping effect for C (263 ms) is almost twice as large as for A (143 ms). We hypothesized that this difference was due to differences in the response identification procedures that were used with these two ensembles in the incongruent mapping condition. In particular, we believe that in Ensemble A, response identification was done by rule, whereas in Ensemble C it was done by search. This would have resulted in the RT for the incongruent condition of Ensemble A being faster than it was for Ensemble C. This hypothesis is tested in Experiment 4 of this article, in which this argument is also more fully developed.

Experiment 2

In the second experiment we examined the effects of irrelevant stimulus dimensions when they do and do not overlap with the response. According to the model, when irrelevant S-R dimensions overlap (e.g., Type 3), the RT for S-R consistent mapping is faster than for S-R inconsistent mapping. When irrelevant S-R dimensions do not overlap (e.g., ensemble Type 1 or 2), the model predicts that they will have no effect on performance. Finally, according to the model, the size of the consistency effect for a particular dimension will be smaller than the size of the mapping effect for that same dimension.

Method

Design and procedures. All aspects of the design and procedures of this experiment are identical to those of Experiment 1. The only difference between the two experiments is in the stimuli themselves.

Stimuli and experimental conditions. In this experiment, regardless of condition, the stimuli always consisted of the hand icons with a letter, instead of an asterisk, on the fingertip (see Figure 6). Depending on what stimulus dimension was relevant, subjects were instructed to make their responses either according to the identity of the finger with the letter on its fingertip (Ensembles A and B) and to ignore the letter's identity, or according to the identity of the letter that had appeared on a fingertip (Ensembles C and D) and to ignore the finger's identity. At the level of the relevant dimensions, therefore, this experiment is identical to Experiment 1. It is at the level of the irrelevant dimensions that the two experiments differ. Ensembles B and D in Experiment 1 were Type 1 ensembles; that is, they had no overlap of either relevant or irrelevant dimensions. In Experiment 2, Ensembles B and D are Type 3 ensembles, with an irrelevant stimulus dimension that now overlaps with the response: That is, in Ensemble B, the set of irrelevant letters in the stimuli overlaps with the set of letter name responses, and in Ensemble D, the set of irrelevant fingers overlaps with the set of keypress responses. In Experiment 1, Ensembles A and C were Type 2 ensembles, that is, they overlapped on the relevant S-R dimension. In Experiment 2, Ensembles A and C are still Type 2 ensembles because the irrelevant S-R dimensions do not overlap with either the responses or the stimuli.

Subjects. Eight individuals were chosen from the same pool, according to the same criteria, and treated in the same manner as those in Experiment 1.

Results

The data selected for analysis met the same criteria and were defined in the same manner as those of Experiment 1.

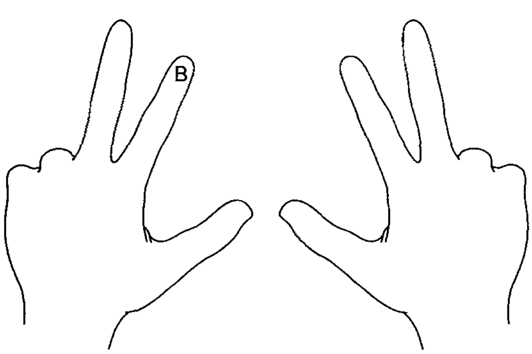

Figure 6. Illustration of the type of stimulus used in Experiment 2. Here, the letter B appears on the fingertip of the left index finger.

These are presented in Figure 7. The analyses parallel those that were done for Experiment 1, with mapping on the irrelevant dimension as an additional factor.

The first ANOVA tested for the overall effects of dimensional overlap on the relevant dimension and included Dimensional Overlap, Mapping, Stimulus Set, and Response Set factors. The factor Dimensional Overlap on the relevant dimension was formed as it was for the analyses of Experiment 1. There was a highly significant interaction of Dimensional Overlap (Relevant) × Mapping, $F(1, 7) = 232.99$, $p < .00001$. These data are illustrated in Figure 8. Dimensional overlap (relevant) also interacted with stimulus set (Footnote 9), $F(1, 7) = 54.44$, $p < .0002$. This interaction is readily apparent by comparing the RTs for the two overlapping and the two nonoverlapping ensembles. The difference between the two overlapping ensembles (A and C) is 212 ms, and the difference between the two nonoverlapping ensembles (B and D) is 53 ms. Dimensional overlap (relevant) had a significant main effect, $F(1, 7) = 68.82$, $p < .0001$, and a significant triple interaction with mapping and stimulus set, $F(1, 7) = 24.39$, $p < .0017$. This interaction is evident from the data in Figure 7 and is examined in more detail in the next two ANOVAs in which the overlapping (A and C) and nonoverlapping (B and D) ensembles are analyzed separately, with dimensional overlap on the irrelevant dimension as an additional factor. First, we report the effects of overlap on the relevant dimension.

For the ensembles with overlapping relevant dimensions (A and C; and necessarily nonoverlapping irrelevant dimensions), mapping had a highly significant effect, $F(1, 7) = 227.95$, $p < .0001$, with congruent mapping being 203 ms faster than incongruent mapping (see Figure 8). For nonoverlapping ensembles (B and D) there was no significant mapping effect (3 ms). Ensemble A (hand icons and keypresses) was significantly faster (428 ms) than Ensemble C (640 ms), $F(1, 7) = 111.77$, $p < .0001$; and the mapping effect of Ensemble A (151 ms) was significantly smaller than for Ensemble C (256 ms), $F(1, 7) = 29.78$, $p < .0009$.

The effect of dimensional overlap on irrelevant S-R dimensions (Ensembles B and D) is highly significant, $F(1, 7) = 48.99$, $p < .0002$, with the RT for S-R consistent trials in Ensembles B and D being 50 ms faster than for inconsistent trials. When the irrelevant dimensions do not overlap (Ensembles A and C), assignment is not a significant factor (see Figure 9).

An overall ANOVA yielded these additional results: RT to hand icons was significantly faster (538 ms) than to letters (617 ms), $F(1, 7) = 104.75$, $p < .00001$; keypress response was significantly faster (511 ms) than letter naming (644 ms), $F(1, 7) = 55.10$, $p < .0001$.

Discussion

The purpose of this experiment was to assess and compare the effects of dimensional overlap and S-R mapping and S-R consistency for relevant and irrelevant dimensions.

First, we shall examine the effects of dimensional overlap and mapping on the relevant dimensions and compare these

Ensemble A				Ensemble B			
Relevant	Irrelevant	Day 2	Day 3	Relevant	Irrelevant	Day 2	Day 3
Congruent	Assignment 1			Mapping 1	Consistent		
	RT	348	359		RT	635	624
	SD	37	34		SD	92	80
	%E	.52	1.04		%E	1.04	.52
	Assignment 2				Inconsistent		
	RT	355	350		RT	675	660
	SD	33	29		SD	90	74
	%E	.69	.52		%E	2.43	1.39
Incongruent	Assignment 1			Mapping 2	Consistent		
	RT	530	484		RT	623	612
	SD	60	52		SD	100	85
	%E	.52	1.04		%E	.52	2.6
	Assignment 2				Inconsistent		
	RT	524	477		RT	673	675
	SD	24	49		SD	82	82
	%E	1.91	.87		%E	4.34	2.26

Ensemble D				Ensemble C			
Relevant	Irrelevant	Day 2	Day 3	Relevant	Irrelevant	Day 2	Day 3
Mapping 1	Consistent			Congruent	Assignment 1		
	RT	572	563		RT	508	512
	SD	53	47		SD	60	64
	%E	2.6	2.6		%E	.52	-0-
	Inconsistent				Assignment 2		
	RT	631	615		RT	515	514
	SD	41	51		SD	70	63
	%E	3.13	1.74		%E	-0-	.17
Mapping 2	Consistent			Incongruent	Assignment 1		
	RT	559	579		RT	782	757
	SD	56	46		SD	119	85
	%E	.52	1.04		%E	5.21	3.12
	Inconsistent				Assignment 2		
	RT	618	617		RT	780	751
	SD	44	45		SD	81	95
	%E	2.78	2.43		%E	3.47	4.51

Figure 7. Mean reaction times (RTs), standard deviations (SDs), and error rates (%Es) for Experiment 2. RTs and SDs are given in milliseconds.

with the same effects in Experiment 1. At the level of the relevant overlapping dimensions (A and C), these two experiments are exact replications of each other, and the overall mapping effects are identical in both experiments (203 ms). At the level of individual ensembles, the mapping effects are also very similar in the two experiments: For Ensemble A, the mapping effect was 143 ms in Experiment 1 and 151 ms in Experiment 2; for Ensemble C, the mapping effect was 263 ms in Experiment 1 and 256 ms in Experiment 2. These differences between ensembles, between experiments are between-subject differences and are not statistically significant. For the ensembles without overlap on the relevant dimensions (B and D), recall that in Experiment 1 these were Type 1 ensembles, whereas in Experiment 2 they are Type 3 ensembles. First we note that the overall mean RT for Ensembles B and D was 65 ms longer in Experiment 2 than in Experiment 1. This difference is statistically significant, $F(1, 7) = 72.54$, $p < .0001$, which suggests that changing a Type 1 ensemble to Type 3 by introducing an irrelevant overlapping dimension affects the overall RT for that ensemble. (We shall return to this point in the General Discussion.) In contrast, adding an irrelevant dimension that does not overlap (as in Ensembles A and C in Experiment 2) has no effect on performance. Second, recall that we had found a 15-ms mapping effect for Ensembles B and D in Experiment 1; this effect vanished in Experiment 2.

The next question is whether the irrelevant dimensions produce consistency effects with overlap and no consistency effects without overlap, as predicted by the model (Hypothesis 5). The interaction in the data that supports this hypothesis is illustrated in Figure 9.

There are several things to be noted. First, when the irrelevant dimensions do not overlap with the response set (Ensembles A and C), these dimensions have no differential consistency effect on performance (Figure 9A). Second, when they do overlap with the response set (B and D), the RT for S-R consistent trials is significantly faster than for S-R inconsistent trials (Figure 9B). Third, note that the magnitude of the S-R consistency effect when the dimen-

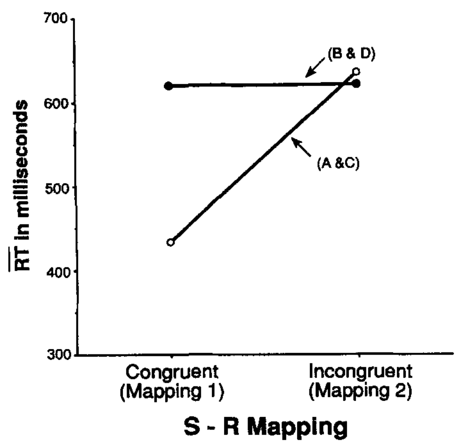

Figure 8. The data for the relevant dimensions of Experiment 2. RT = mean reaction time; S-R = stimulus–response.

sions are irrelevant (50 ms) is much smaller than the mapping effect when these same dimensions are relevant (203 ms), thus supporting Hypothesis 4. We return to this last point in the General Discussion.

Experiment 3

The results of Experiment 2 confirm the model's S-R consistency hypothesis, namely that S-R consistent trials have a faster RT than S-R inconsistent trials when an irrelevant stimulus dimension overlaps with the response (Type 3 ensemble). However, the model goes into further detail. In particular, the neutral, irrelevant S-R hypothesis states that if the verification process is faster than motor programming or program retrieval, then the RT for S-R consistent and inconsistent trials will be faster and slower, respectively, than an appropriate neutral condition. Experiment 3 is designed to test this conjecture by the addition of an appropriate neutral reference point to the conditions of Ensembles B and D of the previous experiment.

Method

Except where indicated, this experiment was procedurally identical to Experiments 1 and 2. The stimuli, instead of being displayed on a Fairchild vector scope, were displayed on a Compuadd (Austin, Texas) amber, cathode-ray tube display with a Hercules (Berkeley, California) graphics card. The hand icons, instead of being restricted to the index and middle fingers of the two hands, included the two ring fingers (which were not used in this experiment). The principal difference between this experiment and Experiment 2 was in the choice of ensembles that were run and in some of the stimuli.

Stimuli, responses, and design. Only two ensembles were used in this experiment, and these consisted of slight modifications of Ensembles B and D from Experiment 2. Recall that in Experiment 2 the physical stimuli, regardless of ensemble, consisted of individual letters appearing on a fingertip of the hand icon. The instructions identified the relevant stimuli; these, together with the response set, defined the ensemble for the subject.

In this experiment, exactly the same stimuli as were used in Experiment 2 (i.e., letter on fingertip) were used for the S-R consistent and the S-R inconsistent trials. In addition, for the

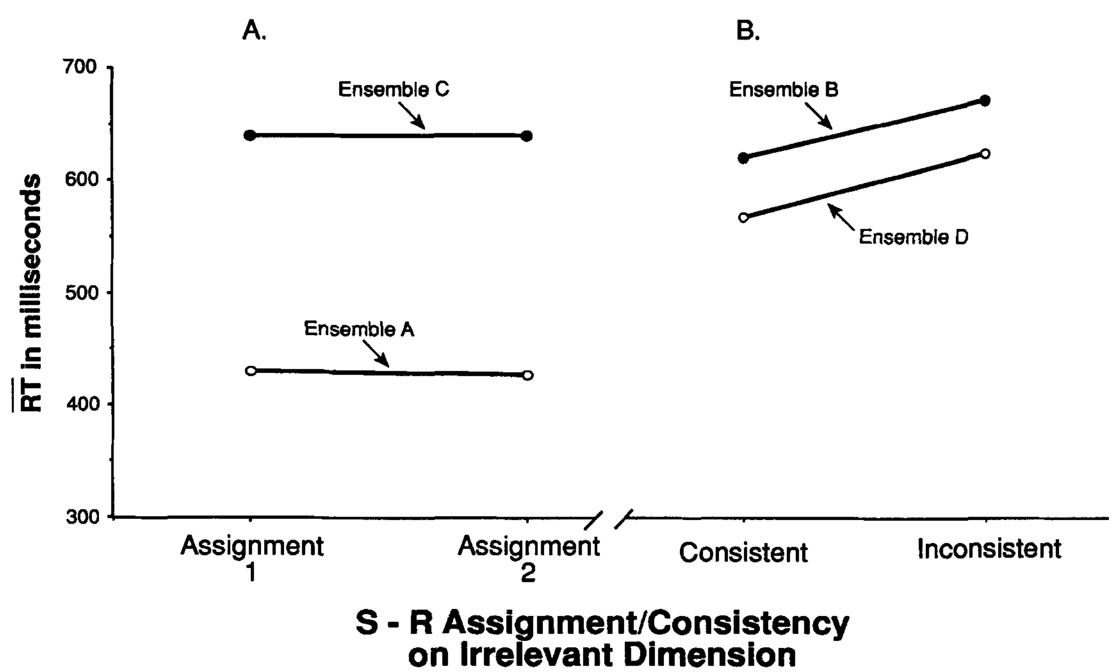

Figure 9. The data for the irrelevant dimensions of Experiment 2, showing (A) the irrelevant (nonoverlapping) dimensions in Ensembles A and C and (B) the irrelevant (overlapping) dimensions in Ensembles B and D. RT = mean reaction time; S-R = stimulus–response.

neutral trials in Ensemble B, we used an asterisk in lieu of a letter to designate the finger stimulus; for the neutral trials in Ensemble D, we presented a letter centrally, between the two hands, in lieu of a letter on a fingertip.

The stimuli were equiprobably presented in blocks of 36 trials. For each ensemble there were two mappings—the same as were used with Ensembles B and D in Experiments 1 and 2 (see Figure 3). The order of ensembles and mappings was counterbalanced over subjects. Subjects were run for three consecutive blocks on each ensemble and each mapping on every day of the experiment.

Subjects. Eight subjects were chosen from the same pool and according to the same criteria as those of the previous experiments.

Results

The data selected for analysis conformed to the same criteria and were defined in the same manner as those of the previous experiment. The results are presented in Table 2.

S-R consistent trials had significantly faster RTs than S-R inconsistent trials in both ensembles: 53 ms in Ensemble B, $F(1, 7) = 31.46, p < .0008$, and 55 ms in Ensemble D, $F(1, 7) = 89.77, p < .0001$. The difference between the neutral and the S-R inconsistent trials was significant for both ensembles—28 ms for Ensemble B, $F(1, 7) = 9.49, p < .0178$, and 10 ms for Ensemble D, $F(1, 7) = 6.89, p < .0342$. The difference between the neutral and the S-R consistent trials was significant for Ensemble D (45 ms), $F(1, 7) = 38.97, p < .004$, but failed to reach statistical significance, $F(1, 7) = 3.6, p = .0995$, even though it was in the right direction (25 ms) for Ensemble B (see Figure 10). Ensemble had a significant main effect, $F(1, 7) = 16.59, p < .004$, with Ensemble D being 84 ms faster than Ensemble B.

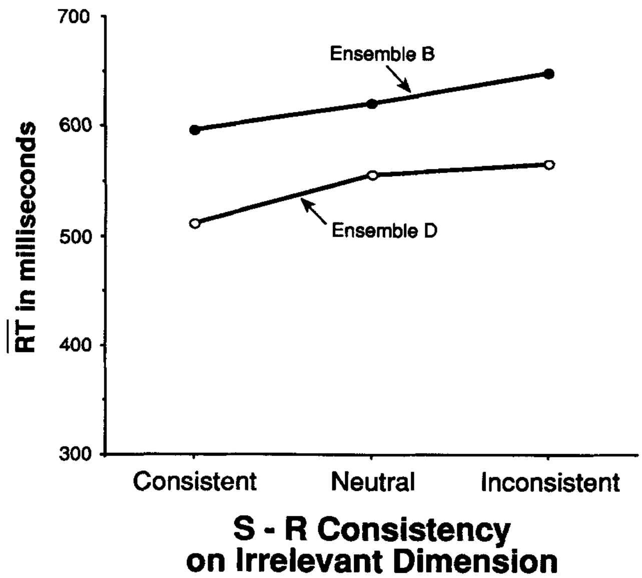

Figure 10. The data for the irrelevant dimensions of Experiment 3. RT = mean reaction time; S-R = stimulus–response.

Table 2
Mean Reaction Times (RTs), Standard Deviations (SDs), and Error Rates (%Es) for Experiment 3

Irrelevant S-R relation	Mapping 1 Day 2	Mapping 1 Day 3	Mapping 2 Day 2	Mapping 2 Day 3
	Ensemble B			
Consistent				
RT	606	579	616	583
SD	181	159	201	159
%E	0.98	0.00	0.49	0.24
Inconsistent				
RT	641	623	687	646
SD	186	184	205	184
%E	4.63	2.93	3.90	2.44
Neutral				
RT	630	600	628	626
SD	175	177	178	193
%E	0.49	0.49	1.22	0.00
	Ensemble D			
Consistent				
RT	540	499	509	495
SD	134	113	109	97
%E	1.46	0.98	0.73	1.46
Inconsistent				
RT	580	562	572	549
SD	119	97	109	92
%E	5.85	8.54	7.07	4.88
Neutral				
RT	596	543	549	534
SD	138	115	132	129
%E	2.44	1.22	1.46	1.22

Note. RTs and *SD*s are in milliseconds. S-R = stimulus–response.

Discussion

The S-R consistency effects in this experiment replicate the results of Experiment 2 in two respects. First, the overall consistency effect for Experiment 3 (54 ms) does not differ significantly from that in Experiment 2 (50 ms). Second, the S-R consistency effects for Ensembles B and D (53 ms and 55 ms, respectively) do not differ significantly from each other, as was the case in Experiment 2. The fact that the neutral condition in Ensemble B differed significantly from both the S-R consistent and the S-R inconsistent trials is consistent with our assumption that response verification is faster than response programming. These findings in Ensemble B also replicate the results that Wallace obtained with a two-choice, spatial, Type 3 ensemble (Wallace, 1971).

Experiment 4

According to the model, if the degree of dimensional overlap is the same for two ensembles and response identification is done by search, then the magnitude of the mapping effects for these two ensembles should also be the same. Yet in Experiments 1 and 2, the mapping effect for Ensemble C was about 80% greater than for Ensemble A. We conjectured that this difference may have been the result of a difference in the response identification procedure in the two ensembles: search in Ensemble C and rule based in Ensemble A. In particular, the stimulus and response sets of Ensemble A have a structure that those of Ensemble C do not have. Each finger in Ensemble A can be represented as a combination of two binary variables: hand (left or right) and finger (index or middle, or inside or outside; see Miller, 1982; Reeve & Proctor, 1984). As a consequence, no matter what incongruent mapping is used, it is impossible with this small number of alternatives to avoid a mapping that cannot be represented in terms of a simple rule (see also the discussion of two-choice tasks in Kornblum et al., 1990), which the model assumes is faster than search. Furthermore, the pictorial nature of the stimulus and the response sets in Ensemble A may have led subjects to use a highly organized visual representation of the task (see Figure 11), which may have been easier to search than a list. Either one or both factors, therefore, may have caused the mapping effect in A to be faster than in C: the use of a simple rule or the visual representation of the task with its consequent search of a visual image or both. Experiment 4 was an attempt to eliminate both factors by complicating the task, thus forcing the response identification process toward a search.

It seemed reasonable that increasing the number of stimulus and response alternatives would increase both the number and the complexity of potential rules and visual representations, thus increasing the likelihood of finding a mapping assignment that would require search for the identification of the correct response.

Method

All the procedural aspects of this experiment were identical to those of Experiment 1. However, only two of the four possible S-R ensembles were used: Ensembles A and C, and instead of four stimulus and response alternatives, this experiment used six.

The stimuli, the responses, and the S-R mappings. For Ensemble A, the left and right ring fingers were added to the set of stimuli and responses; for Ensemble C, the letters *F* and *T* were added to the set of stimulus letters and letter name responses. Each ensemble had one congruent and two incongruent mapping conditions that are shown in Table 3.

Design. The experiment lasted three days. Day 1 was used for training; Days 2 and 3 were experimental days. All subjects were given both ensembles each day, with two mapping conditions for each ensemble. One of the mappings was congruent and the other was incongruent. Half the subjects received one incongruent mapping (Group 1), and the other half received the other incongruent mapping (Group 2). Each subject received the same incongruent mappings on all three days. On Day 1 the order of conditions was the same for all subjects. On Days 2 and 3 the order of ensembles and mappings within ensembles was balanced over subjects. There were two consecutive blocks of 48 trials per condition per day per subject.

Subjects. Eight subjects were chosen from the same pool and according to the same criteria as in previous experiments.

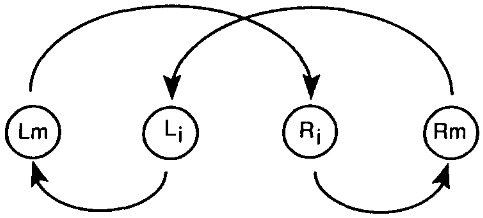

Figure 11. Graphic representation of the incongruent mapping for Ensemble A in Experiments 1 and 2. L = left; R = right; m = middle finger; i = index finger.

Table 3
Stimuli, Responses, and Stimulus–Response Mappings From Experiment 4

Stimulus	R(C)	R(I-1)	R(I-2)
	Ensemble A		
L_r	L_r	R_r	R_i
L_m	L_m	R_i	L_i
L_i	L_i	L_r	R_r
R_i	R_i	R_m	R_m
R_m	R_m	L_i	L_r
R_r	R_r	L_m	L_m
	Ensemble C		
B	"B"	"Y"	"Q"
F	"F"	"Q"	"J"
J	"J"	"B"	"Y"
Q	"Q"	"T"	"T"
T	"T"	"J"	"B"
Y	"Y"	"F"	"F"

Note. Congruent mapping; R(I-1) and R(I-2) = two different incongruent mappings; L = left; R = right; r = ring finger; i = index finger; m = middle finger. Quotation marks around a letter indicate that this is a letter name.

Results

The data of this experiment are shown in Table 4. Group did not have a significant effect, $F(1, 6) = 3.3$, $p = .119$. Mapping had a significant effect for both groups of subjects, $F(1, 3) = 173.58$, $p < .01$; $F(1, 3) = 138.02$, $p < .01$. After the data were collapsed over groups, the mapping effect (287 ms) over the collapsed data was highly significant, $F(1, 7) = 264.19$, $p < .00001$, and did not interact with ensemble (see Figure 12). Even though Ensemble A was 51 ms faster than Ensemble C, this effect was not significant,

Table 4
Mean Reaction Times (RTs), Standard Deviations (SDs), and Error Rates (%Es) for Experiment 4

Measure	Congruent		Incongruent	
	Day 2	Day 3	Day 2	Day 3
	Ensemble A			
RT	385	388	706	674
SD	49	41	88	116
%E	1.17	1.30	3.84	3.66
	Ensemble C			
RT	447	459	741	708
SD	24	39	57	70
%E	0.13	0.26	4.56	2.48

Note. RTs and *SD*s are in milliseconds.

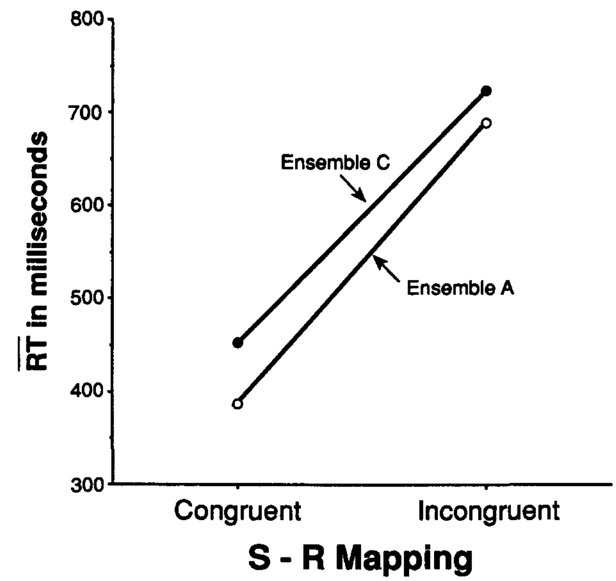

Figure 12. The data for the two six-choice tasks in Experiment 4. RT = mean reaction time; S-R = stimulus–response.

$F(1, 7) = 2.92, p = .1311$. There were no other significant results.

Discussion

The principal motivation for this experiment was the finding in Experiments 1 and 2 of a large and highly significant difference between the mapping effects of Ensembles A and C. According to the model, if the degree of dimensional overlap was the same for the two ensembles and response identification with incongruent mapping had been done by search, then the mapping effects for the two ensembles should have been the same. We attributed the difference between the mapping effects in A and C to differences in the response identification procedures that subjects used in the two ensembles: search in Ensemble C and rule based in Ensemble A. If true, this would have made the effects of mapping in the two ensembles noncomparable. By increasing the number of alternatives from four to six, we sought to increase the complexity of the mapping and thus to induce the search procedure in both ensembles. Although we do not have an independent measure of whether our manipulation succeeded in its goal, the results are consistent with such an interpretation.[10]

Experiment 5

The model generates a number of hypotheses concerning the effects of relevant and irrelevant stimulus dimensions when they overlap with the response; many of these are supported by the results of the previous four experiments. The model also makes predictions about performance when stimulus and response dimensions do not overlap. In particular, according to the model, in the absence of any overlap between the relevant stimulus dimension and the response, the RT for any S-R mapping will be no different from that of any other S-R mapping (the nonoverlap hypothesis). Because the number of different mappings that are possible for an S-R ensemble increases with the number of alternatives to $n!$, it quickly becomes impractical to do an exhaustive test of this hypothesis for ensembles with $n > 4$. Even when $n = 4$, a total of 24 different mappings are possible, and testing them all seems both onerous and unnecessary. However, in Experiment 1, 2 of these 24 mappings were included in Ensembles B and D. The results showed a small (15 ms) but significant difference between them. Experiment 5 has a twofold purpose: First we wanted to test the model's nonoverlap hypothesis on a larger subset of mappings for nonoverlapping ensembles than was used in Experiment 1, and second, we wanted to explore possible reasons for having obtained this 15-ms difference in Experiment 1 in the first place. In particular, an unintentional hint was included in the instructions for Experiments 1 and 2, which may have been responsible for this result. For one of the mappings, subjects were instructed that the correct response was "a clockwise assignment of the letter string B, J, Q, Y to the fingers starting with the right middle finger." This particular phrasing may have suggested to subjects the idea of matching the ordinal positions of fingers and letters for one of the mappings, making this mapping faster than the other.

Method

All the stimuli, responses, and procedures were identical to those of Experiment 1, except that only two out of the four ensembles were used: Ensembles B and D.

The stimuli and responses were identical to those in Experiment 1. Each ensemble was run with four S-R mappings, shown in Table 5, making a total of eight conditions. The experiment was run for 3 days with Day 1 being used for practice and Days 2 and 3 being experimental days. Additionally, the instructions contained no hint concerning any associations or similarities between the stimulus and response sets. All subjects were run on the eight conditions on all 3 days, with two consecutive blocks of 48 trials per condition. Practice trials preceded every block. The order of ensembles and of mappings within ensembles was counterbalanced over subjects.

Results

The data selected for analysis conformed to the same criteria and were defined in the same manner as those of the previous experiments. The results are presented in Table 6.

[10] The same stimulus and response sets as were used in this and the previous experiments were used in another six-choice task with the four ensembles A, B, C, and D. The results, averaged over the 8 subjects that were run and grouped by overlapping (A and C) and nonoverlapping (B and D) ensembles were: RT congruent (A and C) = 450 ms, RT incongruent (A and C) = 740 ms, and RT neutral (B and D) = 661 ms. The mapping effect of 290 ms in this experiment compares favorably with the 288-ms mapping effect in Experiment 4. The facilitation and interference effects are both significant, facilitation $F(1, 7) = 74.03, p < .0001$, and interference $F(1, 7) = 10.75, p < .0135$.

Table 5
Stimulus–Response Mappings for Experiment 5

Stimulus	R(1)	R(2)	R(3)	R(4)
		Ensemble B		
L_m	"Y"	"Q"	"J"	"B"
L_i	"Q"	"B"	"Y"	"J"
R_i	"J"	"Y"	"B"	"Q"
R_m	"B"	"J"	"Q"	"Y"
		Ensemble D		
B	R_m	R_i	L_i	L_m
J	R_i	L_m	R_m	L_i
Q	L_i	R_m	L_m	R_i
Y	L_m	L_i	R_i	R_m

Note. R(1), R(2), R(3), and R(4) = four different stimulus–response mappings; L = left; R = right; m = middle finger; i = index finger. Quotation marks around a letter indicate that this is a letter name.

Ensemble had no significant effect, nor did it interact with any other factor; the data from both ensembles were therefore combined. Mapping had a significant effect, $F(3, 21) = 4.54$, $p < .05$; block had a significant effect as well, $F(1, 7) = 8.65$, $p < .05$. The mean RTs for the four mappings were 558, 571, 565, and 538 ms for Mappings 1 through 4 (see Table 5), respectively.

Discussion

If instructional hints accounted for the effects of mapping found in the nonoverlapping ensembles of Experiment 1, such effects should have been eliminated in the present experiment. Mapping 1, which is the same as the mapping that was found to be significantly faster in Experiment 1, had the second fastest RT; however, it was no longer significantly different from two other mappings in the present experiment. Yet mapping did have an effect. In particular, Mapping 4 (which is a mirror image of the mapping that was fastest in Experiment 1) stands out as the fastest mapping in both ensembles. This appears to be a robust finding, which we believe is due to the ordinal structure that is shared by the set of fingers and the set of letters used as stimulus and response sets in this experiment. We will return to this point in the General Discussion.

General Discussion

Using a single, common set of principles, the dimensional overlap model makes a number of predictions regarding the processing of relevant and irrelevant dimensions when they do and do not overlap with the response. Many of these predictions are confirmed by the experimental results of this study and are also consistent with the literature.

Relevant Dimensions

The model's hypotheses concerning the effects of dimensional overlap in a relevant stimulus dimension are (a) the mapping hypothesis: If the stimulus and response sets of an S-R ensemble overlap on the relevant dimension, the mean RT for the congruent mapping will be faster than the mean RT for the incongruent mapping; (b) the facilitation/interference hypothesis: The mean RTs for the congruent and incongruent mappings will be faster and slower, respectively, than an appropriate neutral control; and (c) the nonoverlap hypothesis: If an S-R ensemble has no overlapping dimensions, then the mean RT for all S-R mappings in that ensemble will not differ significantly from each other. The model, in addition, makes the assumption that when the relevant stimulus dimensions in two S-R ensembles overlap to the same degree in both ensembles, then the mapping effects in the two ensembles will not differ significantly from each other. Call this the *compatibility metric assumption* (see Kornblum et al., 1990).

The mapping hypothesis is confirmed by the results of Ensembles A and C in Experiments 1, 2, and 4: The mapping effect in Experiments 1 and 2 is 203 ms, and in Experiment 4, it is 275 ms.

A test of the facilitation/interference hypothesis requires a neutral condition with respect to which the congruent and incongruent mapping may be compared. According to the model (see the section entitled A Prototypical Experimental Design and Rules of Inference), the overall mean RT of the

Table 6
Mean Reaction Times (RTs), Standard Deviations (SDs), and Error Rates (%Es) for Experiment 5

	Mapping 1		Mapping 2		Mapping 3		Mapping 4	
Measure	Day 2	Day 3	Day 2	Day 3	Day 2	Day 3	Day 2	Day 3
				Ensemble B				
RT	550	522	568	554	556	555	517	528
SD	43	49	70	65	66	57	52	45
%E	2.68	1.79	2.24	2.08	2.23	2.98	1.49	1.19
				Ensemble D				
RT	578	556	569	568	560	553	533	545
SD	85	75	66	65	64	47	62	70
%E	2.08	2.83	1.49	1.49	1.93	2.98	1.49	2.08

Note. RTs and *SD*s are in milliseconds.

nonoverlapping Ensembles B and D in Experiment 1 is such a neutral reference point. For Experiment 1, the overall congruent mean RT for Ensembles A and C is significantly faster than this neutral condition, and the overall incongruent RT is slower, thus confirming the facilitation versus interference hypothesis.

Unlike the results of Experiment 1, however, the analogous comparisons for Experiment 2 would at first blush appear to disconfirm this hypothesis in that the mean RT of Ensembles B and D, instead of falling squarely between the means of the congruent and the incongruent mapping conditions for A and C, is barely different from the mean RT of the incongruent mapping. Recall that Ensembles B and D in Experiment 1 are Type 1 ensembles and, according to the model, are appropriate neutral conditions for Ensembles A and C. In Experiment 2, these same two ensembles (B and D) are Type 3 ensembles. Even though the model gives us no reason to expect the overall mean RTs of Type 1 and Type 3 ensembles to differ from each other (the model is silent on this point), the results show that when an irrelevant stimulus dimension that overlaps with the response is added to a Type 1 ensemble, thus transforming it into a Type 3, the overall RT for that ensemble increases. This suggests that the irrelevant overlapping dimensions in a Type 3 ensemble may make attentional demands that the nonoverlapping irrelevant dimensions in Type 1 ensembles do not make (note also that the mean RT for Ensembles A and C do not differ significantly between Experiments 1 and 2).

The nonoverlapping hypothesis states that in the absence of any dimensional overlap, the mean RT for all the S-R mappings in a nonoverlapping ensemble will not differ significantly from each other. On a priori grounds (see Footnotes 6 and 8), Ensembles B and D in Experiment 1 are nonoverlapping Type 1 ensembles, yet show a 15-ms statistically significant difference between mappings. (Recall that even though this difference vanishes in Ensembles B and D of Experiment 2, those are Type 3 ensembles.) Experiment 5 was run to examine this phenomenon more closely. Four different S-R mappings were used for Ensembles B and D, including the one mapping that had been found to be faster in Experiment 1 (Mapping 1). Although Mapping 1 did not differ significantly from two of the other mappings, Mapping 4 was distinctly faster than the other three mappings in both ensembles. We suggest that this is an instance of structural similarity, hence, dimensional overlap, between ensembles having arisen as a result of the task itself.

Structural Similarity

Structural similarity is an important aspect of the similarity between sets. Like perceptual similarity, which is flexible and not fixed (see Medin, Goldstone, & Gentner, 1993), structural similarity often arises as a result of the task at hand. Note that one of the properties that the four fingers in the stimulus and the response set have is that they can be ordered from left to right or right to left, that is, they have an ordinal position in space. Likewise, the letters each have an ordinal position in the alphabet, going either from early to late or vice versa. The ordinality of the elements in the set of letters and in the set of fingers constitutes a structural property of each set. The fact that these structures are geometrically congruent, or in Gentner's terms can be "aligned" (Gentner, 1983), gives them structural similarity. It would seem reasonable that any mapping that paired individual stimuli with their structurally corresponding responses, and thus mapped one structure directly onto another, would be faster than other mappings that violated this structure. The data are consistent with this hypothesis in that Mapping 4 is precisely such a mapping. The fact that Mapping 1, which is a mirror image of Mapping 4, fails to emerge from the pack (note that it does have the second fastest RT) may indicate a preference in the direction of the order. Note, however, that when it is the only order-preserving mapping around, as in Experiment 1, it does have a significantly faster RT.

This view of similarity has implications for other accounts of stimulus–response compatibility. For example, Proctor (e.g., Reeve & Proctor, 1990; Weeks & Proctor, 1990) has argued that what he calls "salient features" are at the basis of S-R compatibility effects. We view salient features as one respect with which (see Medin et al., 1993) two sets may be structurally similar. For example, consider a typical task used by Proctor in which two letters, say *O* and *Z*, each of which may occur in uppercase and lowercase, are mapped onto the middle and index fingers of the left or right hand. Here, both the stimulus set and the response set may be described in terms of two binary features: letters and case, in the case of the stimulus set, and hands and fingers, in the case of the response set. This descriptive structure—which is shared by both sets—would, by itself, make the two sets structurally similar. If, in addition, one of the binary features in each set is perceptually salient and functions as a perceptual reference point within that set, then both sets become hierarchically structured with consequent constraints on the structural equivalence of their respective elements. It is now possible for some mapping to pair stimulus elements with their structurally equivalent response elements and for other mappings to pair them with structurally disparate response elements and thus obtain incongruent mappings. When the stimulus and response sets have different structures, they may each still have salient features, but structural equivalence becomes meaningless. For example, if instead of the *O, Z* set of letters we now used four different letters, say *B, J, Q,* and *Y,* and presented the *B* in color and the rest of the letters in black and white, the colored *B* would clearly be a salient feature of the stimulus set. However, if we kept the same response set as we had before, the same structural aspects of that response set that were so useful with the *O, Z* letter set would become nonfunctional with the new letter set. One could very easily construct a new response set, say the index finger of the left hand plus the index, middle, and ring fingers of the right hand, whose structure matched that of the stimulus set. The resulting structural similarity, or dimensional overlap, between these new stimulus and response sets would, once again, make such an S-R ensemble susceptible to the influence of different mappings, as predicted by the model.

Irrelevant Dimensions

The model makes three predictions concerning the effects of an irrelevant stimulus when it does and does not overlap with the response. These are (a) the consistency hypotheses: If an irrelevant stimulus dimension of an S-R ensemble overlaps with the response set, the mean RT of the S-R consistent trials will be faster than the mean RT of the S-R inconsistent trials; (b) the neutral irrelevant S-R hypothesis: Assuming that verification is faster than response programming, the RT for S-R consistent trials will be either equal to or faster than that of the neutral condition (the nonoverlap hypothesis for relevant dimensions is, of course, equally applicable to irrevelant dimensions); and (c) given an overlapping dimension, the S-R consistency effect is smaller than the mapping effect.

The first two hypotheses were confirmed by the results of Experiments 2 and 3. The consistency effect for Ensembles B and D is 50 ms for Experiment 2 and 54 ms for Experiment 3. In contrast, the nonoverlapping irrelevant dimensions in Ensembles A and C had no differential effects on RT. And finally, the results of Experiment 3 show that the means for the S-R consistent and S-R inconsistent trials are each significantly different from a neutral condition for Ensemble B; in Ensemble D, both differences are in the right direction, but the difference of the S-R inconsistent condition falls short of significance. It is interesting to note that the model postulates that the effects of S-R (Type 3) and S-S (Type 4) consistency are mediated by different stages, which implies that their effects should be additive. We have recently been able to confirm this additivity (Kornblum, 1994).

According to the model, the irrelevant overlapping dimensions in Type 3 ensembles play no role in response selection; however, they do trigger the automatic response activation process. Several aspects of the data are consistent with this account. First, note that the consistency effect is considerably smaller than the mapping effect for these same dimensions when they are relevant (Hypothesis 4). Second, in contrast to the mapping effects, which differed in magnitude for Ensembles A and C in Experiments 1 and 2, the consistency effects when these same dimensions are irrelevant are not significantly different from each other. If, as we hypothesized, the difference in the mapping effects between A and C is due to differences in the response identification process when the dimensions were relevant and the response identification process is eliminated from the consistency effect, then one would expect the consistency effects for these dimensions not to differ from each other. Third, whereas the size of the mapping effect increases with the number of alternatives (e.g., Sternberg, 1969), the size of the consistency effect in our four-choice task appears to be roughly the same as that reported for two-choice tasks (see Kornblum et al., 1990, Table 3). This, of course, needs to be verified. However, to the extent that response identification proceeds by search, it would be reasonable to expect the duration of the response identification process to increase with the number of alternatives and thus cause the mapping effect to increase with the number of alternatives. Furthermore, if response identification does not contribute to the consistency effect, it would be equally reasonable to find the magnitude of the consistency effect to be independent of the number of alternatives. Finally, a number of studies have produced psychophysiological evidence that supports the hypothesis that on S-R inconsistent trials, it is the S-R congruent response that is first activated; this response is then inhibited, the correct response subsequently activated, and that response is finally executed (Coles, Gehring, Gratton, & Donchin, 1992; DeJong, Liang, & Lauber, 1994; Leuthold, 1993; Osman, Bashore, Coles, Donchin, & Meyer, 1992; Smulders, 1993).

Conclusions

The results of this study permit us to draw the following tentative conclusions. When a stimulus dimension overlaps with the response set of an S-R ensemble, mean RTs are faster for trials on which individual stimuli match individual responses than for trials on which they mismatch. This is true whether the overlapping dimension is relevant or not. This compatibility effect is greater when the overlapping dimension is relevant than when it is irrelevant. Whether relevant or irrelevant, the faster RT is the result of facilitative processes, and the slower RT is the result of interfering processes.

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Appendix

Glossary of Terms

Because we use terms in the model that are in common usage and give them more circumscribed meanings than they ordinarily have, our terminology may be a source of confusion when old connotations intrude on these new constrained meanings. In order to reduce the possible ambiguities that this may lead to, we have included here a brief glossary of some of the critical terms in our model. This glossary may also serve as a summary of some of the model's pivotal concepts.

Compatibility: This is not a technical term in the dimensional overlap model. However, it is a term that is widely employed in the literature to describe sets, mappings, dimensions, tasks, and so forth. We have listed below some of the more commonly used instances of this term with a translation of each instance in terms of the concepts of the model.

(a) *Compatibility of sets:* "Highly compatible sets" are those that are identified in the model as having a high degree of dimensional overlap; "incompatible sets" are more properly called "noncompatible" because here the term usually refers to sets with low or no dimensional overlap.

(b) *Compatibility of mappings:* "Highly compatible mappings" are those identified in the model as congruent; "incompatible mappings" encompass what is defined in the model as "incongruent mappings" in addition to S-R mappings in nonoverlapping S-R ensembles. "Compatible" and "incompatible mapping" are sometimes also used in the literature to refer to what in the model we call "S-R consistent" and "S-R inconsistent."

(c) *Compatibility of stimulus dimensions:* "Highly compatible stimulus dimension" are those identified in our model as either "overlapping" or as "S-S consistent"; "incompatible stimulus dimensions" include those that are identified in the model as "nonoverlapping" or as "S-S inconsistent."

Consistency/inconsistency: When an irrelevant stimulus dimension overlaps with either a response or another stimulus dimension, and the values on these dimensions match on a particular trial, they are called consistent. When they conflict, they are called inconsistent. For example, a stimulus consisting of the word *red* printed in red is S-S consistent; when the word *red* is printed in blue it is S-S inconsistent. Similarly, a color patch mapped onto a left or right keypress response, when presented on the same side as the response, is S-R consistent, and when presented on the opposite side of the response is S-R inconsistent.

Consistency effects: Consistency effects are the equivalent of mapping effects when one or more of the overlapping dimensions is irrelevant.

(a) *S-R consistency effect:* The difference in reaction time between S-R consistent and S-R inconsistent trials or conditions.

(b) *S-S consistency effect:* The difference in reaction time between S-S consistent and S-S inconsistent trials or conditions.

Dimensional overlap: The degree to which a stimulus set and a response set, or two or more aspects of a stimulus set or a response set, are perceptually, structurally, or conceptually similar.

Dimensional relevance

(a) *Relevant dimension:* A dimension that the subject is instructed to attend to and that has a correlation of 1 with the correct response.

(b) *Irrelevant dimension:* A dimension that the subject is instructed to ignore and that has a correlation of zero with the correct response.

Mapping effect: The difference in reaction time between the congruent and the incongruent mapping conditions of an S-R ensemble, where the incongruent mapping precludes the use of a rule and requires a search for the identification of the correct response.

Stimulus or response element: An individual stimulus or response.

Stimulus or response set: A collection of individual stimuli or responses.

Stimulus–response (S-R) ensemble: The stimulus set together with the response set used in a particular task.

Stimulus–response (S-R) mapping: The instructional assignment of the stimulus elements onto the response elements in an S-R ensemble. When the relevant dimensions of an S-R ensemble overlap, the S-R mapping is either congruent or incongruent.

(a) *Congruent S-R mapping:* The mapping of stimulus elements onto the response elements that they automatically activate.

(b) *Incongruent S-R mapping:* Any of the possible S-R mappings in an S-R ensemble, except for the congruent mapping.

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