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Spatial compatibility with a two-dimensional stimulus arrangement

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In this study, spatial compatibility of two-dimensional stimulus arrays versus one-dimensional response and effector arrays was investigated. A two-choice reaction time task was performed with rotating stimuli arranged on the periphery of a black vertical disk. Response was bimanual, with a crossed- and uncrossed hands condition. Depending on the cues presented, subjects tended to use different relations in responding. Furthermore, it was demonstrated that a second dimension in the stimulus arrangement could improve performance in some situations, especially if the transposition of dimensions was facilitated by spatial cues.

The first definition of stimulus-response compatibility, as proffered by Fitts and Seeger (1953), was very general. It defined a task compatible to the extent that the ensemble of stimulus-response combination resulted in a high rate of information transfer. More recently, most researchers (Brebner, 1973, 1979; Wallace, 1971) have argued that it is the complexity of the recoding process by which a stimulus is mapped onto its required response that determines the nature of the ensuing performance.

More important in compatibility research is the question of why some stimulus-response relationships are compatible and others are not. Because of its relative convenience in searching for compatiblity effects produced by varying the spatial arrangement between display of stimuli and an array of response mechanisms, research on spatial compatibility is the most suitable for investigating the mechanisms involved in this phenomenon. It has also been demonstrated that spatial location often overrides other, nonspatial cues (Brebner, 1979; Hedge & Marsh, 1975).

Numerous studies have shown that reaction time (RT) to a signal decreases when the relative spatial location of the stimulus corresponds to the relative spatial location of the required response (Rabbitt, 1967; Simon & Wolf, 1963). This result has been explained as arising from a "natural" tendency to respond in the direction of the source of stimulation (Simon, 1968; Simon & Rudell, 1967). In an incompatible arrangement, this tendency has to be suppressed before a correct response can be generated. Lupker and Katz (1982) observed that influence of compatibility also applies to experiments in which no movement at all is required. Thus, not only is the movement responsible for the subjects' performance, but there is also a relationship between a stimulus and any of the components involved in the execution of the response (Wallace, 1971).

Brebner, Shephard, and Cairney (1972) argued that, in most of these spatial-compatibility studies, three relationships have been confounded: (1) the spatial relationship between stimulus display and the array of response mechanisms; (2) the spatial relationship between stimulus display and the effector's movement or position; and (3) the spatial relationship between the array of response mechanisms and the effector's movement or position. In their study, they attempted to separate the effects of these relationships on RT. Each of the relationships can be compatible or incompatible. Different outcomes were expected, depending on the relationships used by the subjects. The results indicated that the compatibility of the relationships between stimulus and response mechanisms and between response mechanisms and effector positions affected performance, whereas the relationship between stimuli and effector positions was redundant.

One of the shortcomings of the Brebner et al. (1972) study is the assumption that all relationships were equally important. Furthermore, subjects could not opt for any other combination of relationships. One can further argue that incompatibility is not the same in every relation, especially not if the stimulus arrangement is two-dimensional. The main purpose of the present paper is to investigate compatibility effects in relation to a second dimension.

Interesting for this purpose is an experiment conducted by Simon and Wolf (1963). Two stimulus lights were mounted on a vertical panel that could be rotated through 180 deg so that the stimulus lights formed different angular orientations. The results demonstrated a decline in performance when dimensional transpositions were involved.

It is useful to have a better understanding of the processes originating from the use of a seond dimension. Because of spatial limitations or other engineering considerations, it is sometimes difficult to obtain a completely isomorphic relationship between display and key

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arrangements. If dimensional transpositions have to take place, it is interesting to know which orientations give a minimum decline in performance and to search for a way to eliminate this decline, at least partly, with the help of supplementary indications. Therefore, the influence of a spatial cue is examined in the second part of this paper.

EXPERIMENT 1

The same procedure that had been used in the Simon and Wolf (1963) study was used here. Stimuli were rotated in a vertical plane, but conditions were extended to 360 deg to see if compatibility effects were symmetrical. From Wallace (1971), the technique of crossing-uncrossing hands was borrowed to create the opportunity to separate the influence of the different relationships on performance. The same method of analysis was applied that had been applied in the Brebner et al. (1972) paper, which included compatibility and incompatibility for all relations. In addition, a second dimension was introduced.

Complex interactions of two dimensions in different relations were avoided by leaving the response mechanisms and hands in a one-dimensional left-right arrangement.

Method

Subjects. Four subjects, ranging in age from 20 to 22 years, participated. They were unfamiliar with RT tasks.

Apparatus. A black disk was mounted on a black vertical panel. The lights (6-V, 50-mA bulbs of 12-mm diameter), covered with white transparent plastic hoods, were placed opposite each other on the periphery of the disk. Their centers were set 10 cm apart. The stimulus lamps were rotated in eight different positions: 0, 45, 90, 135, 180, 225, 270, and 315 deg.

The subject was seated 2.5 m from the panel, which resulted in a between-stimulus visual angle of approximately 2.5 deg. Two push buttons connected to microswitches were placed on a horizontal response panel in front of the subject, such that they could be manipulated by the subject's forefingers. In the "uncrossed" condition, the left hand operated the left key and the right hand operated the right key. In the "crossed" condition, the left hand operated the right key and the right hand operated the left key.

Procedure. RT was recorded as the time between stimulus onset and the moment that either of the keys was pressed. At the same moment, stimulus exposure was terminated and a 1,000-msec response-stimulus interval started. Complete randomization of all stimulus sequences was accomplished by basing the chance of exposure of a particular stimulus on the RT (in milliseconds) to the previous stimulus.

Each subject participated in 16 different conditions (eight stimulus positions and two hand positions). Sixteen series of 40 RTs were performed. After every four series, there was a rest period. All conditions were counterbalanced.

Results and Discussion

As in the Brebner et al. (1972) paper, three relationships are considered: (1) relationship between stimulus arrangement and key arrangement, abbreviated as SK; (2) relationship between keys and hands, denoted as KH; and (3) relationship between stimuli and hands, denoted as SH.

Figure 1 shows mean RTs and error rates as a function of stimulus positions for both crossed and uncrossed conditions. In the uncrossed condition, three levels of

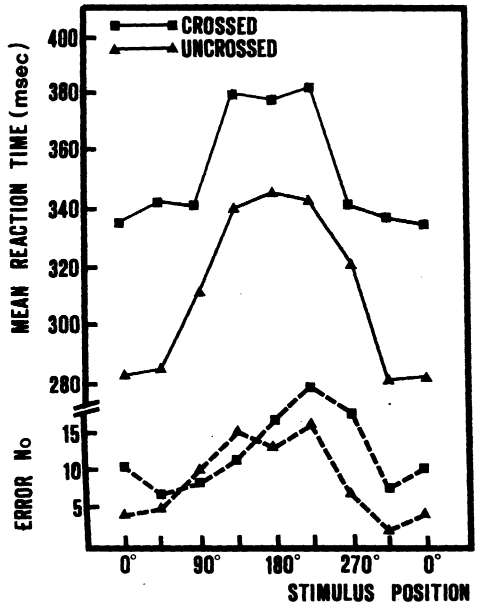

Figure 1. Mean RT and number of errors as a function of stimulus position in both crossed and uncrossed conditions.

mean RTs can be observed. Fastest RTs are for the compatible positions 0, 45, and 315 deg. This is in agreement with the results of Simon and Wolf (1963), who likewise found no difference between mean RTs in these stimulus positions. The second level corresponds to the second dimension, whereas the slowest RTs are recorded for the incompatible situations of 135, 180, and 225 deg. The error curve follows the same pattern as the mean RT curve. In the crossed condition, on the other hand, only two levels of RTs can be distinguished. RTs to the second-dimension stimuli are as fast as those of the compatible SK relation. Note that the slowest level of the uncrossed curve corresponds to the fastest level of the crossed curve. This can be interpreted as an indication that incompatibility between lamps and keys has approximately the same impact on performance as incompatibility between keys and hands. For both curves, Figure 1 shows that RTs to positions greater than 180 deg are a reflection of RTs to positions smaller than 180 deg.

The subjects had three relations at their disposal, of which at least two were necessary for a reaction. For response execution, it can be assumed that relation KH had to be used all the time, since the subjects had to make the physical contact between hands and keys. Aside from this relation, they needed at least one relation for stimulus perception. This leaves the possibility for three different combinations of relations to be used. A first possibility is that all relations are used on an equal basis, in other words, are equally important for the performance of the stimulus-response cycle. In that case, all conditions with two incompatible relations should evoke RTs of the same magnitude. However, there is a significant difference between the crossed-incompatible condition and the other two combinations of two incompatible relations [$F(1,3) = 14.75$, $p < .01$, and $F(1,3) = 11.33$, $p < .01$].

This is illustrated by the two highest levels in Figure 1. This leaves only the possibility of two equally important relations with one redundant or optional relation.

Are KH and SH equally important? In that case, SK should be redundant. However, there is a difference between the conditions with a compatible and an incompatible SK [$F(1,3) = 22.13$, $p < .01$].

There is only one possibility left: SK and KH are equally important. No significant difference should exist between compatible and incompatible SH conditions, which is indeed the case. Also, a significance should be found between conditions in which only one of the relations SK or KH is incompatible and the conditions in which they are both incompatible. This is true according to the analysis on three equal relations. It can be concluded that relations stimulus-key and key-hand are equally important in the present experiment, and relations stimulus-hand is redundant.

RTs in a two-dimensional condition were slower than those in a compatible condition. This is in agreement with the results of Simon and Wolf (1963) and Wallace (1971). Mean RTs are halfway between mean RTs of the compatible and incompatible uncrossed conditions. Compared with the Simon study, the vertical stimulus position with hands crossed is new. Wallace (1971) had a similar setup, in which he found approximately the same relative increase in mean RT in the crossed and uncrossed conditions. However, his stimuli contained information that was irrelevant with respect to the spatial location (squares vs. circles). The crossed-condition curve, shown in Figure 1, demonstrates no difference between the vertical and compatible stimulus conditions [$F(1,3) = 0.03$]. The slowing down of RTs, due to the transposition of dimensions, is compensated in the crossed-hands condition. This could mean that the use of two relations that are very dissimilar are an asset to performance, in comparison with two relations that are more similar.

Two relations are important in the arrangement of Experiment 1, that is, the relation between stimuli and keys and the relation between keys and hands. In comparison with these, the relation between stimuli and hands can be ignored. The second dimension seems to be an asset to performance compared with an incompatible one-dimensional relation. Nevertheless, this advantage cannot equal the positive influence of a totally one-dimensional compatible relation.

In the design of instrument panels, where sometimes many different stimuli are necessary, it is not always possible to arrange stimuli and response mechanisms in exclusively compatible one-dimensional arrays. With the use of a second dimension and the help of a spatial indication as a cue, arrangements that are almost as compatible can be made. Such an indication has to facilitate the transposition of a vertical dimension into a left-right dimension. This idea was worked out in Experiment 2.

EXPERIMENT 2

In Experiment 2, transposition of dimensions was facilitated by adding a spatial indication to the stimulus panel. Wallace (1971) gave subjects supplementary information about the stimuli by using different symbols for the two stimuli. Other investigators (Craft & Simon, 1970; Hedge & Marsh, 1975) tried to influence processing by coloring the stimuli. Such symbolism cannot be very useful for the transposition of dimensions, since translations of symbols are less compatible than are transpositions of dimensions. Moreover, the supplementary information is totally independent of the position of the stimuli in the visual field. Earler studies (e.g., Brebner, 1979) have demonstrated that spatial cues are stronger than nonspatial information. In the present study, a vertical line was drawn, separating the visual field into a left and a right part. It was expected that this indication would assist the subjects in working in the left-right dimension even when stimuli were close to the vertical position.

Method

Subjects. Six subjects, ranging in age from 20 to 23 years, participated. They were unfamiliar with RT tasks.

Apparatus. Unless otherwise mentioned, the apparatus and procedure were the same as in Experiment 1. A white vertical line, 0.5 cm thick, was attached to the disk such that it passed through the center of the disk. Stimulus lamps were moved into nine positions: 0, 30, 70, 80, 90, 100, 110, 150, and 180 deg. From the subject's position, the vertical line was clearly visible.

Procedure. Each subject participated in 18 different conditions (nine lamp positions and two hand positions). Six short sessions (each of 3 x 50 stimuli) were run, with rest periods of 30 min between sessions. All conditions were counterbalanced.

Results and Discussion

Figure 2 shows mean RTs as a function of stimulus position for both crossed and uncrossed conditions.

In the uncrossed condition, the dip on 80 deg, followed by a sharp slope to 100 deg, is remarkable. It demonstrates the expected effect. Due to the division of the visual field by a vertical line, the subjects tend to use the left-right dimension as long as possible, even more so when closing up to the 90-deg position. This has a

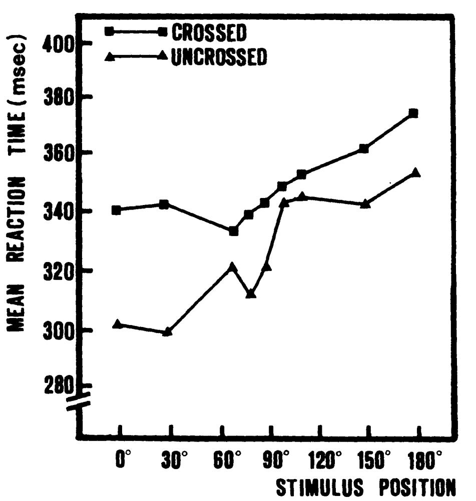

Figure 2. Mean RT as a function of stimulus position in both crossed and uncrossed conditions.

positive effect on RTs in positions smaller than 90 deg, because of the accentuated compatible left-right relation, and a negative effect on RTs to positions over 90 deg, which is an incompatible left-right relation.

In the crossed condition, the curve displays the same dip around 70 and 80 deg. As was predicted, fastest mean RTs were recorded in these positions. In contrast to Experiment 1, the negative influence caused by the diminishing left-right compatibility effect is now suppressed by the presence of the white vertical line, resulting in fast RTs in the near-vertical positions.

As in Experiment 1, it might be interesting to know which relations were used by the subjects. A difference was found between compatible and incompatible crossed conditions [$F(1,5) = 28.15$, $p < .001$]. This rules out the possibility of three equal relations. If relations SK and KH are equally important, as in Experiment 1, there has to be a difference in mean RT between conditions in which both relations are simultaneously incompatible and those in which only one of the relations is incompatible. This is not true [$F(1,5) = 4.17$]. This leaves only the possibility of equal relations KH and SH, which was ascertained: There is no difference between compatible and incompatible SK relations, but, on the other hand, SH is not redundant [$F(1,5) = 29.15$, $p < .001$]. Instead of using relation SK, the subjects, because of the presence of the white vertical line, shifted their preference to relation SH in stimulus perception.

This different use of relations can shed some light on the course of the crossed-condition curve. Indeed, in the 180-deg position, subjects now employ one incompatible relation (KH) and one compatible relation (SH) as being equally important, in contrast to the two incompatible relations used in the same condition of Experiment 1. This results in a practically horizontal curve, with the exception of the dip around 70-80 deg.

It can be concluded that the positive effect of the vertical separation line is limited to stimuli close to this line. Results further indicate that subjects tend to use different relations, but the trend of the crossed curve does not completely ascertain this. The change of strategy might be confined to stimuli close to the separation line and might not affect the processing of remote stimuli.

CONCLUSIONS

In the study of spatial compatibility, it is important to differentiate among the effects of all the relations involved in the execution of a response. In Experiment 1, the results of Brebner et al. (1972) were confirmed. The compatibility of the light-key and the hand-key relations affected performance, whereas the light-hand relation was redundant. More important, the present results indicate that the use of relations depends on the presence of spatial cues. In Experiment 2, a vertical line separated the left and the right visual fields. This resulted in a tendency to use the stimulus-hand relation instead of the stimulus-key relation for stimulus perception.

The use of spatial cues also has an important influence on the transposition of dimensions. In the present study, a vertical line enhanced the use of the left-right dimension, especially for stimuli in the near-vertical positions, close to the cue line. Stimuli in these positions even yielded the fastest RTs in the crossed-hands condition. With uncrossed hands, RTs were only slightly inferior to RTs in a one-dimensional compatible arrangement.

The results described can be important in the development of complex instrument panels, where completely compatible positioning is not always possible. Moreover, there most certainly will exist far more effective spatial cues than the one used in Experiment 2. But the effect of the vertical line has clearly been demonstrated. Further experimenting with different spatial cues is necessary. The use of a second dimension, provided with the right spatial cues, can improve performance up to a point at which results are comparable to those of a one-dimensional compatible arrangement.

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