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CHAPTER 13

PRINCIPLES OF COMPATIBILITY

Stimulus–Response Compatibility

About the same time as the work of Hick and Hyman, another classic choice–reaction time study was reported by Fitts and Seeger (1953). They used three different stimulus and response sets, all with eight alternatives. Thus, the sets were equivalent in terms of the amount of stimulus and response information they contained. The stimulus sets differed in the way that the information was signaled (see Figure 13–8). For set *A*, any one of eight lights could come on; for stimulus sets *B* and *C*, any of four lights alone or any four pairs of these lights could occur. The two sets differed in the spatial configuration of the lights. The three response sets corresponded conceptually to the displays. People were required to move a single stylus to a target location for sets *A* and *B*, and two styli to locations for set *C*. For

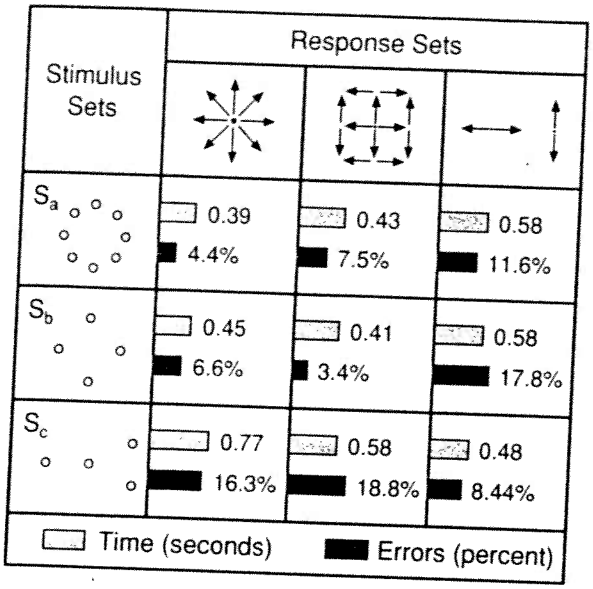

FIGURE 13–8 Stimulus Sets, Response Sets, and Data (Reaction Time and Error Rates).
From P. M. Fitts & C. M. Seeger (1953). S–R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology, 46,* 199–210.

response set *A*, there were eight locations in a circular configuration; for response set *B*, there were also eight locations, but responses were made by moving from the start point along one of four pathways, which then branched into T's; for response set *C*, there were left–right locations for the left hand and up–down locations for the right hand, with the eight responses signaled by combinations of the two hand movements.

Responses in this study were faster and more accurate for the pairings of stimulus sets and response sets that corresponded naturally than for those that did not. In other words, with the number of stimulus–response alternatives constant, performance varied as a function of the correspondence of the stimulus and response sets. Fitts and Seeger called this phenomenon *stimulus–response (S–R) compatibility* and attributed it to cognitive representations or codes based on the spatial locations of the stimulus and response sets.

In a second classic study, Fitts and Deininger (1954) manipulated the assignment of stimuli to responses within a single stimulus and response set. People placed a stylus at the intersection of eight pathways that were organized like the spokes of a wheel (see Figure 13–9). The stimulus set was a corresponding set of eight lights arranged around the periphery of a circle. The person's task was to move the stylus to an assigned response location when one of the stimuli was lit. With the direct assignment, each stimulus location was assigned to the corresponding response location. With the mirrored assignment, the left-side stimulus locations were assigned to their right-side counterparts of the response set, and vice versa. For example, if the light occurred in the upper-left location of the display, the stylus was to be moved to the upper-right location. Finally, with the random assignment, no systematic relation existed between the stimuli and their assigned responses. Responses were faster and more accurate with the direct assignment than

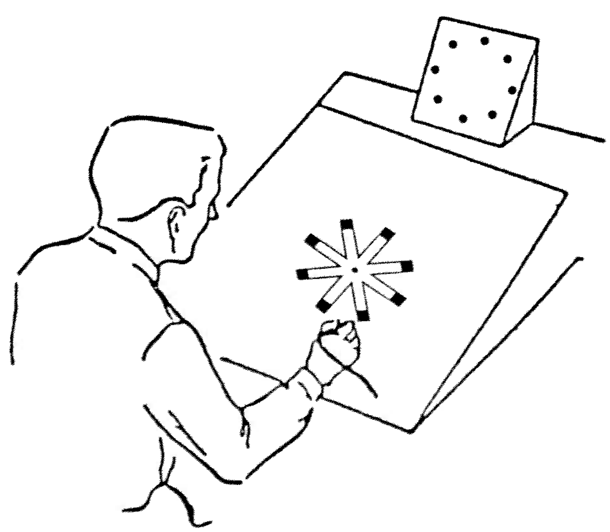

FIGURE 13–9 Fitts and Deininger's Experimental Apparatus (1954).
From P. M. Fitts & R. L. Deininger (1954). S–R compatibility: Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology, 48,* 483–491.

with the mirrored assignment. Even more striking, the reaction times and error rates for the random assignment were over twice those for the mirrored assignment.

Morin and Grant (1955) pursued this ordering of relative compatibility further by having people respond to one of ten lights arranged in a row with one of ten fingers placed on response keys. As would be expected, responses were fastest when there was a direct correspondence between stimulus and response locations (see Figure 13–10). However, responding was also fast when the stimulus and response locations were perfectly negatively correlated (that is, the rightmost response would be made if the leftmost stimulus occurred, and so on), and reaction time increased as the correlation decreased to zero. These findings indicate that people can translate quickly between a stimulus and response when a simple rule (for example, respond at the location opposite to the stimulus location) describes the relation (Duncan, 1977). Moreover, it also has been suggested that the correlation coefficient might provide a metric for compatibility in real-world situations for which several stimuli and responses are involved (Kantowitz, Triggs, & Barnes, 1990).

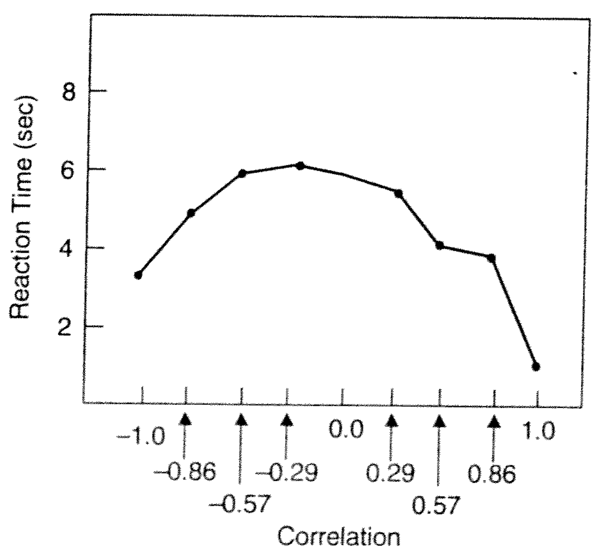

FIGURE 13–10 Reaction Time as a Function of the Correlation Between Stimulus and Response Locations.

From R. E. Morin & D. A. Grant (1955). Learning and performance on a key-pressing task as a function of the degree of spatial stimulus–response correspondence. *Journal of Experimental Psychology, 49,* 39–47.

The implication of the spatial compatibility studies for display–control arrangements is clear. The assignment of controls to display elements should be spatially compatible, when possible. The classic applied illustration of this principle comes from studies of four-burner ranges conducted by Chapanis and Lindenbaum (1959) and Shinar and Acton (1978). A common arrangement is to have two back burners located directly behind two front burners, with the controls arranged linearly across the front of the range (see Figure 13–11, panels 2, 3, 4, and 5). For this arrangement, there is no dominant stereotypic mapping of controls to burners, so there is some confusion about which control operates a particular burner. However, by staggering the burners in a sequential left-to-right order (see Figure 13–11, panel 1), each control location corresponds directly to a burner location and confusion about the relation between controls and burners is eliminated.

Relative Location Coding. The prototypical procedure for studying S–R compatibility is a two-choice task in which visual stimuli are presented to either the left or right of a central fixation point (see Figure 13–12, A and B). In the compatible condition, the observer is to respond to the left stimulus with a key press at a left response location and to the right stimulus with a key press at a right location. In the incompatible condition, the assignment of stimulus locations to response locations is reversed. Responses in the two-choice task are faster and more accurate when they are compatible with the stimulus locations (Umiltà & Nicoletti, 1990). Note that this is not simply a speed–accuracy trade-off because accuracy improves as reaction time decreases.

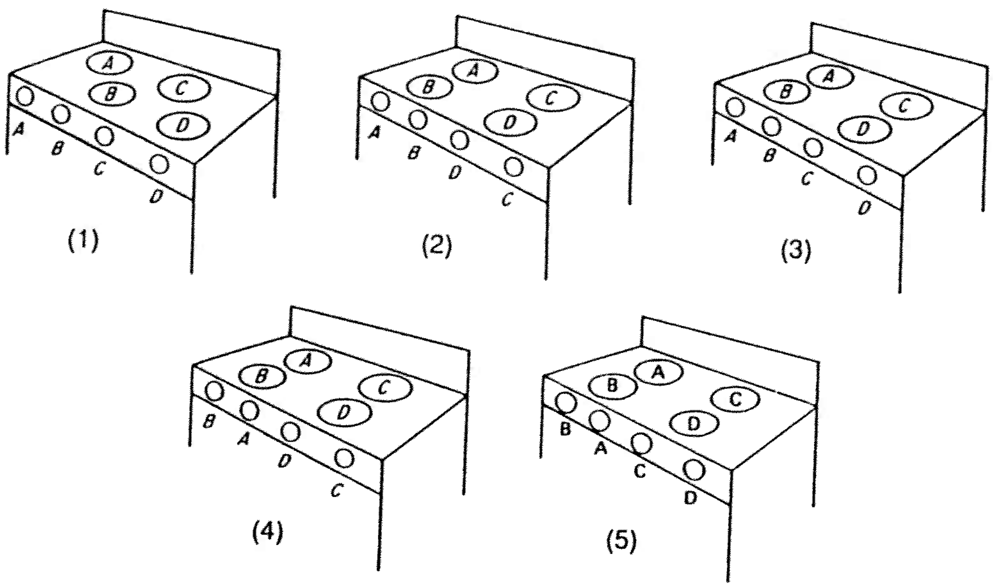

FIGURE 13–11 Control-burner Arrangements of a Stove.
Based on A. Chapanis & L. E. Lindenbaum, A reaction time study of four control-display linkages. Reprinted from *Human Factors*, Vol. 1, No. 4, pp. 1–7, 1959.

When the hands are situated on their anatomical sides (as shown in panels A and B of Figure 13–12), the distinction between left and right response locations is redundant with the distinction between left and right response effectors. To dissociate response locations from effector locations, the left and right hands can be crossed (see Figure 13–12, C and D). With this crossed-hands placement, the left hand is at the right response location and the right hand at the left location. In such situations, responses are still faster when there is a direct correspondence between the stimulus and response locations, even though the opposing hand is used to make the response (for example, Anzola et al., 1977; Brebner, Shephard, & Cairney, 1972). The importance of the response locations, rather than the effectors used to execute the responses, is consistent with the implication of Fitts's earlier discovery that spatial coding underlies S–R compatibility effects.

The dependence of compatibility effects on the spatial relations between stimuli and responses also occurs for unimanual responses (Heister, Schroeder-Heister, & Ehrenstein, 1990) and four-choice tasks (Reeve & Proctor, 1984). Moreover, the standard spatial compatibility effect occurs when both stimuli are located in the same hemispace and when both responses are located to the same side of the body midline (Nicoletti et al., 1982; Umiltà & Liotti, 1987). In other words, it is not the absolute physical locations of the stimuli and responses that determine the degree of compatibility, but their relative locations. These findings are interpreted as indicating that location coding is based on relative position (Umiltà & Nicoletti, 1990). For optimal performance, compatibility of relative locations must be maintained regardless of the absolute locations of the alternative displays and controls.

Not only is correspondence between absolute physical locations unnecessary for the compatibility effect, but the effect also occurs when stimuli and/or responses have no physical spatial dimension. Responses are faster when the words

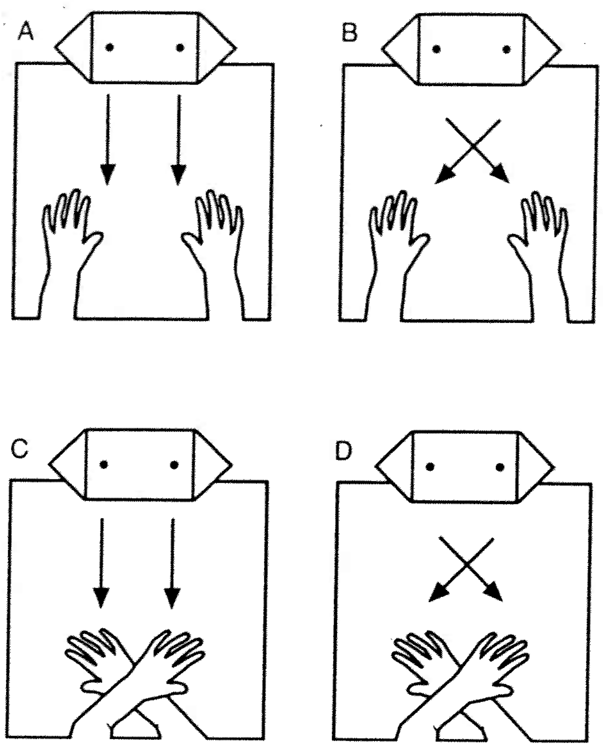

FIGURE 13–12 Compatible (A and C) and Incompatible (B and D) Stimulus–Response Assignments in Two-choice Tasks, with the Hands Uncrossed (A and B) and Crossed (C and D).

left and *right* are assigned directly to left and right physical responses (Magliero et al., 1984; McCarthy & Donchin, 1981) or *left* and *right* vocal responses (Weeks & Proctor, 1990). Similar results are obtained with left- and right-pointing arrow stimuli (Bashore, 1990; Weeks & Proctor, 1990). Compatibility effects can also occur when the stimulus dimension is above–below and the response dimension is left–right, or vice versa (Weeks & Proctor, 1990). For two stimulus-response alternatives, responses tend to be faster when *above* is paired with *right* and *below* with *left* than when the assignment is reversed. Thus, compatibility effects have their basis in the cognitive representations of stimulus and response sets. Such effects are likely to occur for situations in which there is no obvious relation between stimulus and response sets, as well as for situations in which there are.

Theoretical Interpretations. Taken together, the results indicate that spatial compatibility effects do not depend on physical correspondence, but on what Alluisi and Warm (1990) call conceptual correspondence. These findings led to refinements of Fitts and Seeger's (1953) original spatial coding account of S–R compatibility, with an emphasis on the cognitive codes for spatial relationships used to translate between stimuli and responses. Compatibility effects will occur whenever implicit or explicit spatial relationships exist among stimuli and among responses. A stimulus–response mapping will be compatible if the codes are similar for the stimuli and their assigned responses and incompatible if the codes conflict. The spatial coding hypothesis predicts that compatibility effects will be relatively independent of the means by which the stimulus information is presented and the response information effected.

Perhaps the best evidence for spatial coding as the basis for S–R compatibility is that compatibility effects for symbolic stimuli assigned to spatial responses can be predicted from the correspondence between salient nonspatial features of the stimulus set and the spatial features of the response set (Proctor & Reeve, 1985; Proctor, Reeve, & Weeks, 1990). Coding is flexible and is based on these salient features. For stimuli and responses that are distinguishable only by their locations, spatial coding is usually based on where stimuli and responses are located relative to each other. In situations for which location coding is made difficult or is not a factor, symbolic codes for stimuli and anatomical codes for responses can be used. Thus, coding accounts not only explain spatial compatibility effects, but they also provide a means for integrating a range of compatibility effects that appear dissimilar on the surface (Kornblum, Hasbroucq, & Osman, 1990; Proctor, Reeve, & Weeks, 1990).

To summarize, the ease with which an operator can select a response associated with a given stimulus display largely depends on the spatial configurations of the display and response panel. The operator's performance may be impaired if the stimuli and responses are not related by spatial locations or a simple, easy to remember rule. When space allows, control panels should be designed to mimic the spatial relations between elements of the display. If not, an easily remembered rule should be used that relates salient display and control features.

Formal models can be used to predict performance with different display–control relationships. The most detailed model of S–R compatibility to date is that of Rosenbloom and Newell (1987; see also Laird, Rosenbloom, & Newell, 1986). Their algorithmic model is implemented within a production-system framework. By specifying the nature of the productions that must operate to translate between stimuli and responses in different situations, Rosenbloom and Newell have been able to predict compatibility effects across tasks that range from the standard choice–reaction tasks to computer programming. The predictions are sufficiently accurate for John and Newell (1990) to propose an engineering model for use in systems design. Their model is based on Rosenbloom and Newell's theory of S–R compatibility and the Model Human Processor (Card, Moran, & Newell, 1983). From it, the designer can determine the relative compatibilities for alternative display–control configurations.

S–C–R and R–R Compatibility

Most research on S–R compatibility has focused on situations in which simple rules relate stimuli to responses (Kantowitz, Triggs, & Barnes, 1990). However, by attributing compatibility effects to the cognitive codes used to represent the stimulus and response sets, central cognitive processes must be responsible for the effects. Because the role of cognitive mediation in response selection is likely larger for more complex tasks that do not involve simple rules or response tendencies, Wickens, Sandry, and Vidulich (1983) have used the term S–C–R compatibility to emphasize the central processes (C). In short, the mediating processes can be conceived more generally as reflecting the operator's mental model of the task. Compatibility will be observed to the extent that stimuli and responses correspond with the features of the mental model.

Wickens, Sandry, and Vidulich (1983) structured their theory of S–C–R compatibility around the multiple-resource view of attention and, hence, stressed the importance of the cognitive code (verbal or visual) used to represent the task. They proposed that this code must be matched with the types of input and output modes for S–C–R compatibility to be maximized. Wickens et al. provided evidence that tasks represented by a verbal code are most compatible with speech stimuli, whereas tasks represented by a spatial code are most compatible with visual stimuli. Similarly, verbal codes are more compatible with speech responses and spatial codes with manual responses.

Robinson and Eberts (1987) obtained evidence consistent with the coding relations proposed by S–C–R compatibility in a simulated cockpit environment. Either a synthesized speech display or a picture display was used to communicate emergency information, with the response activated manually. As predicted by the S–C–R compatibility hypothesis, the manual responses were made faster to the picture display depicting spatial relationships than to the speech display.

S–C–R compatibility has been expanded by Eberts and Posey (1990) to take other aspects of the operator's mental model into account. Specifically, they propose that a good mental model that accurately represents the conceptual relations of the task should enable better and more efficient performance than a poor mental model. Eberts and Schneider (1985) have obtained several results with a difficult control task that indicate better performance when training incorporates an appropriate mental model. Along with John and Newell's (1990) work on compatibility effects in human–computer interaction, this work indicates that the ramifications of compatibility extend to a range of complex tasks.

The time to select a particular response to a stimulus can also be affected by the other members of the response set. Such phenomena are called response–response (R–R) compatibility effects. Responses are slower when the alternatives are mechanically antagonistic (Berlyne, 1957), when the initial elements of alternative response sequences are unique rather than common to both sequences (Rosenbaum, Hindorff, & Munro, 1987), when different movements (for example, tapping versus alternating between keys) are assigned to the left and right hands (Heuer, 1990), and when two alternative finger responses are on the same hand as opposed to different hands (Reeve & Proctor, 1988).

The implication of R–R compatibility effects for the design of human–machine interfaces is that response time and accuracy can be influenced by the particular set of required responses. Therefore, to optimize performance, the members of the response set also need to be of high compatibility.

PRACTICE AND RESPONSE SELECTION

As with virtually everything else, performance on choice–reaction tasks improves with practice. This improvement is characterized by the power law described in Chapter 12 (also see Newell & Rosenbloom, 1981). Thus, although performance continues to improve indefinitely, the additional benefit for a constant amount of practice becomes less and less as the person continues to perform the task. Moreover, because practice effects are greater for tasks that have more stimulus–response alternatives, the slope of the Hick–Hyman law function becomes progressively less as people become more practiced (Teichner & Krebs, 1974).

A classic study that illustrates the extent to which human performance can improve with practice is one by Crossman (1959). He examined the time required for people to make cigars on a hand-operated machine. Operators were tested whose experience ranged up to 6 years. Speed of performance increased as a power function up to 4 years, at which point the minimum machine-cycle time limited performance from improving further. In other words, the machine reached its limits before the operators reached theirs.

Using a more typical choice–reaction task, Seibel (1963) also showed improvement with practice that followed a power function. He performed a 1,023-choice task in which a stimulus subset of 10 lights required the corresponding subset of response keys to be pressed simultaneously. Initially, his reaction times averaged over 1 s, but they reached 450 ms after 70,000 trials of practice. As can be seen in Figure 13–13, his performance improved continuously over the course of the study.

There are several views of how response-selection processes change as a person becomes skilled at a task. The power law suggests a continuous change from unpracticed to practiced states, leading some authors to treat practice effects as quantitative changes in the number of procedures that are incorporated into a single chunk (for example, Laird, Rosenbloom, & Newell, 1986). Alternatively, a qualitative change, in which the role of the translation stage decreases as performers become practiced, is often hypothesized (for example, Teichner & Krebs, 1974).

S–R compatibility effects usually decrease with practice, but they do not typically disappear (Dutta & Proctor, 1992). For example, Fitts and Seeger (1953) found that responses for an incompatible display–control arrangement were still considerably slower than those for a compatible arrangement after 26 sessions of 16 trials for each arrangement. Such findings are consistent with proposals of Eberts and Posey (1990) and Gopher, Karis, and Koenig (1985) that mental representations continue to play an important role in translating between stimuli and responses even for well-practiced performers. Although the best account for the persistence of compatibility effects is not clear, the obvious point for human factors is that the effects are not short term. An

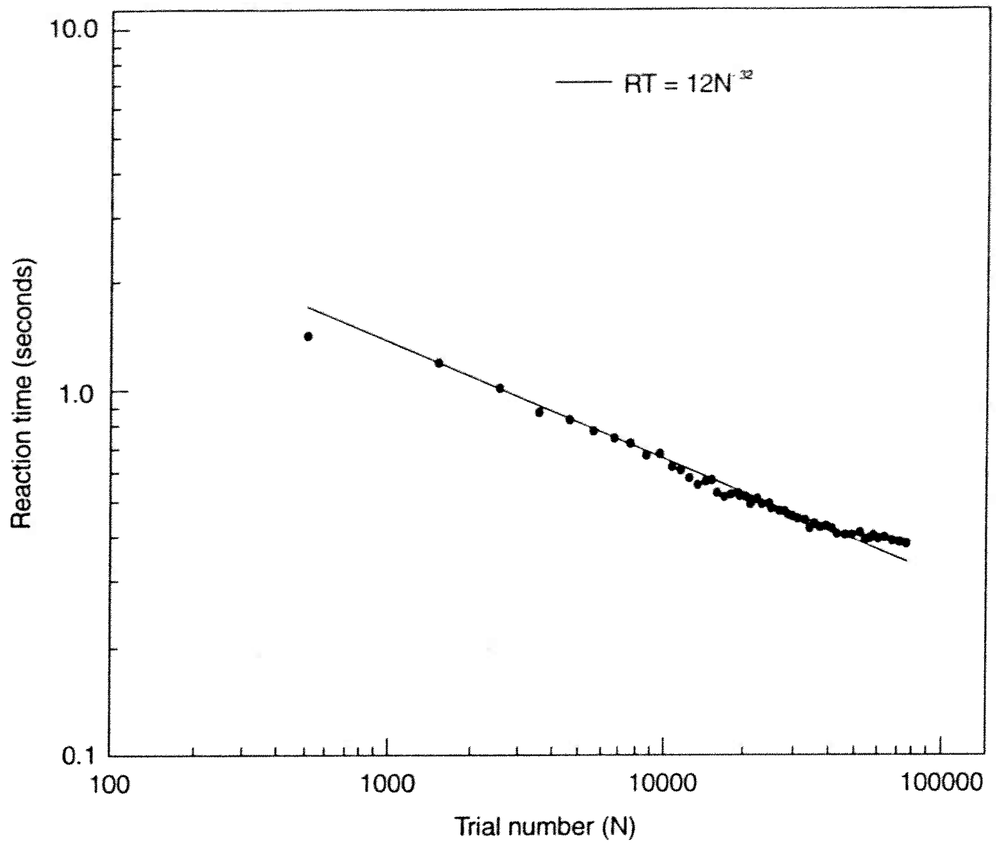

FIGURE 13–13 Reaction Time as a Function of Practice in a 1,023-choice task.
Adapted from R. Seibel, (1963). Discrimination reaction time for a 1,023 alternative task. *Journal of Experimental Psychology, 66,* 215–226. Copyright © 1963 by the American Psychological Association.

incompatible display–control arrangement can result in long-term decrements in performance.

IRRELEVANT STIMULI

Spatial S–R compatibility effects occur not just when stimulus location is relevant for determining the correct response, but also when it is irrelevant (Simon, 1990). For example, if the color of an indicator light is the relevant stimulus dimension to which an operator is to respond, the location in which the light occurs can still influence response selection. Suppose you are to make one response to a red light and another to a green light and that these lights can occur to the left or right of a central point. If you are to respond to the red light by pressing a key with the right index finger and the green light with the left index finger, your responses will be fastest when the red light occurs to the right side or the green light to the left. This phenomenon is called the Simon effect, after its discoverer, J. R. Simon.

Research has shown that the Simon effect generalizes across sensory modalities and that the effect is determined by the relationship between stimulus locations and response locations (for example, Wallace, 1971), as is the case when stimulus location is relevant. Simon initially proposed that the effect reflects an innate tendency to respond in the direction of the stimulus (Simon, 1969). When this response tendency conflicts with the correct response, it must be inhibited before the correct response can be made. Recent accounts have maintained this response competition view (but see Hasbroucq & Guiard, 1991, for a different view), while linking the competition to activation of conflicting spatial codes (Umiltà & Nicoletti, 1990).

A closely related phenomenon to the Simon effect is the Stroop effect, which is named after its discoverer, J. Ridley Stroop (Stroop, 1935/1992). The standard Stroop task requires naming the ink colors of words that specify conflicting colors. For example, the word *green* could be printed in red ink. The Stroop effect is that responses are considerably slower and less accurate in this conflict situation than when the ink colors are presented as patches of color rather than spelled words. The Stroop task has been thoroughly investigated, and the interference has been found to occur for numerous variations, including picture–word combinations, physical locations and words that spell location names, and auditory stimuli (MacLeod, 1991). The difference between the Stroop and Simon paradigms is that the two stimulus dimensions are closely related for the former, but not for the latter.

Explanations of the Stroop effect have tended to focus on response competition, much like accounts of the Simon effect. Cohen, Dunbar, and McClelland (1990) have provided a neural network model that generates many of the basic findings for the Stroop effect. According to this model, processing occurs through activation along pathways of different strengths. When two pathways are active simultaneously and produce conflicting activation at their intersection, interference occurs. Consequently, interference is not restricted to overt responses but can occur at different processing levels.

A final phenomenon arising from irrelevant stimuli is called the Eriksen effect. Observers are to identify a target stimulus (usually a letter) presented at the point of fixation. On most trials the target is flanked by noise letters. The primary finding is that responses are slower and less accurate when the flanking letters include a letter assigned to the alternative response from that required by the target. Eriksen and his associates have interpreted such results in terms of response competition in a continuous activation model (Eriksen & Schultz, 1979), much like that proposed by Cohen, Dunbar, and McClelland (1990) for the Stroop effect.

All three of these effects illustrate that irrelevant stimulus attributes can interfere with performance when they conflict with the stimulus and response attributes relevant to the task at hand. They reflect people's limited ability to selectively attend to relevant stimulus attributes and to ignore irrelevant ones. The human factors specialist should be aware of such possibilities for interference and minimize potential sources of conflict, such as irrelevant location cues, when designing display panels and other interface devices.