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2 Sequential effects of dimensional overlap: findings and issues

Sylvan Kornblum and Gregory Stevens

Abstract. We begin this chapter by outlining some of the basic principles of the dimensional overlap (DO) model (Kornblum, Hasbroucq, and Osman 1990; Kornblum, Stevens, Whipple, and Requin 1999), spelling out how these principles generate a taxonomy of tasks, and showing how, based on these principles, the structure of four of these tasks can be represented by a common processing architecture, and performance with them accounted for. We then consider the effects of stimulus and response repetitions in choice reaction time (RT) tasks and the influence that DO has on this repetition effect. We report data from four experiments that demonstrate this influence with a prime-probe, trial pair procedure in which the relevant or irrelevant stimuli in either or both trials of the pair have DO and, in the case of relevant DO, repeat either physically or conceptually. The DO model is able to account for the results by postulating that the information requirements on repeated trials are less than on non-repeated trials. We call this the Information Reduction Hypothesis. When the relevant stimuli overlap, the repetition effects are accounted for by a reduction in either the stimulus and/or the response thresholds. When the irrelevant stimuli overlap, the repetition effects are accounted for by a reduction in the time needed to distinguish between relevant and irrelevant stimuli. Thus, depending on whether the relevant or irrelevant stimulus dimension has DO, one or the other of two parameters in the DO model is modified, contingent on the occurrence of a repetition. Simulations, based on this implementation of the hypothesis in the DO model, fit the experimental results well.

2.1 Introduction

Thirty years ago, at the fourth International Symposium on Attention and Performance, one of us presented a tutorial on sequential effects in choice reaction time (RT) (Kornblum 1973). Ten years ago we published the initial version of the dimensional overlap (DO) model in which we addressed, what we viewed as, some of the basic issues in stimulus–stimulus (S–S) and stimulus–response (S–R) compatibility (Kornblum, Hasbroucq, and Osman 1990). In this chapter we would like to bring these two problem areas together theoretically and empirically. As will be evident, even though this effort has resulted in modest successes it has also uncovered some interesting problems that remain to be solved.

This is roughly how the chapter is organized:

- We start with a brief description of the computational version of the DO model (Kornblum, Stevens, Whipple, and Requin 1999);
- this is followed by a set of experiments in which we look at basic sequential effects in tasks with and without DO between relevant stimuli and responses;
- we then present the DO model's account of those results;

- this is followed by a second set of experiments in which we take a further look at sequential effects in tasks with and without DO between the relevant and irrelevant stimuli, and between the irrelevant stimuli and the responses;
- we then present the DO model's account for those results;
- we end with a summary and conclusions.

2.2 The dimensional overlap model

2.2.1 Representational component

From the very outset, we have always made a sharp distinction between the representational and the processing parts of the model (see Kornblum *et al.* 1990). The representational component of a theory spells out how the phenomena to be explained are to be described and abstracted; the processing component specifies a set of possible mechanisms that might account for these observations.[1] At the heart of the representational component of the DO model is the notion of dimensional overlap (DO). This is defined as the degree to which stimulus and/or response sets are perceptually, conceptually, or structurally similar. Dimensional overlap is, therefore, an attribute of the mental representations of sets, and patterns of DO define certain task properties. We have used these dimensional relationships as the basis of a taxonomy which, up to now, has identified eight unique types of compatibility tasks (see Kornblum *et al.* 1999, for the most recent version of this taxonomy). In a poster shown at this meeting, Stevens (Stevens and Kornblum 2000) has extended this representational aspect of the model to include response effects and ends up with a taxonomy of over a dozen tasks. He also presents the results of simulations that demonstrate the critical role that DO and the patterns of dimensional relationships play in the functional interpretation of response effects. In this chapter, we shall focus on just four of these tasks.

A task in which the set of relevant stimuli, or features, does not have DO with either the set of responses or with the set of irrelevant stimuli, or features, we call a Type 1 task. This is the basic choice RT task in which the relevant stimuli could, for example, be color patches presented in different shapes that are irrelevant, and the responses are key presses. In the context of S–R compatibility, this is a neutral task for which, in principle, any stimulus–response pairing is as good as any other pairing (see Fig. 2.1).

When the DO is between the set of *relevant* stimuli and the set of responses, we call it a Type 2 task (e.g. Fitts and Seeger 1953). In the literature this is often referred to as a straightforward 'stimulus–response compatibility' (SRC) task. Depending on the S–R mapping rule, the individual stimuli in such tasks either do or do not match the responses; we call this S–R relation 'stimulus–response (S–R) congruence' (see Fig. 2.1).

When the overlap is between the set of *irrelevant* stimuli and the set of responses, we call it a Type 3 task (see Kornblum and Lee 1995). When the overlapping dimension is spatial the literature refers to it as a 'Simon task' (see Simon 1990). We often refer to Type 3 tasks as 'Simon-like' when the irrelevant dimension is non-spatial. Because of the pattern of overlap, individual irrelevant stimuli are either consistent or inconsistent with the responses; we call this property 'stimulus–response (S–R) consistency' (see Fig. 2.1).

When the overlap is between the set of relevant and irrelevant stimuli, it is a Type 4 task (see Keele 1967; Kornblum 1994). When the overlapping dimension is color, the literature often refers to it as a 'Stroop' task. This, we believe is an error that leads to confusion. 'Stroop-like' task, which is also

Type 1 – Neutral Task

Type 2 – SRC Task

Type 3 – Simon Task

Type 4 – Stroop-like Task

Type 8 – Stroop Task
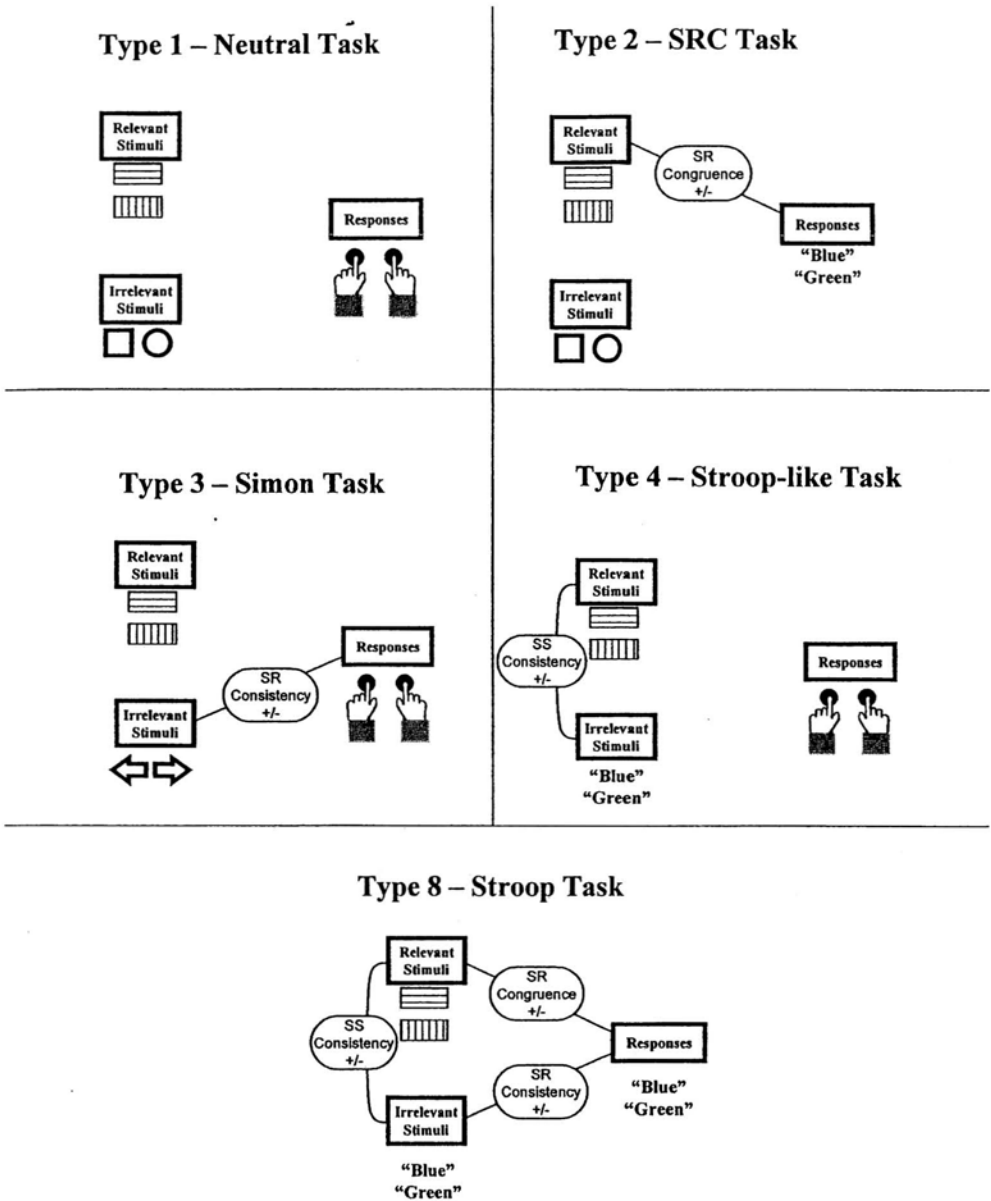
Fig. 2.1 Dimensional relationships between relevant stimuli, irrelevant stimuli and responses that characterize five of the eight tasks in the current DO taxonomy. Whenever any two aspects of a task have dimensional overlap they are joined by a line indicating the nature (S–S or S–R) and value (+/–) of the consistency or congruence relationship between them. Horizontal and vertical striations in the stimulus rectangles depict blue and green color patches respectively.

Table 2.1 Five of the eight task types in the DO taxonomy with indications in columns 2, 3, and 4 of the locus of overlap[2]

Task type	Overlapping relevant stimulus and response	Overlapping irrelevant stimulus and response	Overlapping irrelevant and relevant stimulus
#1 Neutral	No	No	No
#2 SRC	Yes	No	No
#3 Simon	No	Yes	No
#4 Stroop-like	No	No	Yes
#8 Stroop	Yes	Yes	Yes

often used, seems more accurate. The important criterion is that the irrelevant stimulus dimension overlap with the relevant stimulus dimension, and that this be the only overlap in the task. Because of the pattern of overlap, irrelevant stimuli on particular trials are either consistent or inconsistent with the *relevant* stimuli; we call this property 'stimulus–stimulus (S–S) consistency' (see Fig. 2.1).

When DO is between the sets of irrelevant and relevant stimuli as well as the set of responses, *and the dimension is the same*, we call it a Type 8 task. In the literature, when that dimension is color, it is usually referred to as a 'Stroop' task—correctly this time (see McLeod 1991; Stroop 1935). Because of the pattern of overlap, the mapping instructions can be either congruent or incongruent; moreover, when the mapping is congruent, the individual irrelevant stimuli are consistent or inconsistent with both the relevant stimuli and the responses, which leads to a serious confounding. We have shown that these factors can be unconfounded by using incongruent S–R mapping with Stroop tasks (Zhang and Kornblum 1998; but see also Stevens and Kornblum 2001).

Because we will be using the DO terminology throughout this article we have summarized it in Table 2.1. If these taxonomic classes have any functional significance at all, then one would expect all tasks in the same taxonomic category to show the same pattern of effects regardless of the particular stimuli or responses used—and this, for the most part, has been verified by the results of many studies in the literature (for a review, see Kornblum 1992). Based purely on this representational scheme, the DO model asserts that RT is generally faster for consistent than for inconsistent conditions, and the RT for congruent mapping is faster than for incongruent mapping. Differences in the magnitude of these effects occur between tasks, of course; most of these may attributed to differences in the degree of DO between sets.

2.2.2 The processing component

The processing part of the model is where we have been proposing, what seemed to us, plausible sets of mechanisms that might underlie the compatibility effects observed in the family of tasks encompassed by the representational part of the model. Ten years ago, the model started out as a boxology. However, this was recently replaced by a connectionist architecture (Kornblum *et al.* 1999) where processing takes place in a system of interconnected modules, arranged in two layers: a stimulus layer and a response layer (see Fig. 2.2). Each stimulus and response module represents a dimension, or class of features. Within each module are individual units that represent the individual features of the stimulus or response. The activation of a unit within a module, therefore, represents activation of a feature along that dimension.
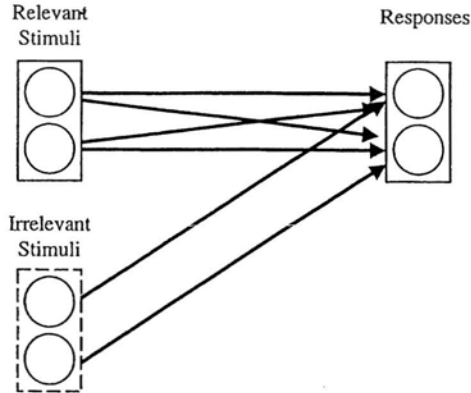
Fig. 2.2 The three generic processing modules of a task (relevant stimuli, irrelevant stimuli, and responses) and the possible positive connections between them, according to the DO model. Negative connections are not shown (but see text).

2.2.2.1 Architecture and connectivity

The connections between modules are of two types: automatic and controlled. Automatic lines, which have also been called Long Term Memory (LTM) connections (Barber and O'Leary 1997), connect modules that represent overlapping dimensions. These could both be stimulus dimensions, or one could be a response and the other a stimulus dimension—relevant or irrelevant. Controlled lines, which have also been called Short Term Memory (STM) connections (Barber and O'Leary 1997), are specified by the task instructions instead of by the DO. They connect each unit in the relevant stimulus module with the correct unit in the response module. The strength of the signal sent over the automatic lines is a function of the level of stimulus activation, weighted by the degree of DO between the pair of connected modules. Because the activation level of the stimulus unit changes over time, the signal sent over the automatic lines changes over time as well, and is thus continuous. In contrast, the signal that is sent over the controlled lines is all or none, and may be said to represent a binary decision (for details see Kornblum *et al.* 1999). These simple architectural principles can be used to represent each of the tasks that we have described thus far (these are all illustrated in the 'architecture' column of Fig. 2.3).

The first task is a Type 1, neutral, task in which the relevant stimuli are color patches mapped onto left and right keypress responses. Because there is no DO in this task, there are no automatic connections. Controlled lines connect the relevant stimulus units to their assigned response units (see Fig. 2.3).

Next is a Type 2 task, in which color stimuli are mapped onto color-name responses. As is true in Type 1 tasks, the controlled lines connect the relevant stimulus and response units in accordance with the task instructions. However, because of the dimensional overlap between the set of relevant stimuli and the set of responses, automatic lines also connect the relevant stimulus units to the response units. Whenever two modules represent overlapping dimensions, positive automatic lines connect corresponding units, and negative automatic lines connect non-corresponding units. Only the positive connections are shown in the figure. When the mapping instructions are congruent, both the automatic and the controlled lines connect each stimulus unit to its matching response unit (see

Fig. 2.3—Type 2, congruent mapping). In effect, then, each correct response unit receives two positive inputs: one from the controlled line, the other from the automatic line. When the mapping instructions are incongruent (see Fig. 2.3—Type 2, incongruent mapping), each correct response unit receives one positive input from the controlled line, and one negative input from the automatic line. As a result, the total net input to the correct response unit is less than in the congruent case.

The same general rules apply to Type 3, Simon-like, tasks. Here, controlled lines connect the relevant stimulus units to their assigned response units; and, because the DO is between the irrelevant stimuli and the responses, positive automatic lines connect the irrelevant stimulus units to their corresponding response units, with negative connections between non-corresponding units, not shown here (see Fig. 2.3). Similarly for Type 4, Stroop-like, tasks: controlled lines connect the relevant stimulus and response units; with positive automatic connections between the irrelevant stimulus and their corresponding relevant stimulus units, and negative connections between non-corresponding irrelevant and relevant stimulus units (see Fig. 2.3).

To get a clearer picture of how this architecture and pattern of connectivity works in processing information we need to spend a brief moment on the details of activation in individual units.

2.2.2.2 Activation and information flow

According to the model, inputs to both the relevant and irrelevant stimulus units start at the same value—say 1. The input to the relevant unit remains at one. The input to the irrelevant unit starts decaying at a fixed rate shortly after onset. The time (identified by the parameter τ in Kornblum et al. 1999) between when these two inputs begin and when their values start to diverge is the time the system takes to distinguish between the relevant and the irrelevant input.[3] Whether one believes that attention remains focused on the relevant input and is withdrawn from the irrelevant input after this distinction is made, or that the irrelevant input just gradually decays away, is not a question that we deal with in this paper. Suffice it to say that this decrease in the irrelevant stimulus input is a critical property of the model that enables it to account for the time-course and distributional properties of reaction times in S–S and S–R consistency tasks (see Kornblum et al. 1999). Given these two sources of input, the activation levels in the relevant and irrelevant stimulus units change over time according to a gradual, time-averaging activation function. Given a constant input, as in the case of the relevant stimulus unit, activation gradually increases and asymptotically approaches the input level. With a decreasing input, as in the case of the irrelevant stimulus unit, activation is an inverted U-shaped function of time (see Kornblum et al. 1999 for the details).

Now let us examine the actual flow of information over time for each of the tasks that we have listed (these are illustrated in the 'activation' column in Fig. 2.3). The three fundamental steps to keep in mind are:

- the stimulus is presented;
- the input is turned on; and
- activation accumulates.

Consider a Type 1, neutral, task first. The information flow in this task can be thought of as a baseline, or generic activation flow, as specified by the model (see Fig. 2.3). It represents the simplest instance of the three basic steps: the stimulus is presented causing the input to the relevant stimulus unit to turn on which, in turn, causes activation in the relevant stimulus unit to start accumulating
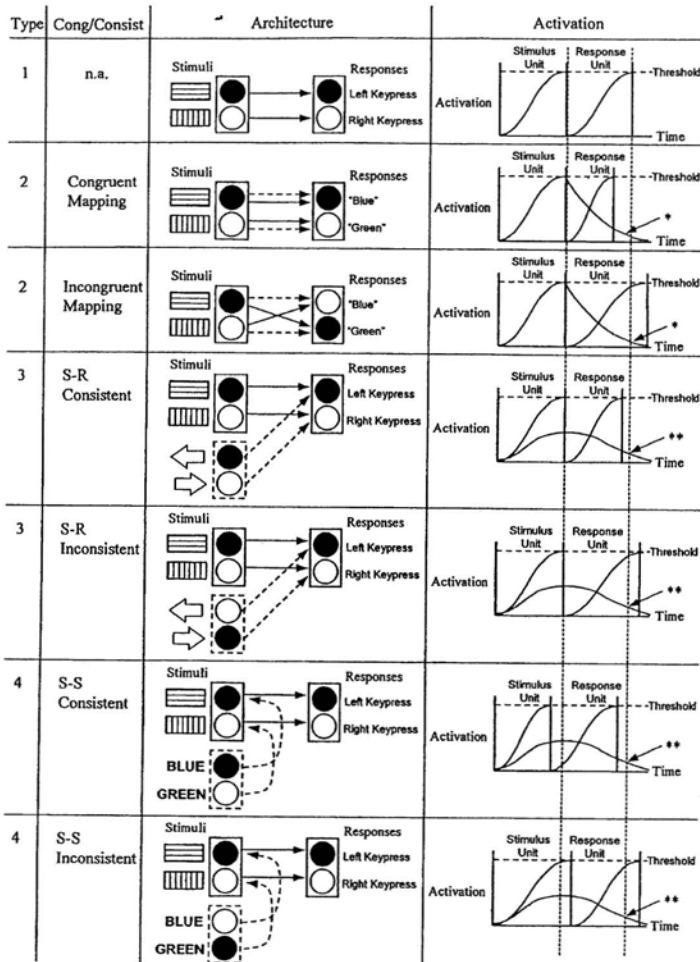
Type	Cong/Consist	Architecture	Activation
1	n.a.	Stimuli — Responses: Left Keypress, Right Keypress	Stimulus Unit / Response Unit — Threshold; Time
2	Congruent Mapping	Stimuli — Responses: "Blue", "Green"	Stimulus Unit / Response Unit — Threshold; Time (*)
2	Incongruent Mapping	Stimuli — Responses: "Blue", "Green"	Stimulus Unit / Response Unit — Threshold; Time (*)
3	S-R Consistent	Stimuli — Responses: Left Keypress, Right Keypress	Stimulus Unit / Response Unit — Threshold; Time (**)
3	S-R Inconsistent	Stimuli — Responses: Left Keypress, Right Keypress	Stimulus Unit / Response Unit — Threshold; Time (**)
4	S-S Consistent	Stimuli — Responses: Left Keypress, Right Keypress; BLUE, GREEN	Stimulus Unit / Response Unit — Threshold; Time (**)
4	S-S Inconsistent	Stimuli — Responses: Left Keypress, Right Keypress; BLUE, GREEN	Stimulus Unit / Response Unit — Threshold; Time (**)

Fig. 2.3 Processing architecture and activation patterns for 2-choice tasks (used for illustrative purposes only) of Types 1, 2, 3, and 4 showing the congruent/incongruent cases for Type 2, and the consistent/inconsistent cases for Types 3 and 4 tasks. Whenever two modules represent overlapping dimensions, positive automatic lines connect corresponding units, and negative automatic lines connect non-corresponding units. Only the positive connections are shown in this figure. The rectangles in the architecture column represent modules, the circles represent features. Shaded circles indicate activated feature units. Horizontal and vertical striations in the stimulus rectangles depict blue and green color patches, respectively. The vertical dotted line in the activation column marks the combined duration of the stimulus and response units for the neutral, Type 1 task; this is included for purposes of comparison.

(*) This curve depicts the decaying, relevant stimulus activation value after it has reached threshold.

(**) This curve depicts the level of activation for the irrelevant stimulus (see also Fig. 2.4).

until it reaches threshold. When this threshold has been reached, it indicates that the stimulus has been fully identified. At this point, and not before, the controlled line sends a discrete 'on' signal (equal 1) from the relevant stimulus to the correct response unit. Because this input is 1, activation in the response unit accumulates in exactly the same fashion as it did in the relevant stimulus unit. Once it reaches *its* threshold, the response is considered fully selected, and the overt response is initiated. Because of the existence of a threshold in both the relevant stimulus and the response units, and because the controlled line sends a discrete 'on' signal from the stimulus to the correct response unit, reaction times can be partitioned into two distinct, stage-like, intervals: a stimulus identification time, and a response selection time. This discrete characteristic was present in the boxology (Kornblum *et al.* 1990), and is retained in the PDP version of the model. The total time taken from the moment the relevant stimulus is presented to when the response unit reaches threshold, is defined in the model as the RT, and is what the model simulates as the RT. As will be apparent, the activation patterns in all the other tasks in the taxonomy are modifications of this basic pattern.

Consider a Type 2 task next. Processing in the stimulus module is, of course, identical to what it was for the Type 1 task. Stimulus is presented, input is turned on, activation accumulates, and threshold is reached in the relevant stimulus unit (see Fig. 2.3). Once the stimulus activation reaches this threshold, it is no longer needed and starts decaying back to zero. This decay was utterly inconsequential in Type 1 tasks, because the only signal being sent from the stimulus to the response unit was the 'on' signal on the controlled line. That same 'on' signal is now being sent along the controlled line in the Type 2 task as well. However, because of the DO between the relevant stimulus set and the response set, an automatic signal is also being sent from the stimulus unit to the response unit. The strength of that signal, you will recall, is proportional to the amount of activation in the stimulus unit, so that as activation level changes, so does the strength of that signal.

When the mapping instructions are congruent, the positive automatic signal goes to the same response unit that is getting the 'on' signal via the controlled line. Thus, even though activation in the stimulus unit is decaying, the total positive input to the response unit is high, and activation in that unit accumulates quickly.

When mapping is incongruent, *stimulus* processing remains the same. However, the *response* unit that is getting the 'on' signal via the controlled line is now connected to the stimulus unit by a *negative* automatic line. As a result, the activation in the stimulus unit is subtracted from the total input to the response unit, making its activation accumulate more slowly. This, of course, increases the total reaction time which, when compared to the RT with congruent mapping, is the mapping effect or, as it is known in the literature, 'the SR compatibility effect'.

We now come to tasks in which there is dimensional overlap between the irrelevant stimulus dimension and some other dimension of the task, either the response or the relevant stimulus (see also Kornblum *et al.* 1999, Fig. 7). Type 3 tasks are those in which the irrelevant stimulus dimension overlaps with the response. The stimulus identification stage in these tasks is no different from what it is in the two tasks that we just finished discussing (Types 1 and 2). However, simultaneously with the presentation of the relevant stimulus, we are now also presenting an irrelevant stimulus. The basic three-step activation process is still in place, but is now modified to take this new fact into account: the stimulus is presented; inputs to *both* relevant and irrelevant stimulus units are turned on, and activation accumulates in *both* the relevant and irrelevant stimulus units. Because there is no DO between the relevant and irrelevant stimuli, the irrelevant stimulus has no influence on processing in the relevant stimulus unit. So, when relevant stimulus activation reaches threshold, the controlled line sends its discrete 'on' signal to the correct response unit, just as it did in the Type 1 neutral task.
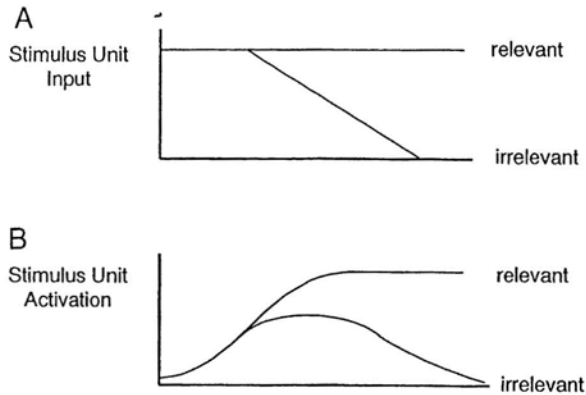
A

Stimulus Unit
Input

relevant

irrelevant

B

Stimulus Unit
Activation

relevant

irrelevant

Fig. 2.4 A: Input to the relevant and irrelevant stimulus units shown as a function of time. The irrelevant input starts decreasing after a duration (τ).
B: Activation functions in the relevant and irrelevant stimulus units shown as a function of time.

However, there *is* DO between the irrelevant stimuli and the responses, which means that the irrelevant stimulus units have automatic connections to the response units. On S–R consistent trials, these automatic connections with the correct response units are positive, which means that activation in the correct response unit gets a boost, and accumulates more rapidly, thus reaching threshold sooner (see Fig. 2.3). On S–R inconsistent trials, these automatic connections between the irrelevant stimuli and the correct responses are negative. The net effect of this is to slow the rate of accumulation of activation for the correct response, thus causing it to reach threshold more slowly. It is this processing difference between S–R consistent and S–R inconsistent trials that, according to our model, generates the S–R consistency, or Simon, effect.

Exactly the same argument holds for Type 4 tasks when the overlap is between the relevant and irrelevant stimuli: the stimulus is presented; inputs to both relevant and irrelevant stimulus units are turned on; activation accumulates in *both* the relevant and irrelevant stimulus units; but now because the DO is between the irrelevant and relevant stimuli, they have automatic connections between them, so that the irrelevant stimulus does influence processing in the relevant stimulus unit. Evidence in support of this assumption has recently been reported by Stevens (2000). On S–S consistent trials the input of the irrelevant stimulus to the corresponding relevant stimulus unit is positive, which means that activation in that unit accumulates faster than it would without this added input, thus reaching threshold sooner. On S–S inconsistent trials, instead of providing positive input to the relevant stimulus, the input of the irrelevant stimulus is negative, thus slowing the rate of accumulation of activation for the relevant stimulus. Once activation reaches threshold in the relevant stimulus unit an on signal is sent to the correct response along the controlled line, just as in the Type 1 neutral task.

To summarize:

1. Activation and information flow in the DO model consists of three basic steps:
   (a) a stimulus is presented;
   (b) input is turned on;
   (c) activation accumulates in the relevant, and possibly irrelevant, stimulus units.

2. When activation reaches the stimulus identification threshold:
   (a) the controlled line sends a discrete signal to the correct response unit; and
   (b) the relevant stimulus activation level starts decaying back to zero.

3. This process is repeated in the response unit until the response threshold is reached.

4. The strength of the automatic signal being sent from a stimulus unit to either a response or to another stimulus unit is a function of the level of stimulus activation weighted by the level of DO between the sets of relevant stimuli and responses, or the two sets of stimuli.

5. This means that when there is either S–R or S–S overlap, activation in the irrelevant stimulus unit produces either facilitation (in the consistent case) or interference (in the inconsistent case).

There are many technical details of the model that we have not presented here that an interested reader may find elsewhere (Kornblum *et al.* 1999). We now turn to the second theme of our tale: sequential effects.

2.3 Sequential effects

2.3.1 *Introduction*

In his classic book on reaction times Luce observed that: '... sequential effects ... have a major impact on ... response times ... any model or experiment that ignores this or fails to predict it surely is incomplete and likely wrong, as well.' (Luce 1986, p. 405). Because of our current work on the DO model, together with our past interest in sequential effects, it should come as no surprise that we should have been doubly attentive to Luce's admonition. In this second portion of our chapter, therefore, we shall be looking into the DO model to see whether it is sufficiently complete, at least in principle, to account for sequential effects. This goal is doubly appealing, for to be able to demonstrate this would: (1) extend and provide further validation of the DO model, and (2) account for some of the sequential effects that up to now have proven difficult to explain.

The DO model as it stands, like most (non-learning) models of human performance, assumes that successive trials are independent. That is, every trial starts fresh, unaffected by the history of earlier trials in the block. Empirically, we have known for a long time that this is patently false and that sequential effects of all sorts permeate the data. By 'sequential effects' we mean that: 'If a subset of trials can be selected from a series of consecutive trials on the basis of a particular relationship that each of these selected trials bear to their predecessor(s) in the series, and the data for that subset differ significantly from the rest of the trials, then these data may be said to exhibit sequential effects' (Kornblum 1973, p. 260). Defined in this way, the term 'sequential effects' covers many different phenomena including stimulus and/or response repetitions and non-repetitions (of first and higher orders), task switching, set or einstellung effects, etc. The sequential effects that we consider in this chapter are first-order stimulus and/or response repetitions and non-repetitions, in which relevant and irrelevant stimuli do or do not have DO. As will be evident, task switching effects are also present in our data; however, because of space limitations these are not discussed. Readers interested in pursuing them should consult recent reviews (e.g. Allport, Styles, and Hsieh 1994; Monsell and Driver 2000).

2.3.2 Summary of earlier empirical findings

Sequential effects in RT tasks were first reported by Hyman (1953). Shortly thereafter, Bertelson and his colleagues published a series of influential studies in which they described important properties of this new phenomenon (e.g. Bertelson 1961, 1963, 1965; Bertelson and Renkin 1966; Bertelson and Tysseyre 1966). Studies by other investigators followed that verified and extended many of Bertelson's original findings, and added new observations as well. Some of these are briefly summarized below:[4]

1. Given equiprobable stimuli and responses, the RT for repetitions is faster than for non-repetitions (e.g. Bertelson 1961).

2. Given equiprobable stimuli and responses, the size of the repetition effect (where 'repetition effect' is defined as the difference in RT between non-repetitions and repetitions) is greater for incompatible than for compatible tasks (Bertelson 1963). This is principally due to the increase in RT with incompatible tasks being greater for non-repetitions than for repetitions (see Kirby 1980 and Kornblum 1973 for reviews).

3. Given equiprobable stimuli and responses, the RT for repetitions and non repetitions is inversely related to the probability of these transitions. In the case of two-choice tasks this often results in the RT for non-repetitions (often called 'alternations' in two-choice) being faster than for repetitions (e.g. Hyman 1953; Kornblum 1969; Williams 1966).

4. The magnitude of the repetition effect increases as the number (k) of equiprobable stimuli and responses increases. This is due primarily to the fact that increasing (k) increases the RT for non-repetitions much more than for repetitions (even though the probability of non-repetitions *increases* with (k)—see Kornblum 1969, 1973 for more detail).

5. Repetition effects extend beyond immediate, first order repetitions and non-repetitions up to about fourth order (e.g. see Remington 1969, 1971).

6. The probability of error is usually higher for non-repetitions than for repetitions (e.g. Falmagne 1965; for a review see Luce 1986).

7. The response to stimulus interval (RSI) has extensive, albeit difficult to systematize, effects on the magnitude the repetition effect (see Kirby 1980; Kornblum 1973; Luce 1986; Soetens 1998).

   This list is not intended to be exhaustive. However, it includes the principal findings that investigators in the area regard as having been reasonably well established.

2.3.3 Summary of earlier accounts

As the empirical findings accumulated, various proposals were made to account for different aspects of the data. Most of these explanations fall into one of two major lines of argument first formulated by Bertelson (1961). He suggested that sequential effects might need to be accounted for by two different types of mechanisms: the first, based on the subjects' 'expectation of', hence 'preparation for', certain events; the second, an otherwise unspecified 'residual effect' generated

by one trial that facilitated repetitions on the next trial. Both mechanisms, according to Bertelson (1961), were sensitive to changes in RSI: the effects of expectation increased with RSI, whereas the residual effects decreased with RSI. As these conjectures were elaborated, expectation came to be viewed as a controlled, or strategic component, while residual effects were viewed as an automatic part of the process. This dichotomy has held up fairly well, supported in part by the data of Soetens and his colleagues (Soetens 1998; Soetens, Boer, and Hueting 1985) whose work has focused on substantiating and spelling out the conditions under which one or the other component would be evident. Further support has also comes from ERP (event related potentials) data (e.g. Leuthold and Sommer 1993; Squires, Wickens, Squires, and Donchin 1976). Some have characterized the automatic component in terms of activation, or sensory stimulation produced by one stimulus that leaves a trace so that if the next stimulus is the same it gets a boost by being superimposed on the traces of the first (e.g. Vervaeck and Boer 1980). Others have characterized it in terms of repeated stimuli being able to bypass some of the processing stages (e.g. Bertelson 1965). Others still, speak of the stimulus (or response) on one trial priming the occurrence of the same stimulus (or response) on the next trial. None of these conjectures is spelled out in sufficient detail to be tested, however. The most detailed model of sequential effects was constructed by Falmagne and his colleagues (Falmagne 1965; Falmagne and Theios 1969; Falmagne, Cohen, and Dwivedi 1975). Falmagne bases his model on the notion of preparation and treats preparation in the conceptual framework of a memory search. According to the model, the relative position of an item in a memory stack determines the probability with which a subject is prepared, or not prepared, for that item: the higher in the stack, the more prepared and the shorter the RT. Quantitative predictions of the model are well supported by their data.

The DO model, and the extensions made to it to accommodate the sequential data, do not fit easily into either camp, as we shall see.

2.4 Overview of the experiments

2.4.1 Objectives

Our first objective, and the issue of greatest concern and interest to us in this chapter, was to examine the interaction of the repetition effect with SRC (Bertelson 1963; Kirby 1976; Schvaneveldt and Chase 1969) wherein the increase of RT with incompatible tasks is greater for non-repetitions than for repetitions. Bertelson (1963) originally accounted for this result in terms of a processing short cut that favors repetitions. He suggested that the first thing a subject does when presented with a stimulus is check to see if it matches the stimulus on the previous trial. If the match is confirmed, stimulus processing is bypassed and the response made on the previous trial is retrieved from memory and made again on this trial. If there is no match, processing proceeds until the correct response is identified and executed. Because, by assumption, this processing is more complex, hence more time consuming, for incompatible than for compatible tasks, incompatibility will increase the RT for non-repetition more than for repetitions. On the surface this reasoning seems straightforward. However, nowhere is the underlying processing structure made explicit. The particular subprocesses that are being short-circuited on the one hand, and those that increase in complexity on the other, therefore, remain vague and difficult to identify. Our first experiment is explicitly designed to address this issue.

Our second objective was to examine and compare DO and sequential effects in terms of their underlying stimulus coding processes. In particular, DO, whether based on physical or conceptual similarity, produces robust compatibility effects. Some of the best known examples of the effects of conceptual similarity are the Stroop (Type 8) and Stroop-like tasks in which the presence of color words interferes with the processing of physical colors even though these two aspects of the stimulus are physically very different. Sequential effects have been reported for the repetition of physically identical stimuli (Bertelson 1961), the repetition of categories (Marcel and Forrin 1974), and the repetition of S–R mapping rules (Shaffer 1965). However, the effects of repeating conceptually similar but physically different stimuli are not known. Because of the functional significance of conceptual similarity in the DO model, it was important to learn what role, if any, this type of similarity plays in the production of sequential effects. This question was addressed in Experiment 1. In the 'same carrier' condition, the stimuli on the prime and probe trials were physically identical; i.e. they were either both color patches, color words, digits, etc. In the 'different carrier' condition the stimuli on the prime and probe trials were conceptually similar but physically different; e.g. if the stimulus on the prime was a color patch, then the stimulus on the probe was a color word, etc.

Our third objective, and concern, not unrelated to the first, is the question of the locus of the repetition effect. As is true of many issues in this area, this question was first broached by Bertelson (1963) using a task in which he mapped different pairs of stimuli onto each of two responses. This generated three types of transitions: 'identical', in which both the stimulus and the response of one trial were repeated on the next trial; 'equivalent', in which only the response of the preceding trial was repeated on the next trial; and 'different', in which neither the stimulus nor the response of one trial was repeated on the next. The logic was simple: the effect of stimulus repetition was obtained by subtracting identical from equivalent RTs, and the effect of response repetition was obtained by subtracting equivalent from different RTs. Based on this procedure Bertelson concluded that the principal component of sequential effects was the repetition of the response. Pashler and Bayliss (1991), using a three-response task with the same basic paradigm, reached the same conclusion. According to Soetens (1998), however, whether one attributes sequential effects to stimulus or to response repetitions depends on RSI: response processes appear to be responsible at long RSIs, and stimulus processes at short RSIs. The basic logic of this many-to-one procedure is brought into question by Smith (1968), who reported the results of an experiment in which the equivalent RT, instead of lying between the identical and different RTs, was actually longer than the different RT. Rabbitt (1968) also reported that the relative position of the equivalent RT, between identical and different, changed with training. Overall, therefore, the locus of the repetition effect appears to be an important open question. Furthermore, based on the results of our first experiment we shall conclude that both stimulus and response repetitions play a critical role in the repetition effect. Our second experiment will follow up these results and address the locus question using a one-to-one rather than a many-to-one procedure.

Our fourth objective was to examine the effects of repeating and not repeating *irrelevant* stimuli in task Types 1, 3, and 4. We know of no other work that explicitly addresses this question in tasks with more than two choices. Experiments 3 and 4 do so.

2.4.2 General procedures

1. All experiments use four-choice tasks. The basic experimental unit is the trial pair. The first trial in such pairs is called the prime, the second trial the probe. The stimulus transition probabilities

between primes and probes were randomized and balanced. The time interval between primes and probes (700 ms and 1500 ms) was blocked. The data that are reported for the two shortest RPIs are from the probe trials; the data for RSI = 3000 ms are from prime trials.

2. It is clear from the literature that the effects of RSI are capricious and problematic (see e.g. Kirby 1980; and Kornblum 1973, Table 3). Yet they cannot be ignored. In order to present a more complete empirical picture of the phenomena that we are investigating we included RSI in the design of our experiments (700 ms and 1500 ms within pairs for all four experiments, and 3000 ms between balanced pairs for Experiments 1 and 2). However, because of space limitations, we analyze the details and discuss the data for the shortest RSI only. One general observation that can be made is that the longer the RSI the slower the overall RT. The individual results of RSI for particular experiments are presented in Appendices B–D.

3. Errors are reported in Appendix A for all experiments.

2.5 Experiment 1

In this first experiment we were interested in examining the interaction between sequential effects and stimulus–response compatibility. Our experimental prime–probe pairs consisted of either Type 1 or Type 2 pairs.

2.5.1 Methods

2.5.1.1 Time line
A trial (whether it was a prime or probe) began with a warning signal. Seven hundred milliseconds later, the stimulus was presented and was terminated by the response.

The prime-to-probe interval was either 700 ms or 1500 ms and was constant for a block. The time interval between prime–probe pairs was always three seconds.

2.5.1.2 Stimuli and responses
The stimuli were presented on a CRT screen, and consisted of either four color words (RED, BLUE, GREEN, and YELLOW) or four rectangular color patches (red, blue, green, and yellow). The responses were verbal and consisted of either four color names ('red', 'blue', 'green', and 'yellow') or four-digit names ('two', 'four', 'six', and 'eight'). When the responses were color names it was a Type 2 task for which the mapping was either congruent (e.g. RED→'red'), or incongruent (RED→'blue'). When the responses were digit names it was a Type 1 task, for which the mapping was neutral (e.g. RED→'two').

2.5.1.3 Same/different carrier
The stimuli on the prime and probe trials were either color words or color patches. In our illustration (see Fig. 2.5) we use color patches as the prime stimuli (however, note that the experiment included another set of prime–probe pairs in which the prime stimuli are color words). Following this illustration, a Type 1 prime with a color patch stimulus was followed by a Type 1 probe with either a color patch or a color word as the stimulus. In the same carrier condition, if the probe stimulus was a color patch, the *nature* of the probe stimulus remained what it was on the prime (color patch–color patch); this is true whether it was a repetition or a non-repetition. In the different carrier condition if the probe stimulus was a color-word, the nature of the probe stimulus changed from what it was on
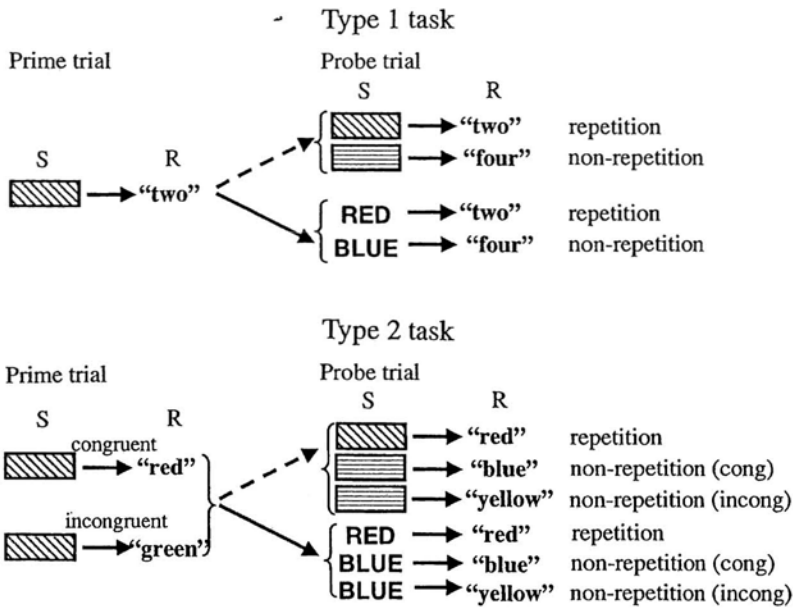
Type 1 task

Prime trial   Probe trial

           S   R

                → "two"   repetition

                → "four"   non-repetition

S   R

→ "two"

             RED → "two"   repetition

             BLUE → "four"   non-repetition

Type 2 task

Prime trial   Probe trial

S   R   S   R

congruent

→ "red"

                → "red"   repetition

                → "blue"   non-repetition (cong)

                → "yellow"   non-repetition (incong)

incongruent

→ "green"

             RED → "red"   repetition

             BLUE → "blue"   non-repetition (cong)

             BLUE → "yellow"   non-repetition (incong)

Fig. 2.5 The different prime–probe pairs for Type 1 and Type 2 tasks in Experiment 1 for which the prime stimuli were color patches. (There is another set of prime–probe pairs (not shown) for which the prime stimuli were color words; same/different carrier transitions with these prime stimuli are simply the reverse of what is shown on this figure.) The particular colors used are for illustrative purposes only; horizontal striations indicate the color blue, diagonal striations the color red. Same carrier transitions (see text for explanation) are indicated by a dotted line, different carriers by a solid line. Whether the probe was a repetition or a non-repetition is indicated on the right. In Type 2 tasks the prime could be either congruent or incongruent, as shown. Similarly, the probe, in addition to being a congruent repetition or non-repetition, could also be an incongruent non-repetition; these are marked as 'congruent' or 'incongruent', respectively, on the right.

the prime (color *patch*–color *word*); this is true whether it was a repetition or a non-repetition. This same/different carrier designation was, of course, reversed when the prime stimulus was a color word.

    The Type 2 task had exactly the same properties. A prime with a color patch stimulus and congruent or incongruent mapping was followed by a probe with either a color patch or a color word as the stimulus. Same and different carrier conditions were defined in precisely the same manner as they were for the Type 1 tasks.

2.5.1.4 Conditions, blocks, and procedure

There were three groups of six subjects each: congruent mapping (Type 2), incongruent mapping (Type 2), and neutral (Type 1). The incongruent mapping group was further divided into three subgroups, each with a different S–R mapping. The neutral group also included three subgroups each
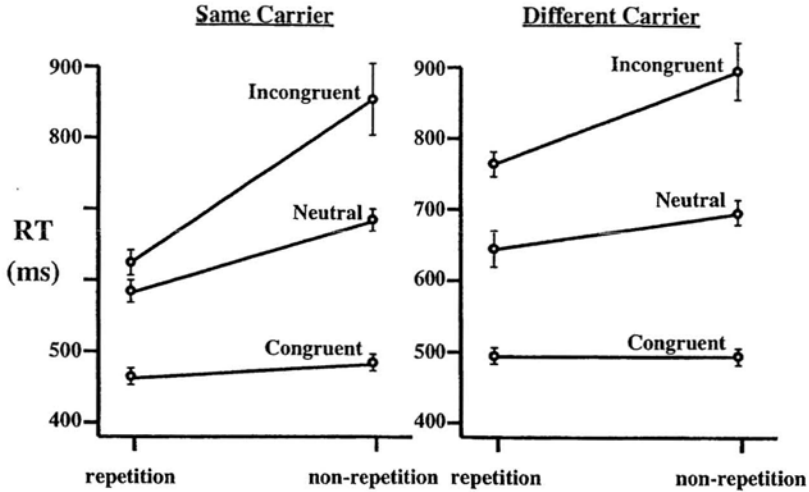
Fig. 2.6 Results of Experiment 1 for RSI = 700 ms.

with its own S–R mapping. Each subject in each group was run on six experimental blocks of 32 trials each at one RSI, followed by six more experimental blocks at the other RSI. This order was balanced. At the start of each series of trials each subject was run on one practice block. The prime–probe transition frequencies were balanced within 64 prime–probe pairs presented in two sub-blocks of 32 pairs.

Mapping (which included DO, i.e. task type), carrier, and repetition were factorially combined and constituted the three principal independent variables of the experiment.

2.5.1.5 Subjects
Eighteen University of Michigan students participated in this experiment. They were all right handed, native English speakers with self reported normal hearing and vision, and tested normal color vision. They were volunteers and were paid for their participation.

2.5.2 Results

The principal results that we report for this and all the other experiments are for the shortest RSI (700 ms). (For the results of different RSIs see Appendices B–D.)

2.5.2.1 Same carrier
We start with the results for the same carrier condition. In Type 1 tasks the RT for repetitions is 100 ms faster than for non-repetitions [$F(1, 3) = 94.72$, $p < 0.0023$]—no surprises. In Type 2 tasks a number of things should be noted:

1. The overall RT with congruent mapping is 335 ms faster than with incongruent mapping [$F(1, 10) = 82.95$, $p < 0.0001$], and the RT for the neutral mapping is almost exactly half way in between: neutral vs. congruent [$F(1, 10) = 76.62$, $p < 0.0001$], neutral vs. incongruent [$F(1, 10) = 12.96$, $p < 0.0049$].
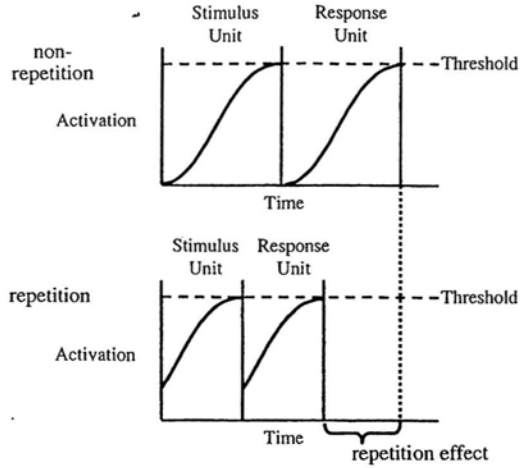
Fig. 2.7   Activation pattern, according to the Residual Activation Hypothesis, for a probe trial in a Type 1 task in which neither (*upper panel*) or both (*lower panel*) the stimulus and the response repeat.

2. There is also a highly significant interaction between mapping, and repetition. When the S–R mapping is congruent, there is a significant 21 ms difference between repetitions and non repetitions [$F(1, 5) = 12.11$, $p < 0.0176$]; when it is incongruent this difference is 235 ms [$F(1, 3) = 22.63$, $p < 0.0176$]; and when it is neutral it is in between, at 100 ms [$F(1, 3) = 94.72$, $p < 0.0023$].

These results generally replicate earlier findings in the literature.

2.5.2.2 Different carrier

We turn to the results with different carrier next. Recall that in the different carrier condition when the prime stimulus is a color patch the probe stimulus is a color word, and vice versa.

The basic results that we obtained with the same carrier condition replicate: the overall RT for congruent mapping is 382 ms faster than for incongruent mapping [$F(1, 10) = 124.04$, $p < 0.0001$], with the neutral mapping condition falling between the two: neutral vs. congruent, [$F(1, 10) = 53.47$, $p < 0.0001$]; neutral vs. incongruent, [$F(1, 10) = 22.88$, $p < 0.0007$].

As was also true in the same carrier condition there is a highly significant interaction between mapping, and repetition. When the S–R mapping is congruent the difference between repetitions and non repetitions is not statistically significant (1 ms) [$F(1, 5) = 0.13$ $p < 0.7315$]. When it is incongruent, it is 132 ms [$F(1,3) = 9.48$, $p < 0.0542$], and when it is neutral it is in between at 55 ms [$F(1, 3) = 12.06$, $p < 0.0403$].

Note that the mapping effect for repetitions with different carriers (264 ms) is larger than with same carriers (155 ms). This generates the highly significant triple interaction between carrier, mapping, and repetition [$F(1, 10) = 20.35$, $p < 0.001$].

2.5.3 Discussion: the Information Reduction Hypothesis

The model must now show that it can account for the following: (1) the effects of repetition; (2) the interaction between repetition and S–R mapping; and (3) the interaction between repetition, S–R mapping, and carrier.
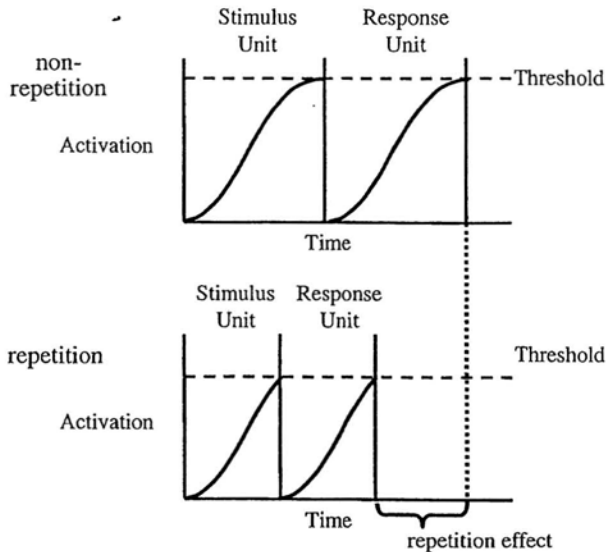
Fig. 2.8 Activation pattern, according to the Information Reduction Hypothesis, for a probe trial in a Type 1 task in which neither (*upper panel*) or both (*lower panel*) the stimulus and the response repeat. Note that repetitions, instead of having a higher starting point, as in the Residual Activation Hypothesis (Fig. 2.7), have a lower threshold. See text for the implications of this difference.

Common to all the 'automatic' accounts of the repetition effect, as we have seen, is the notion that having performed a certain action, residual traces (e.g. memory, perceptual, or response traces) are left that automatically facilitate the processing of subsequently repeated stimuli or responses. One easy way of implementing this view in our model would be to represent this trace as residual activation left over from the previous trial that has not yet decayed all the way to zero by the time the current trial begins (see Fig. 2.7). Let us call this the 'Residual Activation Hypothesis'.[5] Given the head-start provided by the residual activation, activation levels in the stimulus and response units would reach threshold earlier than they otherwise might. This would reduce overall processing time, hence overall RT—thus producing a repetition effect. Simple?—Yes; correct?—Unfortunately, no. This scheme can be shown to account for the effects of repetitions, the effects of mapping, and their interaction. However, it cannot account for the interaction with carrier which is one of the striking aspects of our results. We will now argue that what we are calling the 'Information Reduction Hypothesis', can.

It is a property of the DO model that each individual stimulus and response unit has its own threshold. According to the information reduction hypothesis, whenever a stimulus is identified or a response made or selected, the amount of information required to identify that stimulus or select that response again is temporarily lowered. This is implemented as a decrease in the stimulus or response threshold associated with the appropriate unit (see Fig. 2.8). If the same stimulus is presented again, or the same response is selected on the next trial, activation has a shorter way to go before it reaches this lower threshold, and the processing durations of the stimulus or response units are consequently reduced.
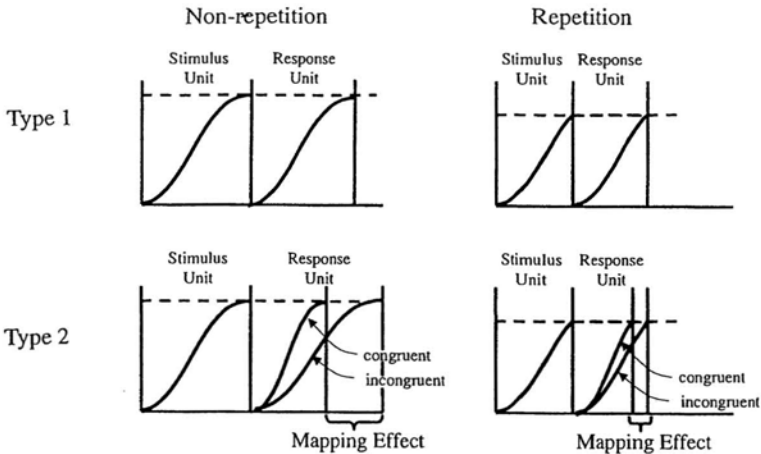
Fig. 2.9 Activation patterns, according to the Information Reduction Hypothesis, for probe trials in Type 1 and Type 2 tasks for same carrier condition where, by hypothesis, both or neither the stimulus and the response repeat. As illustrated here, for the non-repetitions, activation on probe trials is identical to activation on primes. Note that not only is the overall RT for repetitions faster than for non-repetition (the repetition effect), but the mapping effect is smaller as well.

At first glance these two hypotheses seem equivalent. Exactly the same reduction in processing time is achieved by postulating residual activation as is by lowering thresholds. However, these two hypotheses have profoundly different consequences further down the line (see * in Fig. 2.3, Type 2 tasks).

2.5.3.1 Same carrier

We start with the results from the same carrier condition. According to the information reduction hypothesis, performance in the three different mapping conditions is determined as follows:

In Type 1 tasks, when the mapping is neutral, the only factor influencing the RT is whether the stimulus or response repeat or not. When neither repeat, the thresholds of the stimulus and response units are identical on probe and prime trials. The RTs on probe trials are, therefore, the same as on primes.

When both the stimulus and the response repeat, the thresholds of both the stimulus and the response units are lower on probe trials than they were on prime trials. The RTs on probe trials are, therefore, faster than on primes. This is the baseline, the basic repetition effect (see Fig. 2.9, Type 1).

In Type 2 tasks, when the mapping is either congruent or incongruent two factors come into play: the first is whether the stimulus or response repeat or not, and we just saw how this factor affects RT just by itself in the Type 1 task where the mapping is neutral; the second is the facilitation and interference produced by the congruent and incongruent mappings.

When neither stimulus nor response repeat, the thresholds of the stimulus and response units are identical on probe and prime trials—just like in Type 1 tasks. Irrespective of mapping, the RTs on probes are the same as on primes.

When both the stimulus and response repeat, the thresholds of both the stimulus and response units are lower on probe trials than they were on primes. The effect of this lowered threshold in the stimulus unit is identical for the congruent, incongruent, and neutral mappings (see Fig. 2.9). However,

because of the DO between the relevant stimulus and the response, this lower stimulus threshold affects the input to the response unit. In particular, the lower threshold reduces the level to which stimulus activation rises, hence from which it starts to decay (see * in Fig. 2.3, Type 2 tasks). Therefore, the automatic input to the response unit is less when the stimulus repeats than when it does not repeat. In addition, because the rate at which activation accumulates in the response unit is faster for congruent than for incongruent mapping, lowering the response selection threshold has differential effects for congruent and incongruent mapping: it decreases the RT for both, however, it decreases the RT for incongruent mapping more than for congruent mapping. The observed interaction between repetition and S–R mapping is, therefore, the result of lowering both the stimulus and the response threshold.

2.5.3.2 Different carrier

Now consider the different carrier condition. This is when the prime stimulus is a color word and the probe stimulus is a color patch, or vice versa. We shall look at the repetition effect first, and the mapping effect next.

We've already seen that in Type 1 tasks, when the mapping is neutral, the only factor influencing RT is whether or not the stimulus or the response repeat. When neither repeat, according to the model, the RTs for same (682 ms) and different (690 ms) carriers ought to be identical—which they are; this 8 ms difference in the data is not statistically significant [$F(1, 5) = 1.63, p < 0.2583$]. The Type 2 results are not as clean. When the mapping is congruent and neither stimulus nor response repeat, the RT for same carrier (484 ms) is faster than for different carrier (490 ms), and this 6 ms difference is statistically significant [$F(1, 5) = 11.47, p < 0.0195$]. The same is true for the incongruent mapping. The RT for non-repetitions with the same carrier (853 ms) is faster than with the different carrier (885 ms); and this 32 ms difference is also statistically significant [$F(1, 5) = 6.75, p < 0.0484$]. It seemed reasonable to us to attribute these small differences to the cost of switching between carriers (i.e. from color patch to word and vice versa). For consider, these differences are for *total* non-repetitions, which means that *neither* the stimulus *nor* the response on the prime are repeated on the probe. Therefore, the most plausible contrast between the same and different carrier conditions that might account for this difference in RT is that repetition of the carrier itself had an effect. This interpretation of the data is consistent with the fact that same carrier RTs were faster than different carrier RTs.

Consider the repetitions next. Recall that repetitions with different carriers were 49 ms slower than with same carrier. This probably reflects the difference between the physical and the *possible* conceptual repetition, or *total* non-repetition of the stimulus. However, we had no way of assessing whether conceptual repetition contributed in any way to the repetition effect in this experiment. In our modeling, therefore, we treated repetition trials in different carrier conditions as pure response repetitions (see Fig. 2.10). Thus, when *only* the response repeats, as it does by hypothesis, the threshold of the response unit is lower on the probe than on the prime and RTs on probe trials are, therefore, faster than on primes, but not as fast as with probes in the same carrier condition where both the stimulus and response are repeated.

We go to the mapping effects next.

When the mapping is either congruent or incongruent, we again have two factors coming into play: repetition and mapping. On non-repetition trials, when neither stimulus nor response are repeated, probe RTs are the same as on prime trials by the same argument that we made in the case of same carrier. On repetition trials, when only the response is repeated, only the threshold for the
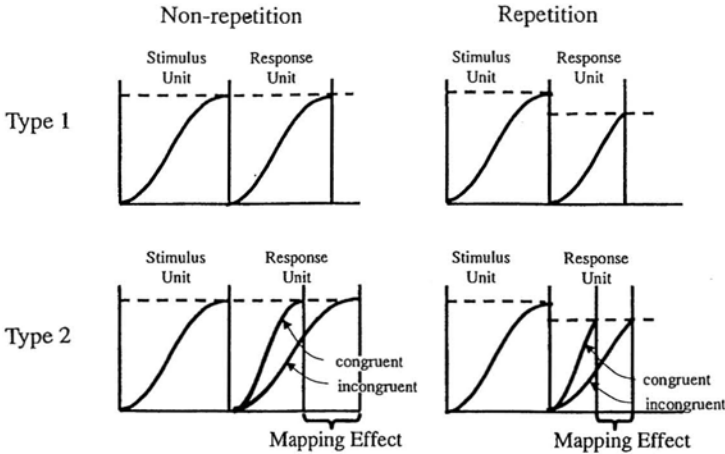
Fig. 2.10 Activation patterns for probe trials in Type 1 and Type 2 tasks for different carrier condition where, by hypothesis, the stimulus does not repeat but the response may. As was true for the same carrier condition, the non-repetition probe trials are identical to the primes. The overall RT for repetitions is faster than for non-repetitions. However, the repetition effect is smaller here than it was for the same carrier condition (Fig. 2.9). This is because here only the response repeats. Note also, that as was true for the same carrier condition, the mapping effect is smaller for repetitions than for non-repetitions, but this reduction is not as large here as it was for the same carrier condition.

response unit is lower on the probe than on the prime trial. This means that stimulus activation will start its decaying process from a higher level in the different carrier than in the same carrier condition producing a larger mapping effect thus generating the triple interaction between repetition, mapping, and carrier.

Based on these principles we used the model to simulate the results for Experiment 1. As can be seen on Fig. 2.11 they appear to match the empirical data reasonably well.

Thus, based on our results and model, repetitions of both stimulus and response play an important role in the production of the repetition effect. However, as we have seen, previous studies that have explicitly addressed the question of locus (e.g. Bertelson 1963) concluded that the bulk of the repetition effect lies with the repetition of the response. Our next experiment addresses this issue directly.

2.6 Experiment 2

Here we examine the locus of the repetition effect. Because of our interest in the interaction of S–R compatibility with the repetition effect, our primary focus will be on Type 2 tasks. However, we shall also be looking at the effects of repetitions and non-repetitions for Type 1 and Type 2 tasks, each preceded by the other.

Consider a Type 2 probe—for example, one where the stimulus is drawn from a set of color patches and the response from a set of color names. Now consider the Type 1 prime preceding this probe, where
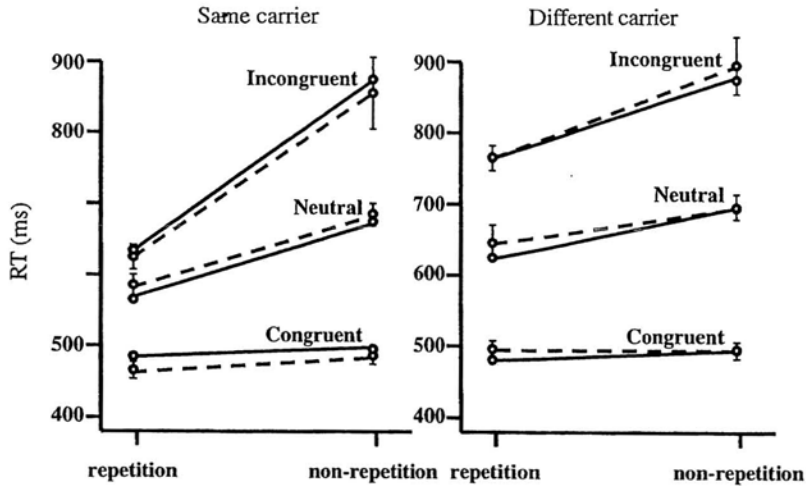
Fig. 2.11 Simulated data for Experiment 1 are shown as solid lines; the empirical data are shown as dashed lines for comparison.

either the stimulus is drawn from a set of color patches, with digit names as responses, or the response is drawn from a set of color names with digits as the stimuli. Depending on which of these two primes one chose, the probe in such a prime–probe pair would display either a stimulus repetition or a response repetition, but not both. This is precisely how we designed the prime–probe pairs for this experiment.

2.6.1 Methods

2.6.1.1 Time line
The temporal relationships within and between trials were the same as they were in Experiment 1.

2.6.1.2 Stimuli and responses
The stimuli were presented on a CRT screen, and consisted of either four rectangular color patches (red, blue, green, and yellow) or four digits (2, 4, 6, 8). The responses were verbal and consisted of either four color names ('red', 'blue', 'green', and 'yellow') or four digit names ('two', 'four', 'six', and 'eight'). For Type 1 tasks, we used either color patch stimuli and mapped them onto digit name responses, or digit stimuli and mapped them onto color name responses. For Type 2 tasks, we used the same sets of stimuli and responses but paired them differently: color patch stimuli were mapped onto color name responses—congruently and incongruently, and digit stimuli were mapped onto digit name responses—congruently or incongruently.

2.6.1.2.1 Type 1 →Type 2, and Type 2→Type 1, prime–probe pairs
Consider first the case in which the prime-probe pairs consisted of Type1–Type 2 tasks, respectively. In our illustrations (Fig. 2.12) we show the stimuli and responses for the probe as color patches and color names respectively; of course, as was true of experiment 1, in this experiment there was another set of probe trials for which the stimuli and responses consisted of digits and digit names.
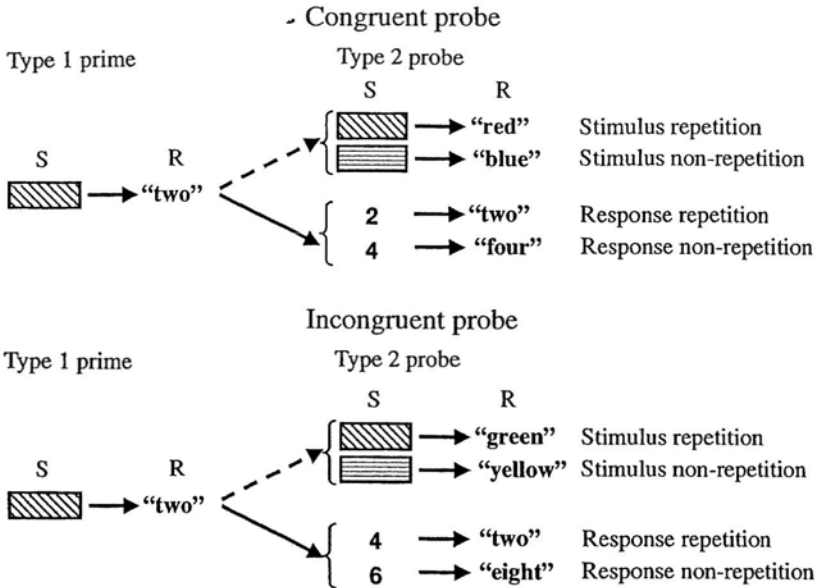
Fig. 2.12 Illustrative stimuli and responses for different prime–probe pairs in Experiment 2 in which the primes are Type 1 and the probes are Type 2 tasks. For this illustration the prime stimuli are color patches. There is another set of prime–probe pairs (not shown) for which the prime stimuli are digits. With those primes, the S–R pairing on probe trials remains the same as what is shown except that what are here identified as response set switches (see text) become stimulus switches and vice versa. The particular colors and digits are for illustrative purposes only. Horizontal striations indicate the color blue, diagonal striations the color red. Response set switches are indicated by a dotted line, stimulus set switches are indicated by a solid line. Whether the probe is a stimulus or response, repetition or non-repetition is indicated on the right.

Stimulus repetitions with Type 2 color probes, whether congruent or incongruent, were produced by Type 1 primes for which the stimuli were color patches and the responses digit names. Similarly, response repetitions with Type 2 color probes were produced by Type 1 primes for which the responses were color names and the stimuli were digits.

When the order of task types in the prime–probe pairs was reversed, and consisted of Type 2–Type 1 tasks, respectively (see Fig. 2.13), the procedure for obtaining stimulus and response repetitions was identical to what we just saw. For example, if the Type 1 probe stimulus was a color patch and the response a digit name, a stimulus repetition was produced by a Type 2 color prime, with either congruent or incongruent mapping. Similarly, a response repetition was produced by a Type 2 digit prime, with either congruent or incongruent mapping.

2.6.1.3 Conditions, blocks, and procedures

Thirty-two subjects participated in the experiment; for half the subjects the prime stimulus was color, for the other half it was digits. These two groups were further subdivided into four groups of
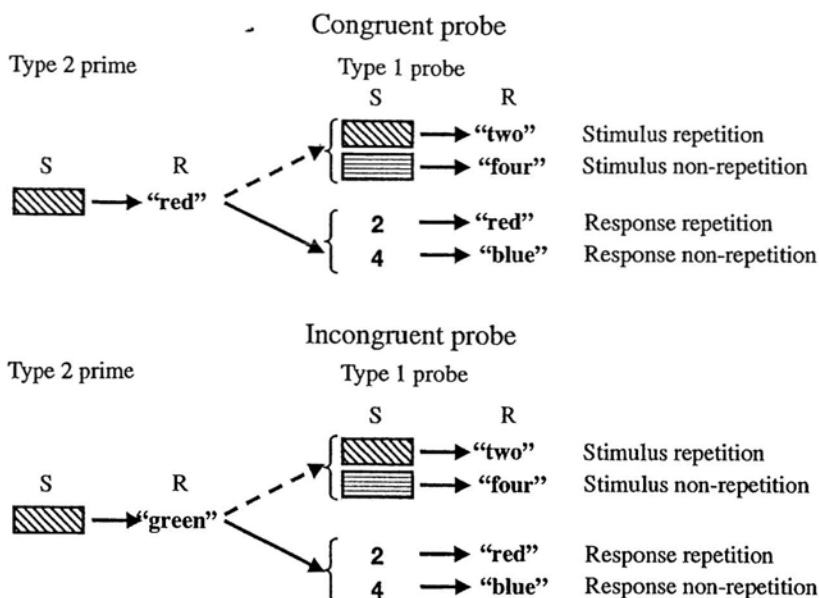
Fig. 2.13 Illustrative stimuli and responses for different prime–probe pairs in Experiment 2 in which the primes are Type 2 and the probes are Type 1 tasks. For this illustration the prime stimuli are color patches. There is another set of prime–probe pairs for which the prime stimuli are digits. With those primes, the S–R pairing on probe trials remains the same as what is shown except that what are here identified as response set switches become stimulus switches (see text) and vice versa. The particular colors and digits are for illustrative purposes only. Horizontal striations indicate the color blue, diagonal striations the color red. Response set switches are indicated by a dotted line, stimulus set switches are indicated by a solid line. Whether the probe is a stimulus or response, repetition or non-repetition is indicated on the right.

four subjects each. Each of these subgroups was identified by the mapping instructions that it received for the Type 2 task: one subgroup was given the congruent mapping, and each of the other three subgroups was given a different incongruent mapping. Each of the four subjects in these subgroups received a different mapping for the Type 1 task.

Each subject was run on six experimental blocks of 32 trials each at one RSI, followed by six more experimental blocks at the other RSI. This order was balanced. Half the subjects in each subgroup of four started with a Type 1 prime, the other half started with a Type 2 prime.

Prime stimulus and S–R mapping were between subject variables. At the start of each series of trials each subject was run on one practice block. The prime–probe transition frequencies were balanced within 64 prime–probe pairs presented in two sub-blocks of 32 pairs.

2.6.1.4 Subjects
Thirty-two University of Michigan students volunteered for the experiment and were paid for their participation. They were all right-handed, native English speakers with self-reported normal hearing and vision. Their color vision tests were normal.
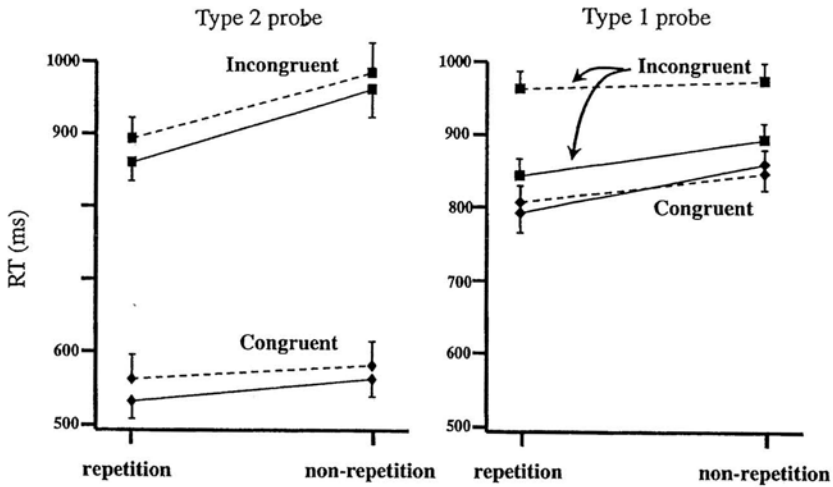
Fig. 2.14 Results of Experiment 2. The left panel shows the data when the prime–probe pair consisted of Type 1–Type 2 tasks, respectively; the right panel shows the results when the prime–probe pairs consisted of Type 2–Type 1 tasks. 'Congruent' and 'incongruent' refer to the S–R mapping for the Type 2 tasks, irrespective of order. The dotted lines are the data for the stimulus repetitions and non-repetitions, when the response set was switched; the solid lines are the data for the response repetitions and non-repetitions, when the stimulus set was switched.

2.6.2 Type 1→Type 2

2.6.2.1 Results

First we present the results for the Type 2 probes preceded by Type 1 primes averaged over the digit and color patch stimuli (see Fig. 2.14).

1. As expected, there is a highly significant effect of mapping: the RT for congruent mapping is over 365 ms faster than for incongruent mapping [$F(1, 30) = 44.31$, $p < 0.0001$].

2. The interaction between mapping and the size of the repetition effect is also significant [$F(1, 30) = 5.48$, $p < 0.0260$]: when the S–R mapping is congruent, the repetition effect is 25 ms. [$F(1, 23) = 9.06$, $p < 0.0197$]; when it is incongruent it is 96 ms [$F(1, 23) = 31.01$, $p < 0.0001$], a fourfold increase.

3. Note that when we speak of repetition effects in this experiment we are speaking of repetitions of either the stimulus or the response, *with corresponding shifts in response and stimulus sets respectively* (see Fig. 2.14). That is, when a stimulus repetition or non-repetition occurs (the dotted lines in Fig. 2.14), the prime stimulus and the probe stimulus are both drawn from the same stimulus set (they are either both color patches or both digits). In contrast, the prime response and the probe response are each drawn from different response sets (digit names for the one and color names for the other, or vice versa). This means that the subject must shift from one response set to another (i.e. digit names to color names or vice versa). The symmetric situation holds for response repetitions and non-repetitions (the solid lines in Fig. 2.14). Here, the responses on the prime and probe are

both drawn from the same response set (they are either both color names or both digit names) and it is the prime and probe *stimuli* that are each drawn from a different stimulus set (color patch for one and digit for the other, or vice versa). This means that subjects must shift from one stimulus set to another (digits to colors, or vice versa). These shifts appear to have exacted a cost. Shifting from one response set to another (digit names to color names, or vice versa) takes about 27 ms longer than shifting from one stimulus set to another (digits to color patches or vice versa) $[F(1, 30) = 6.76, p < 0.0143]$. These set shifting costs (25 ms for congruent mapping ($[F(1, 7) = 10.15, p < 0.0154]$, and 29 ms for incongruent mapping $[F(1, 7) = 4.32, p < 0.0489]$) are additive with the effects of repetition and mapping [set-shift × congruence : $F(1, 30) = 0.03, p < 0.8643$].

2.6.2.2 Discussion
Our results, in contrast to earlier reports, and using a different experimental paradigm, show that stimulus and response repetition effects are both fairly large, and roughly equal in size. The locus of the repetition effect thus appears to be equally apportioned between stimulus and response processes. These findings also disconfirm a prediction recently made by Hommel (1998; Hommel *et al.* in press).

In a recent paper in which he extends the notion of feature integration (Treisman 1988) to include action features to construct, what he calls 'event files', Hommel (1998; Hommel *et al.* in press) makes specific predictions about the relative costs and benefits of certain kinds of repetitions. In particular, according to Hommel's view, if one takes as a baseline the *total* non-repetition condition, when neither the stimulus nor the response are repeated, then the RT for the total repetition condition, when both the stimulus and the response are repeated, should show a distinct benefit. The partial repetition condition, on the other hand, when either the stimulus or the response, but not both, are repeated, would show no benefit, *at best*, and possibly a cost. Our results, in which we obtain clear benefits from stimulus repetitions and response repetitions, each in the absence of the other, are clearly inconsistent with these predictions.

The results of the interaction between mapping and repetition are qualitatively similar to the results obtained in Experiment 1. That is, the probe which was a Type 2 task, unsurprisingly, behaved like a Type 2 task: there was a very large mapping effect (365 ms), and the repetition effect was much smaller for the congruent (25 ms) than for the incongruent (96 ms) mapping conditions.

There are, of course, differences between the two experiments as well. First, note that the overall RT in this experiment is marginally longer than in Experiment 1 $[F(1, 40) = 3.38, p < 0.0735]$. (Even though this difference appears to interact with mapping, this between-subjects difference is not statistically significant $[F(1, 40) = 0.16, p < 0.6899]$.) Recall that in the present experiment the Type 2 probes were preceded by Type 1 primes. In the previous experiment these Type 2 probes were preceded by primes that were Type 2 as well and also used the same stimulus and response sets. In this experiment the RT for congruent mapping was 79 ms slower than in the different carrier condition of Experiment 1, and the overall RT for incongruent mapping was 149 ms. slower than in Experiment 1. We suggest that these differences are attributable to task switching. Let us anticipate the results of the second half of this experiment in which the *primes* were congruent/incongruent Type 2 tasks, and the probes were Type 1. There we find a similar effect, with the primes and probes reversed: the cost of switching from a congruent prime to a neutral probe is much less than the cost of switching from an incongruent prime to the same neutral probe. So, whether one switches to or from a trial with congruent mapping, RT appears to be faster than when one is switching to or from a trial with incongruent mapping.
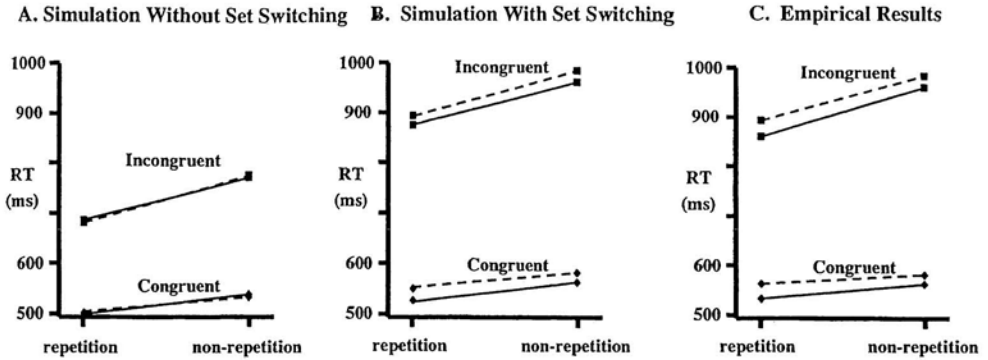
A. Simulation Without Set Switching   B. Simulation With Set Switching   C. Empirical Results

Fig. 2.15 Simulation of the results of Experiment 2 with Type 2 probes. *Panel A* shows the simulated results when the effects of stimulus and response set switching is not taken into account. *Panel B* shows the simulated results when a constant is added for set switching: 60 ms and 80 ms have been added for the stimulus and response set switches, respectively, for the congruent conditions; 165 and 200 ms have been added for the stimulus and response set switches, respectively for the incongruent conditions. Panel C shows the empirical results on the same scale (these are the same data as are shown on Fig. 2.14). The dotted lines are the data for the stimulus repetitions and non-repetitions, when the response set was switched; the solid lines are the data for the response repetitions and non-repetitions, when the stimulus set was switched.

Another result that we believe is due to switching is the finding that switching from one response set to another generated a longer RT than switching from one stimulus set to another.

One final observation worth noting is that Rogers and Monsell (1995) reported that in their study the response repetition effect vanishes following a task switch. We, on the other hand, obtained a robust response repetition effect in Type 2 probe trials following a Type 1 prime. As we indicated in the introduction to these experiments we have not tried to make our model account for either this or any other effects of switching.

We would, of course, have liked to use the same parameter values for the simulation of these results as we used to fit the data of the previous experiment. However, because of the effects of task and set switching, and their interactions, we were unable to do that. Nevertheless, the new simulations capture the repetition effects quite nicely as is evident by comparing the slopes of the empirical data in Panel C (Fig. 2.15) with the slopes of the simulated data in Panel A (Fig. 2.15). If we now treat the vertical displacements as due to task and set switching, and add these as arbitrary constants (Panel B, Fig. 2.15), which we confess is far from theoretically satisfying, then the overall fit is quite good.

2.6.3 Type 2→Type 1

2.6.3.1 Results
Next we turn to the results of the Type 1 probes preceded by Type 2 primes (see Fig. 2.14, right panel).

1. One of the most striking aspects of these data is the large and reliable effect that mapping of the preceding prime had on these neutral probes. This is a result that we have already alluded to: when

the mapping for the *prime* was congruent, the RT for the probe was 92 ms faster than when the mapping was incongruent [$F(1, 30) = 4.19, p < 0.0494$].

2. Also, the time to switch between response sets was 100 ms longer than the time to switch between stimulus sets [$F(1, 30) = 40.20, p < 0.0001$]. This, of course, was much larger than the set switching effect that we had seen with Type 2 probes, and was observed with incongruent primes only [$F(1, 23) = 43.18, p < 0.0001$]; when the prime was congruent, set switching failed to have a significant effect [$F(1, 23) = 0.01, p < 0.9228$].

3. Finally we note that in Experiment 1, when Type 1 probes are preceded by the same type primes, so that there was no task switching, the overall RT is much faster than in this experiment— as expected.

Now we come to the repetition effects. When the prime was congruent, the repetition effect was 54 ms [$F(1, 7) = 43.6, p < 0.0003$]; when the prime was incongruent it was 31 ms [$F(1, 23) = 10.31, p < 0.0039$]. The difference between these two repetition effects is not significant [Rep × Cong interaction: $F(1, 30) = 1.72, p < 0.1999$]. Thus, even though the congruence and incongruence of the Type 2 primes seem to have influenced the overall RT of the Type 1 probe, they did not have a differential influence on the repetition effect.

Because these effects all appear to be due to switching of one kind or another we shall have nothing further to say about them from the point of view of the DO model, and we leave them with the reader to ponder as empirical results that pose theoretical puzzles.

2.7 Irrelevant stimuli and sequential effects

In this next section we shall look at the results of some experiments in which the prime and probe trials have irrelevant stimuli that either do or do not overlap with some other aspect of the task. These are either neutral Type 1 tasks in which there is no DO, Type 3, or Simon tasks, in which the irrelevant stimulus dimension overlaps with the response, or Type 4, Stroop-like tasks, in which the irrelevant stimulus dimension overlaps with the relevant stimulus dimension. All these experiments used the same procedures; we will, therefore, describe them just once at the start. As was true of all the experiments up to now, the experimental unit consisted of trial pairs: a prime and a probe trial.

2.7.1 General procedures

2.7.1.1 Stimuli and responses
In all cases the relevant stimuli were the letters B, J, Q, Z. The responses consisted of joystick movements up, down, left or right. The S–R mapping was arbitrary. The irrelevant stimuli were presented as flankers to the left and right of the relevant letters, and differed depending on the task type. There were four possible irrelevant stimuli for each task type, which generated 16 different stimuli of each type: For the Type 1 tasks, the irrelevant stimuli were diacritical marks and a plus sign (#, %, &, +); for the Type 3 tasks, the irrelevant stimuli were up, down, left, and right arrows; and for the Type 4 tasks, the irrelevant stimuli were the letters B, J, Q, Z.

2.7.1.2 Experimental factors and design
Given the task type (Type 1, 3, or 4) for the prime and probe, the factors of interest were:

1. the consistency of the prime and probe;
2. the repetition/non-repetition of this consistency state;
3. the repetition/non-repetition of the relevant and/or irrelevant stimulus;
4. RSI.

Because in two-choice tasks some of these factors are confounded with each other as well as with negative priming, we used four-choice tasks and constructed a transition matrix (see Fig. 2.16) in which the first three factors were explicitly represented. This matrix, which revealed a surprising number of constraints, makes the confounding that necessarily occurs in two-choice tasks very clear. For example, whether the relevant stimulus in a two-choice task repeats or not, the repetition/non-repetition of the irrelevant stimulus is confounded with the repetition/non-repetition of consistency and negative priming preconditions. This matrix was the starting point for the design of all our experiments.

2.8 Experiment 3

In this first experiment we were interested in examining the question of whether the consistency or inconsistency effects of probe trials was affected by the consistency or inconsistency of primes. According to the DO model there is no reason why such contingencies should occur. However, such effects have been reported in the literature for Type 3 tasks, so we wanted to verify these reports before proceeding (e.g. Mordkoff 1998).

2.8.1 Design

We used Type 3 and Type 4 tasks, presented in different experimental blocks. Each block also contained a Type 1 task. The prime in a Type 3 block was, therefore, S–R consistent, inconsistent, or neutral. The prime in a Type 4 block was S–S consistent, inconsistent, or neutral. The probe, similarly, was either consistent, inconsistent, or neutral. Each block, therefore, contained nine different prime-to-probe transitions, whether it was a Type 3 or a Type 4 block (see Fig. 2.17). From the master transition matrix (see Fig. 2.16) it was also evident that in order for these nine conditions to be comparable and not be confounded with other variables, neither the relevant nor the irrelevant stimuli of the prime could be repeated in the probe.

Each block included four randomized instances of each of the nine prime-to-probe transitions; there were two blocks per task type and RSI (700 and 1500 ms). Twelve subjects participated in the experiment. Four different mappings were used for each task type, and mapping was as between subjects variable.

2.8.2 Results

We start with the results of the Type 3 task (see Fig. 2.18). When both the prime and the probe are Type 3 tasks, there is a highly significant S–R consistency effect of 80 ms that is totally immune to differences in the consistency of the prime [consistent prime, 87 ms; inconsistent prime, 73 ms; the prime × probe interaction is not significant: $F(1, 8) = 0.25$, $p < 0.6275$]. However, when the prime is neutral, the consistency effect of the probe jumps to 140 ms. This 75% increase is achieved by having both a faster RT for consistent probes, and a slower RT for inconsistent probes. When the probe is

Transitions in four-choice tasks:
Type 3 or 4 with neutrals (Type 1)

Fig. 2.16 Generic prime-to-probe transition matrix for four-choice tasks with irrelevant stimuli. The capital letters A, B, C, and D designate either relevant stimuli or responses, depending on the task being represented; for Types 1 and 4, they represent relevant stimuli, for Type 3 they represent responses. This generated sixteen large square areas representing all the transitions between the four capital letters (relevant stimuli for Types 1 and 4, or responses for Type 3). The lower-case letters a, b, c, d designate irrelevant stimuli that overlap either with the relevant stimuli (Type 4) or with the responses (Type 3). The lower-case letters w, x, y, z designate irrelevant stimuli that have no DO with any aspect of the task (Type 1). Each of these large square areas is thus subdivided into four quadrants that represent the two-by-two combination of overlapping (DO) and non-overlapping (N) prime–probe pairs: DO→DO; DO→N; N→N; and N→DO. Inside these four quadrants are sixteen individual cells identified by the letters c and i, as well as by dashes; they have the following meaning: 'c' stands for a consistent trial, 'i' for an inconsistent trial, and '-' for a neutral trial. These letters and dashes appear in pairs, where the first position in the pair denotes the nature of the prime

neutral, the RT falls between the RTs for consistent and inconsistent probes and is completely unaffected by the prime [$F(1, 8) = 0.07, p < 0.8008$].

We turn next to the results of the Type 4 task (see Fig. 2.18). When both the prime and the probe are Type 4 tasks, there is a highly reliable S–S consistency effect of 62 ms [$F(1, 8) = 6.70$, $p < 0.0322$] which is not significantly altered by neutral primes (59 ms) [$F(1, 8) = 0.44, p < 0.5260$]. (There also appears to be a 31 ms interaction between prime and probe consistency which, however, is not significant [$F(1,8) = 0.82, p < 0.3907$] and appears to be due entirely to the effects of the prime on inconsistent probes: the RTs for consistent probes all fall within a range of 11 ms for the various primes that they are paired with. The RTs for inconsistent probes span a range of 47 ms.)

To summarize. First, just as there are clear differences in performance between Type 3 and Type 4 tasks in terms of overall mean RTs, we again see differences in performance between these task types when merely considering the sequence of consistent inconsistent trials. Second, the results for Type 3 tasks are clear and systematic: the consistency or inconsistency of the prime has no effect whatsoever on the size of the consistency effect of the probe. However, whether or not the prime has DO has an enormous influence on the size of the S–R consistency effect: a neutral prime almost doubles the size of that effect. The results with the Type 3 task are inconsistent with Mordkoff's (1998) earlier reports. However, as we have indicated, these reports, which are based on two-choice data, may have included confoundings between the repetition effects of relevant and irrelevant stimuli with other factors in the experiment. The results with Type 4 tasks are not as clean and, obviously, need further work.

2.9 Experiment 4

In this next experiment we examine the basic repetition effects of relevant and irrelevant stimuli in four-choice tasks of Types 1, 3, and 4.

trial and the second position the nature of the probe. Thus, for example, a 'cc' in a cell identifies this cell as the transition between a consistent prime and a consistent probe; a 'ci' cell would be the transition between a consistent prime and an inconsistent probe; 'i-' would be the transition between an inconsistent prime and a neutral probe, etc. We now come to the repetition/non-repetition properties of the prime–probe pairs in this matrix. The only repetitions of relevant stimuli or response occur in the four large square areas on the main diagonal. The remaining twelve large, off-diagonal, square areas represent non-repetitions of relevant stimuli or responses. The cells on the main diagonal of these sixteen large square areas all represent repetitions of the irrelevant stimuli; the off-diagonal cells are all non-repetitions of the irrelevant stimuli. This matrix makes it relatively easy to identify some transitions with special properties that may be interesting. For example, consider the large A × A square area. The first column represents transitions in which the irrelevant stimulus on the probe trial is the same as either the relevant stimulus, or the response on the prime. The first row represents transitions in which the irrelevant stimulus on the prime becomes the relevant stimulus, or the response on the probe. Each of the sixteen large square areas has one row and one column with these same properties. Other interesting transitions may be those in which the relevant and irrelevant stimuli on the prime are switched on the probe; by definition, of course, these can only occur in the large, off-diagonal squares.
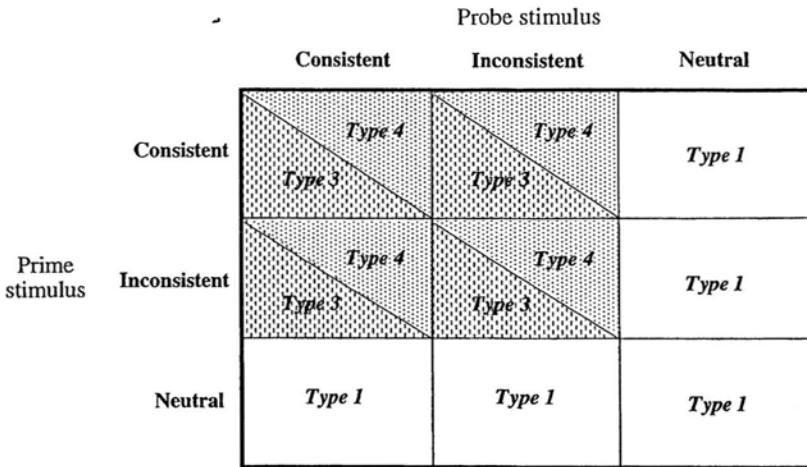
Fig. 2.17 Basic design for Experiment 3 showing the nine different prime-to-probe transitions in a block. Task types were blocked so that some experimental blocks had task Types 3 and 1, and other blocks had task Types 4 and 1.
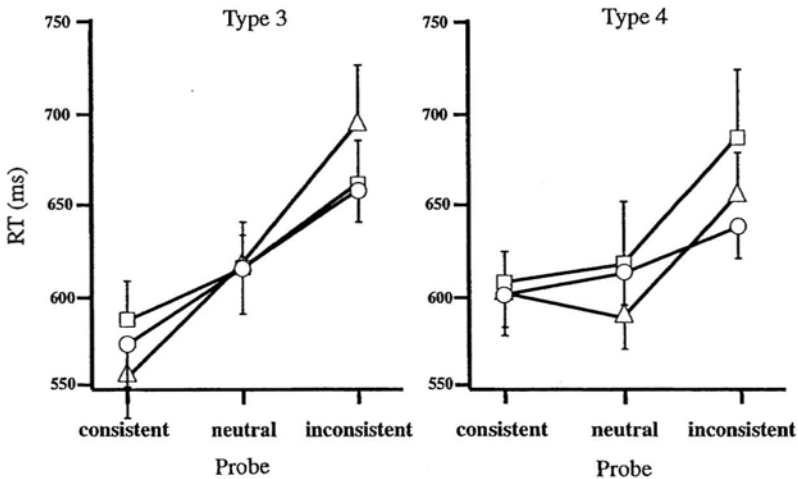
Fig. 2.18 Results of Experiment 3 for Type 3 and Type 4 blocks; each of these blocks included Type 1 neutral trials. On the abscissa are the three values of the probe: consistent, inconsistent and neutral. The parameters for the data lines are the nature of the prime: circles (o) indicate consistent primes; squares (□) indicate inconsistent primes; triangles (△) indicate neutral primes.

2.9.1 Methods and procedures

The relevant stimuli were the four letters and the responses were the up, down, left, and right movements of a joystick. The irrelevant stimuli differed depending on the type of task: for the Type 1 task,

they were diacritical marks, for the Type 2 task they were directional arrows, and for the Type 4 task they were letters (see the general description of the stimuli and responses at the beginning of this section).

The Type 1 task was run on one group of 12 subjects, the Type 3 and 4 tasks were run on another group of 12 subjects in a balanced order. For each task type there were four different mappings, each assigned to a different group of subjects.

We used a simple 2×2 design: the repetitions and non-repetitions of the relevant stimuli were crossed with the repetitions and non-repetitions of the irrelevant stimuli. In order to obtain this factorial combination in the Types 3 and 4 tasks, both the prime and the probe trials in each pair had to be inconsistent; in the Type 1 task, of course, this issue was moot (see Fig. 2.16).

There were two experimental blocks for each task type and RSI value (700 ms and 1500 ms). Each block contained eight randomized presentations of the four repetition/non-repetitions prime-to-probe transitions for a total of 32 pairs.

2.9.2 Results

The results of the Type 1 task are illustrated in Fig. 2.19. There was a highly significant repetition effect of 90 ms $[F(1, 8) = 38.26, p < 0.0003]$ for the relevant stimulus which, of course, includes repetition of the response. This is almost indistinguishable from the repetition effect that we observed with Type 1 tasks in Experiment 1 (100 ms), where we used very different stimuli and responses, and where the overall RT was also more than 120 ms longer than in this experiment. The repetition of the irrelevant stimulus had no significant effect $[F(1, 8) = 0.01, p < 0.9393]$, and there was no significant interaction $[F(1, 8) = 0.01, p < 0.9393]$. The repetition of irrelevant stimuli in Type 1 neutral tasks, therefore, has no effect on performance.

In the Type 3 task repeating the relevant stimulus had a significant 116 ms effect $[F(1, 8) = 69.34, p < 0.0001]$, whereas the repetition of the irrelevant stimulus had no significant effect $[F(1, 8) = 0.09, p < 0.7753]$, and there was no interaction. (Even though the repetition effect for the relevant stimulus is 22 ms greater when the irrelevant stimulus does not repeat than when it repeats, this interaction is not significant $[F(1, 8) = 0.89, p < 0.3740]$.) Thus, as was true for the Type 1, neutral, task, repeating or not repeating the irrelevant stimulus has no effect on performance in Type 3 tasks.

In the Type 4 task, repeating the relevant stimulus had a significant effect of 110 ms $[F(1, 8) = 95.87, p < 0.0001]$. And, unlike the results obtained with the Types 1 and 3 tasks, there is a 26 ms repetition effect for the irrelevant stimulus $[F(1, 8) = 17.47, p < 0.0031]$. There was no significant interaction between the repetitions of the relevant and irrelevant stimulus.

2.9.3 Discussion

These results are inconsistent with Hommel's event file view (Hommel 1998; Hommel *et al.* in press) in at least three different ways: first, according to that view, if the relevant stimulus repeats then repeating the irrelevant stimulus should show a benefit compared to the non-repetition of that irrelevant stimulus. We fail to confirm this in both Type 1 and Type 3 tasks. Second, the event file view predicts an interaction between the repetition of relevant and irrelevant stimuli. The results of our Type 4 task fail to confirm this. Third, according to our reading, Hommel's event file position would make identical predictions for Type 1, Type 3, and Type 4 tasks. Our results show that performance on these three tasks is quite different and appears to be based on the patterns of dimensional overlap.
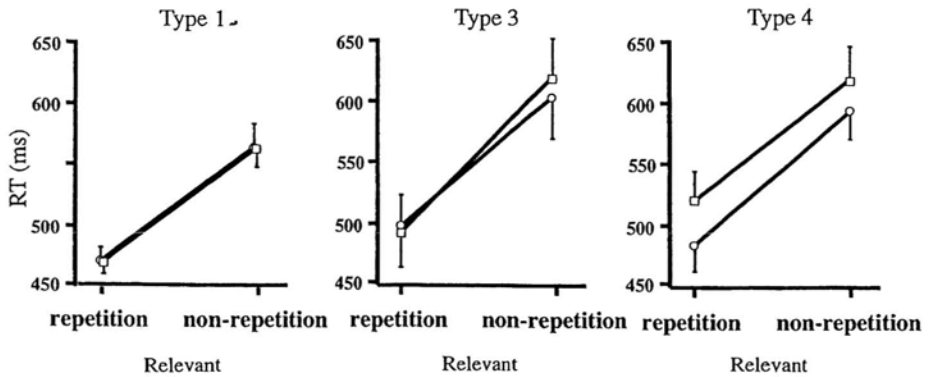
Fig. 2.19 Results of Experiment 4 for task Types 1, 3, and 4. On the abscissa is indicated whether the relevant stimulus repeats or not. The parameter for the data line is whether the irrelevant stimulus repeats or not: the circle indicates a repetition, the square a non-repetition.

These results are consistent with one of the DO model's principal assertions, namely: whether and how irrelevant stimuli affect performance, depends on what they overlap with. In this case we see that the repetition of irrelevant stimuli in Type 3 and Type 4 tasks clearly affects performance in very different ways—ways that, as we will now show, the model is able to account for.

2.9.3.1 The Information Reduction Hypothesis for irrelevant stimuli

Let us first consider the finding that the overall RT for Type 1 is faster than for Types 3 and 4. Recall that in this experiment, in order to avoid the confounding between factors, the Type 3 and Type 4 trials were all inconsistent; the Type 1 trials, in contrast, were all neutral . The RTs for S–R (Type 3) and S–S (Type 4) inconsistent trials are known to be slower than for neutral trials. The DO model's account for these consistency effects was summarized in Sections 2.2.2.1 and 2.2.2.2 at the beginning of this chapter.

Now consider the effects of repetitions for the relevant and irrelevant stimuli. Recall that the basic way in which the model accounts for the effects of relevant stimulus, and response repetitions is by lowering the threshold in the stimulus and response units when stimuli or responses are repeated (see Fig. 2.8). That is, less information is required to reach threshold after a repetition than after a non-repetition. We suggest that the Information Reduction Hypothesis is equally applicable to the effects of irrelevant stimulus repetitions: whatever the process that distinguishes between relevant and irrelevant stimuli (see Fig. 2.4), that process requires less information when irrelevant stimuli are repeated than when they are not repeated.

This proposition is easily implemented in the model: if less information is required, it is reasonable to assume that less time would be required to process that reduced amount of information. Following a repetition, therefore, we shorten the time parameter (τ) (see Kornblum et al. 1999) which, in the model, determines how long it takes to distinguish between relevant and irrelevant inputs (see Fig. 2.4). The effect of this time reduction on the irrelevant stimulus activation curve is to reduce the
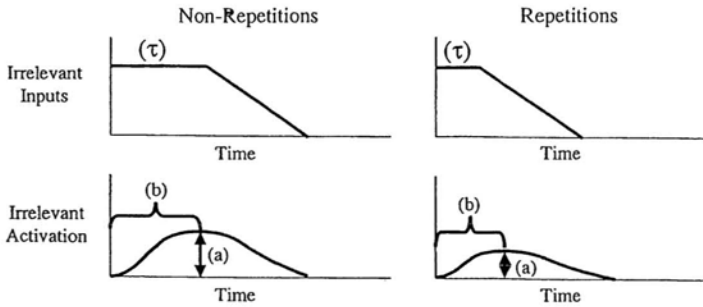
Fig. 2.20 Illustration of the Information Reduction Hypothesis for irrelevant stimuli. According to the hypothesis, when an irrelevant stimulus is repeated less information is needed to distinguish between the inputs of the relevant and the irrelevant stimuli. This translates into less time (τ) being required to make that distinction, which means that the input for the irrelevant stimulus (see also Fig. 2.4) will start decreasing sooner after a repetition than after a non-repetition. This means that the peak of the irrelevant stimulus activation curve will be shallower (a) and occur earlier (b) for repetitions (right) than for non-repetitions (left).
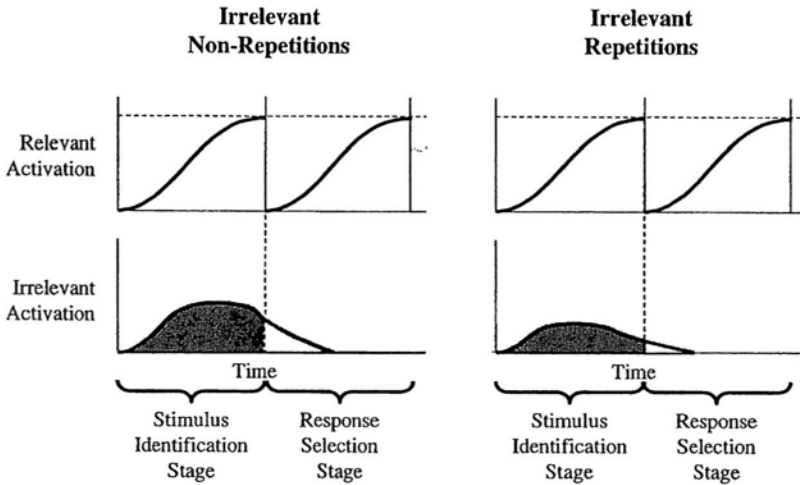
Fig. 2.21 Illustration of how the magnitude of the repetition effect for irrelevant stimuli depends on what the irrelevant stimuli overlap with, and whether the bulk of the irrelevant stimulus activation curve is in the stimulus identification or the response selection stage. As illustrated, the bulk of the irrelevant stimulus activation curve is in the stimulus identification stage. Note that when the irrelevant stimulus repeats, that curve is shallower and peaks earlier than when it does not repeat, which reiterates what was shown on Fig. 2.20. The shaded and unshaded portions of the irrelevant activation curves show the amount of irrelevant activation in the stimulus and response stages, respectively. The fact that the difference between the two shaded portions of the curves (in the stimulus stage) is greater than between the two unshaded portions of the curves (in the response stage) generates the greater repetition effect of irrelevant stimuli for Types 4 (with S–S overlap) than for Types 3 (with S–R overlap), according to the Information Reduction Hypothesis.
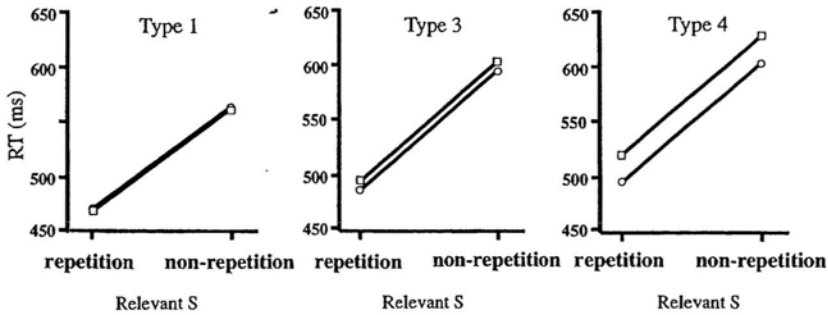
Fig. 2.22 Simulation of the results for Experiment 4. See Fig. 2.19 for the empirical results.

level to which the irrelevant stimulus activation curve rises following a repetition, and to move its peak earlier in time (see Fig. 2.20).

Because the overall irrelevant stimulus activation is now less for repetitions (see the bottom right panels in Fig. 2.20) than for non-repetitions (see the bottom left panel in Fig. 2.20), the influence of the irrelevant stimuli on performance will necessarily be less for repetitions than for non-repetitions. However, the magnitude of this effect depends on whether the irrelevant stimulus activation curve affects stimulus processing, as in the Type 4 tasks, or response processing, as in the Type 3 tasks.

For example, suppose that most of the irrelevant stimulus activation curve lies in the stimulus identification stage (see shaded areas of the curve in Fig. 2.21). This would produce a relatively large irrelevant stimulus repetition effect (e.g. Type 4) because the difference between the shaded areas for repetitions and non-repetitions is large. In the meantime, the amount of activation in the response stage (the unshaded areas of the curve in Fig. 2.21) is very small whether it is repetition or a non-repetition. As a result, there will be a very small, and perhaps undetectable, effect of irrelevant stimulus repetition in the Type 3 condition.

Figure 2.22 shows the actual simulation of the data, illustrating numerically how these principles generate the reaction time for Experiment 4. The correspondence with the empirical data (Fig. 2.19) is quite good.

2.10 Summary and conclusions

We began this chapter by outlining the representational and functional principles of the DO model, spelled out how these principles generated a taxonomy of tasks, selected four tasks from this taxonomy, and showed how, based on these principles, the structure of these tasks could be represented by a common processing architecture, and performance with them accounted for by the model. One of the effects of S–R compatibility that we had not considered in our model up to this point, however, was its interaction with the repetition effect (Bertelson 1963). These effects are ubiquitous and have a pervasive influence on RT.

If the DO model is to be considered as having contributed to our understanding of performance in S–R compatibility tasks, then we needed to find out whether, and, if so, how the model handled sequential effects. If it had turned out that these effects were beyond the model's ability to deal with,

then, as Luce pointed out, the model would have been incomplete (at best) and probably wrong to boot (see Luce 1986).

We reported the results of four experiments. In the first two experiments we examined the sequential effects of relevant dimensions, congruent and incongruent mapping, and the repetition of physically identical, as well as conceptually similar, but physically different, stimuli in task Types 1 and 2. In the third experiment we looked at sequential effects of consistency (consistent, inconsistent, and neutral) in task Types 1, 3, and 4. In the fourth experiment we examined the sequential effects of relevant and irrelevant stimuli in task Types 1, 3, and 4.

In the first experiment we found a large repetition effect that interacted with congruent/incongruent mapping as well as with the repetition/non-repetition of conceptually similar stimuli. That is, the overall RT was longer and the repetition effect larger for incongruent than for congruent mapping. In addition, the mapping effect for repetitions was larger with conceptually similar (different carrier) than with physically identical (same carrier) stimuli

In the second experiment, which was aimed at identifying the locus of the repetition effect, we again found an interaction between the repetition effect and congruent/incongruent mapping. This interaction was present whether the stimulus or the response was repeated, each in the absence of the other, which placed the locus of the repetition effect in both the stimulus and the response processing modules. This finding contrasts with earlier reports (e.g. Bertelson 1965; Pashler and Bayliss 1991) that attributed the bulk of the repetition effect to the repetition of the response. These results were accounted for by the DO model's newly formulated Information Reduction Hypothesis, which states: information requirements on repeated trials are less than on non-repeated trials. According to this hypothesis, when a relevant stimulus or a response is repeated, the stimulus or response threshold on the repeated trial drops so that both the information and the time required to reach this lower threshold are reduced—hence the repetition effect.

The results of Experiment 3 showed the expected differences in the effects of irrelevant stimuli for task Types 1, 3, and 4, none for Type 1, and robust consistency effects for Types 3 and 4. However, there was no significant sequential effect of consistency for either Type 3 or Type 4 prime–probe pairs. The only sequential effect of consistency was the finding that the size of the S–R consistency effect in the Type 3 tasks was greater when the prime was neutral than when it was another Type 3 task.

In Experiment 4, we obtained significant repetition effects of the relevant stimulus, and response, in task Types 1, 3, and 4. Repetition of the irrelevant stimulus produced no significant effects for task Types 1 and 3; however, that effect was significant for task Type 4. These results were also accounted for by the Information Reduction Hypothesis. According to the hypothesis, when an irrelevant stimulus is repeated the information, and hence the time, required to distinguish between the relevant and irrelevant stimuli are both reduced. This was implemented in the model by reducing the value of the parameter (τ) following a repetition. Because a shorter value of (τ) causes the irrelevant stimulus input to start falling sooner than it otherwise would, the resulting irrelevant stimulus activation curve, following a repetition, has a shallower peak and is also shifted earlier in time so that a proportionately greater portion of the curve coincides in time with the stimulus module. The net result is for the repetition of an irrelevant stimulus that overlaps with the relevant stimulus (Type 4) to have a greater effect than the repetition of an irrelevant stimulus that overlaps with the response Type 3).

Thus, the underlying reasoning for the repetition effects of relevant stimuli, irrelevant stimuli, and responses is the same: repetition leads to reduced information requirements which, in turn, leads to

faster processing. Depending on whether the relevant or irrelevant stimuli have DO, the repetition effect is accounted for by modifying one or the other of two parameters in the DO model, contingent on the occurrence of a repetition, thus leaving the basic mechanisms of the model intact.

Acknowledgements

Notes

1. It is interesting to note that theories that deal with fundamental (i.e. irreducible) concepts (e.g. gravity) express the lawful relationships between the entities identified (and defined) in the representational part of the theory. Such theories have no processing component because, in principle, these relationships are irreducible. Ecological theories, and so-called dynamic theories in psychology, often take this approach—prematurely and erroneously, in our opinion. Boyle's law illustrates this point well. When it was first formulated it expressed the systematic relationship between the pressure, volume, and temperature of an enclosed gas and was thought to be fundamental. It was not until Dalton's atomic theory that a mechanism was discovered that could give rise to this relationship. This mechanism became the functional part of Boyle's model.

2. We have included the Type 8, or Stroop, task in this table because of the broad interest that people have in it and also to show how, in accordance with DO principles, it could be parsed into separate components. In the rest of the article, however, we shall have nothing further to say about this task.

3. This time plays an important role later on in this paper in enabling the model to account for the sequential effects of irrelevant stimuli.

4. Thorough reviews of this literature exist that interested readers may wish to consult (Audley 1973; Kirby 1980; Kornblum 1973; Luce 1986).

5. Within the framework of the DO model there is no way to literally implement the version of the Residual Activation Hypothesis in which a process is bypassed without doing violence to the model itself and radically altering its structure. However, the duration of any process in the DO model could, in principle, be made arbitrarily small.

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Appendix A

Experiment 1

	Same carrier		Different carrier	
	Rep	*Non-Rep*	*Rep*	*Non-Rep*
Congruent	0.0	0.7	0.7	1.4
Neutral	2.1	1.9	0.7	3.2
Incongruent	0.0	3.7	1.4	4.9

Experiment 2

		Type 2 probe		Type 1 probe	
		Rep	*Non-Rep*	*Rep*	*Non-Rep*
Cong	Stim. Rep/Non-Rep	1.0	1.0	4.2	2.1
	Resp. Rep/Non-Rep	0.0	1.0	0.0	3.1
Incong	Stim. Rep/Non-Rep	0.4	1.1	3.5	1.7
	Resp. Rep/Non-Rep	3.2	2.5	2.5	2.5

Experiment 3

Prime	Probe					
	Type 3			Type 4		
	Consist	*Neut*	*Inconsist*	*Consist*	*Neut*	*Inconsist*
Consistent	4.2	2.1	0.0	4.2	1.0	2.1
Neutral	2.1	2.1	0.0	0.0	2.1	3.1
Inconsistent	2.1	1.0	0.0	3.1	0.0	4.2

Experiment 4

Irrel S	Rel S					
	Type 1		Type 3		Type 4	
	Rep	*Non-Rep*	*Rep*	*Non-Rep*	*Rep*	*Non-Rep*
Rep	0.0	3.1	0.5	2.6	1.0	3.1
Non-Rep	1.6	3.1	1.0	1.6	0.5	1.6

Error rates at the 700 ms RSI for the four experiments reported.

Appendix B

Experiment 1
Type 2 → Type 2; Congruent

	Prime	Probe	RSI			
			700	1500	3000	
Same	red → 'red'	red → 'red'	463 (27)	460 (24)	473 (17)	Rep
carrier	blue → 'blue'	red → 'red'	484 (28)	488 (30)	490 (25)	Non-Rep
Different	RED → 'red'	red → 'red'	489 (29)	494 (31)	494 (19)	Rep
carrier	BLUE → 'blue'	red → 'red'	490 (27)	495 (24)	492 (25)	Non-Rep

Type 2→Type 2; Incongruent

	Prime	Probe	RSI			
			700	1500	3000	
Same	red → 'green'	red → 'green'	618 (42)	629 (86)	730 (68)	Rep
carrier	blue → 'yellow'	red → 'green'	853 (125)	849 (157)	872 (112)	Non-Rep
	green → 'blue'	red → 'green'	890 (145)	905 (199)	912 (123)	NR (S→R)
	blue → 'yellow'	yellow → 'red'	871 (81)	863 (168)	895 (122)	NR (R→S)
Different	RED → 'green'	red → 'green'	753 (45)	738 (61)	798 (85)	Rep
carrier	BLUE → 'yellow'	red → 'green'	885 (98)	842 (157)	875 (120)	Non-Rep
	GREEN → 'blue'	red → 'green'	933 (154)	935 (236)	901 (112)	NR (S→R)
	BLUE → 'yellow'	yellow → 'red'	915 (122)	915 (193)	908 (122)	NR (R→S)

Type 1→Type 1

	Prime	Probe	RSI			
			700	1500	3000	
Same	red → 'two'	red → 'two'	582 (37)	593 (54)	623 (50)	Rep
carrier	blue → 'four'	red → 'two'	682 (38)	695 (62)	691 (43)	Non-Rep
Different	RED → 'two'	red → 'two'	635 (62)	650 (76)	677 (52)	Rep
carrier	BLUE → 'four'	red → 'two'	690 (44)	711 (65)	700 (42)	Non-Rep

Mean RTs (and standard deviations) for Experiment 1 at three values of RSI. Because all possible prime–probe pairs were randomized and equiprobable, and the interval between prime–probe pairs was three seconds, RTs for RSI values of three seconds were obtained by considering the probes of regular prime–probe pairs as primes, and the primes of the next regular pair as probes of new pairs.

Even though the RTs for the 700 ms RSI are discussed in detail in the text, we have included them in this table for ease of comparison. The stimuli and responses for the primes and probes are prototypical, generic descriptions. Thus, for example, the probe stimuli in this table are all shown as color

patches; however, we know (see text) that the probe stimuli were either color patches or color words. This generic description is intended to encompass both cases, and the data shown are averaged over both cases.

Note also that we distinguish between three cases of non-repetitions. The first is the case of pure, or total, non-repetitions in which no aspect of the prime is repeated in the probe. When we speak of 'non-repetitions' in the text, these are the trials to which we refer. The second is the case in which the label of, or the congruent responses to, the stimulus on the prime becomes the response on the probe (S → R). We view these as negative priming (NP) trials (see Shiu and Kornblum 1996). At RSI of 700 ms, the RT for this case is significantly longer than for the total non-repetitions [$F(1, 5) = 10.85$, $p < 0.0216$], which confirms Shiu and Kornblum's (1996) earlier findings. The third is the case in which the response on the prime trial becomes the label of the probe stimulus (R → S). Even though the RT for this case is also longer than for the total non-repetitions (but shorter than on NP trials) this difference is not statistically significant [$F(1, 5) = 2.12$, $p < 0.2051$].

The statistical results of RSI for this experiment are summarized below:

Type 1 tasks

- Main effect: the longer the RSI, the slower the RT [$F(2, 6) = 7.61$, $p < 0.0226$)];
- Interesting to note that as RSI increases the repetition effect decreases. This effect is not statistically significant. Nevertheless, the fact that this appears to be due principally to the fact that as RSI increases the RT for repetitions increases more than for non-repetitions is consistent with the Information Reduction Hypothesis: as RSI increases the threshold goes back to normal thus reducing the advantage of the reps.

Type 2 tasks

- RSI has no significant main effect with Type 2 tasks, either congruent or incongruent;
- RSI has an 8 ms interaction with carrier for congruent mapping, which is significant [$F(2, 10) = 8.01$, $p < 0.0084$].

Appendix C

Experiment 2
Type 1 → Type 2; Congruent

Prime	Probe	RSI			
		700	*1500*	*3000*	
red → 'two'	2 → 'two'	533 (53)	555 (85)	547 (51)	Resp Rep
red → 'two'	4 → four'	565 (58)	566 (64)	562 (53)	Resp Non-Rep
red → 'two'	red → 'red'	565 (71)	568 (80)	550 (55)	Stim Rep
red → 'two'	blue → 'blue'	583 (71)	580 (73)	564 (70)	Stim Non-Rep

Appendix C Continued

Type 1→Type 2; Incongruent

Prime	Probe	RSI			
		700	1500	3000	
red → 'two'	4 → 'two'	861 (132)	902 (162)	949 (190)	Resp Rep
red → 'two'	6 → 'eight'	962 (173)	954 (178)	974 (187)	Resp Non-Rep
red → 'two'	2 → 'six'	920 (169)	912 (182)	986 (209)	Non-Rep (R→S)
red → 'two'	red → 'green'	895 (148)	916 (179)	968 (194)	Stim Rep
red → 'two'	blue → 'yellow'	986 (186)	988 (212)	990 (205)	Stim Non-Rep
red → 'two'	yellow → 'red'	964 (183)	980 (216)	1049 (224)	Non-Rep (S→R)

Type 2→Type 1; Congruent

Prime	Probe	RSI			
		700	1500	3000	
red → 'red'	2 → 'red'	793 (110)	835 (156)	830 (132)	Resp Rep
red → 'red'	4 → 'blue'	860 (114)	907 (187)	862 (150)	Resp Non-Rep
red → 'red'	red → 'two'	808 (126)	823 (104)	853 (168)	Stim Rep
red → 'red'	blue → 'four'	847 (96)	862 (133)	864 (149)	Stim Non-Rep

Type 2→Type 1; Incongruent

Prime	Probe	RSI			
		700	1500	3000	
red → 'green'	8 → 'green'	844 (112)	845 (115)	892 (110)	Resp Rep
red → 'green'	4 → 'blue'	894 (121)	882 (111)	897 (110)	Resp Non-Rep
red → 'green''	2 → 'red'	872 (119)	894 (139)	900 (127)	Non-Rep (S→R)
red → 'green'	red → 'two'	963 (128)	971 (153)	1039 (144)	Stim Rep
red → 'green'	blue → 'four''	974 (126)	966 (120)	1036 (149)	Stim Non-Rep
red → 'green'	green → 'six'	931 (133)	951 (163)	1018 (147)	Non-Rep (R→S)

Mean RTs (and standard deviations) for Experiment 2 at three values of RSI. As was true of Appendix B, the stimuli and responses for the primes and probes are prototypical cases, or generic descriptions. Thus, for example, the prime stimuli in this table are all shown as red color patches; however, as is made clear in the text, not only were there four different color patches, but the stimuli on prime trials could also be digits. The generic descriptions in this table are, therefore, intended to encompass both cases, and the data shown are averaged over both cases.

Again, similarly to what we did in Appendix B, when the mapping is incongruent we distinguish between three different cases of non-repetitions: total non-repetitions; non-repetitions in which the label of, or the congruent response to, the prime stimulus becomes the response on the probe; and non-repetitions in which the response on the prime becomes the label on the probe. In contrast to the

results of Experiment 1, none of the differences between the total non-repetitions and the other non-repetition case within a particular incongruent condition are significant.

The statistical results of RSI for this experiment are summarized below:

- Main effect: The longer the RSI the slower the RT [$F(2, 62) = 6.24$, $p < 0.0034$].

Type 1→Type 2

- The increase of RT with RSI was greater for repetitions than for non-repetitions: this interaction is significant for stimulus rep/non-rep [$F(2, 46) = 4.24$, $p < 0.0204$], and response rep/non-rep [$F(2, 46) = 6.8$, $p < 0.0026$].

Type 2→Type 1

- RSI interacted with response repetition whether the mapping of the prime was congruent [$F(2, 14) = 3.95$, $p < 0.0436$], or incongruent [$F(2, 46) = 4.37$, $p < 0.0183$].

Appendix D

Experiment 3

		RSI					
		700			*1500*		
		Con.	*Incon.*	*Neut.*	*Con.*	*Incon.*	*Neut.*
Type 3 (+1)	Con.	572 (80)	659 (63)	616 (86)	606 (118)	681 (105)	634 (98)
	Incon.	586 (75)	659 (81)	614 (63)	627 (105)	687 (107)	709 (134)
	Neut.	557 (71)	697 (108)	614 (68)	637 (103)	710 (145)	633 (90)
Type 4 (+1)	Con.	594 (77)	640 (78)	605 (77)	627 (96)	682 (101)	634 (99)
	Incon.	609 (52)	687 (128)	619 (115)	627 (87)	695 (115)	655 (112)
	Neut.	598 (92)	657 (91)	589 (78)	627 (99)	710 (120)	604 (100)

Mean RT (and standard deviations) for Experiment 3 at the two values of RSI that were used. RSI did not have any statistically significant effects in this experiment, although the same trend is observable here as in the other experiments: the longer the RSI, the slower the RT.

Experiment 4

		RSI			
		700		*1500*	
		Rel. Rep	*Rel. Non-Rep*	*Rel. Rep*	*Rel. Non-Rep*
Type 1	Irr. Rep	470 (43)	559 (77)	506 (60)	585 (60)
nn	Irr. Non-Rep	469 (30)	561 (45)	497 (63)	593. (65)
Type 3	Irr. Rep	498 (75)	606 (105)	520 (94)	619 (108)
ii	Irr. Non-Rep	491 (58)	616 (114)	521 (82)	612 (121)

Experiment (Continued)

		RSI			
		700		1500	
		Rel. Rep	*Rel. Non-Rep*	*Rel. Rep*	*Rel. Non-Rep*
Type 4	Irr. Rep	484 (63)	599 (78)	538 (67)	616 (90)
ii	Irr. Non-Rep	516 (78)	620 (71)	543 (73)	631 (88)

Mean RT (and standard deviations) for Experiment 4 at the two values of RSI that were used. The row labels are for the irrelevant (Irr.) transitions; the column labels are for the relevant (Rel.) transitions. Included in the Task type identification for the rows are reminders of consistency status of the prime–probe pairs. Thus, nn indicates that both the prime and probe were neutral, ii indicates that both the prime and the probe were inconsistent.

The statistical results of RSI for this experiment are easily summarized: the longer the RSI the slower the RT. This is significant for Type 1 [$F(1, 8) = 6.49$, $p < 00343$], Type 3, and Type 4 [$F(1, 8) = 10.05$, $p < 0.0132$]. There are no significant interactions. However, In Type 3 the effect of relevant stimulus repetitions appears to decrease as RSI increases, and in Type 4 there appears to be that same trend except that now it is for the irrelevant stimulus whose effect of repetition decreases as RSI increases.