Effects of Stimulus Orientation, Grouping and Alignment on Spatial S-R Compatibility

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Abstract. Effects of stimulus orientation, grouping, and alignment on spatial compatibility were investigated in this study. With eight possible stimulus locations mapped to two response keys, the parallel orientation was found to be responded to faster than the orthogonal orientation. As to the grouping effect, responses for the split stimulus array were superior to that for the continuous one, which seems to be the result of better reference frames and clearer distinction between visual signals. Comparing the single relative position (Left-Right-Left-Right/Up-Down-Up-Down) alignment to the double one (Left-Left-Right-Right/Up-Up-Down-Down), no significant difference in RT was noted, but the single relative position alignment was less prone to error responses than the double one. The effect of stimulus grouping and alignment interacted significantly that the single relative position alignment with split grouping was responded to much faster than that with continuous grouping. Also, the significant interaction effect of orientation and S-R compatibility showed that the up-left and down-right stimulus-response mappings were better than the mappings the other way round.

Keywords: Spatial Compatibility, Human-Computer Interfaces, Horizontal and Orthogonal displays.

1 Introduction

Around 60 years ago, Fitts and his colleagues introduced the concept of spatial stimulus-response compatibility (SRC), showing that some spatial arrangements for displays and controls are better than others for good human performance [1, 2]. When the spatial relation between stimuli and responses is direct and natural, it is described as compatible, while when the relation is indirect and unnatural, it is described as incompatible [3, 4]. Spatially compatible S-R mappings were always responded to faster than incompatible S-R pairings [4] - [9] as a result of lower coding demands and higher rates of information transfer, and as well more attentional resources are available for attending to the target [10, 11].

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Aircraft cockpits, nuclear plant control rooms, interactive driving simulation and interfaces for industrial equipment always involve a lot of displays and controls interacting with human operators [12] - [15]. Because of the limited and confined work space, the number of control keys need to be reduced to a minimum and they may need to be closely spaced; the human operators have to monitor several displays or signals at the same time and produce timely responses to the stimuli. In many situations, the stimulus sets are placed in close proximity and located in parallel or orthogonally to the response sets [4, 16], making the display-control mappings far from simple. Therefore, it is of utmost importance to understand the effects of variations in stimulus presentation in terms of orientation, grouping and alignment on response preference as well as spatial compatibility in order to enhance the overall human-machine system performance.

In the past, spatial S-R correspondence was always regarded as an underlying requirement for the existence of spatial compatibility effects, and thereby such effects existed only when the stimulus and response sets shared the same spatial dimensions. However, Bauer and Miller [17] demonstrated that when the stimulus and response sets are oriented orthogonally, e.g. the vertical (up-down) stimulus (response) mapped to the horizontal (right-left) response (stimulus), significant orthogonal S-R compatibility effects with up-right/down-left mapping were found. This up-right/down-left advantage was then explained by salient features coding principle [18] that the codes for right and up (or above) are more salient than those for left and down, such that the up-right/down-left mapping can benefit from the correspondence of relative salience of the positions (or correspondence of asymmetric stimulus and response codes), resulting in faster translation of stimuli to responses.

Apart from stimulus-response orientation, another factor needs to be considered was the grouping effect of the stimuli. Several studies have shown that stimuli are coded relative to multiple frames of reference [19] - [21]. In this experiment, different from previous studies with precue showing the hemispace/size of the stimulus before stimulus presentation [4, 19], eight prefixed existing outline boxes were displayed in the experiment and the stimulus could occur in any of the eight possible locations. The boxes on each side were further grouped either into two (split field) or four (continuous field) for testing, forming different frames of reference. As most, if not all, of previous studies concerning the effects of reference frames were tested with precuing, it is then believed that the results of this experiment can provide further evidence on whether stimulus coding with multiple reference frames depends upon the precuing effect. It was expected that when stimuli were grouped into two, the relative right-left (up-down) position of the stimulus was salient, leading to significant response advantages. However, when the stimuli were grouped into four, the right-left (up-down) reference cue was minimized, resulting in relatively worse response performance compared with the split field condition.

As to the effect of alignment, two types of stimulus alignments – single relative position (Left-Right-Left-Right/Up-Down-Up-Down (LRLR/UDUD)) and double relative position (Left-Left-Right-Right/Up-Up-Down-Down (LLRR/UUDD)) – were investigated in the experiment. The LRLR/UDUD condition was similar to any previous studies in which the left (up) and right (down) directions can provide relative position of the stimulus for spatial coding. However, for the LLRR/UUDD condition, the stimulus coding rendered by the relative left (up) and right (down) difference was minimized or even eliminated and the result of which might be a lengthening in translation time for mapping the stimulus-response relationship. The experimental layouts of different combinations of stimulus orientation, grouping, alignment and S-R compatibility are shown in Fig. 1 and 2.

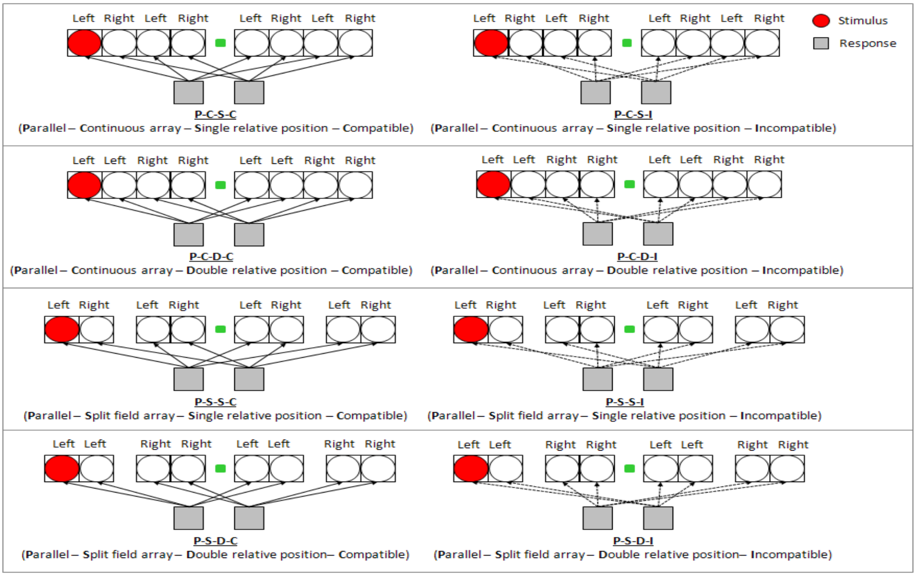

Fig. 1. Eight testing conditions in parallel S-R spatial orientation

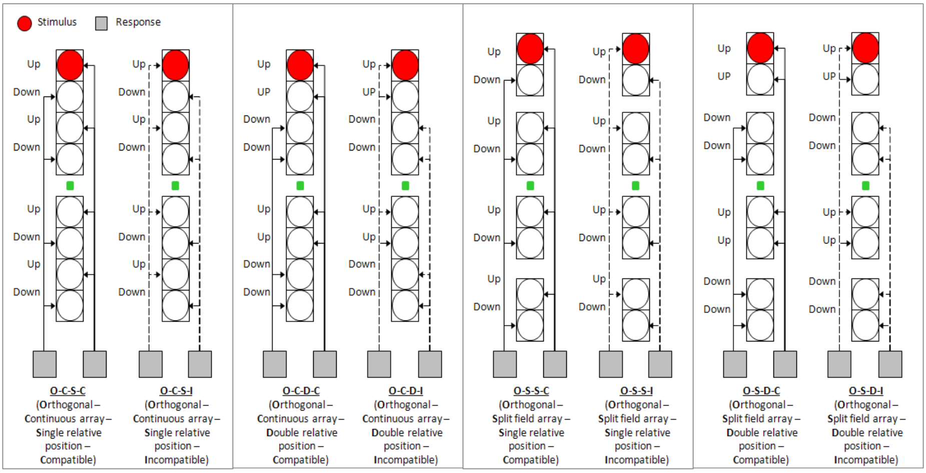

Fig. 2. Eight testing conditions in orthogonal S-R spatial orientation

It was hypothesized that: a) parallel configurations between displays and controls were better than orthogonal configurations as a result of the congruent spatial dimensions (both in horizontal dimension) of the stimulus and response sets; b) the performance under the split array – with only two boxes connected – surpassed that under the continuous array – with four boxes connected, as the relative position of right-left (up-down) was more salient in the split field setting, providing a strong cue for producing responses; c) the mappings under compatible conditions were superior to those under incompatible ones in terms of reaction time and accuracy due to the less recoding and higher rate of information transfer during the responding process [10]; d) the response performance on the single relative position alignment was better than the double one as the right-left (up-down) cue (reference frame) was more prominent.

2 Method

2.1 Design

In this study, two stimulus-response orientations (parallel and orthogonal) were tested. For the parallel orientation, the stimulus and response sets were placed horizontally and in parallel to each other, while for the orthogonal orientation, the stimulus array was vertically presented and perpendicular to the response keys. In each spatial orientation, there were eight testing conditions combining the factors of stimulus grouping (continuous array vs. split field array), alignment (single vs. double) and S-R compatibility (compatible vs. incompatible). Eight code names were defined to represent the eight testing conditions that to be tested for each participant in the parallel orientation: P (Parallel)-C (Continuous array)-S (Single relative position alignment)-C (Compatible), P-C-S-I (Incompatible), P-C-D (double relative position alignment)-C, P-C-D-I, P-S (Split field array)-S-C, P-S-S-I, P-S-D-C and P-S-D-I. For testing of the orthogonal orientation, eight similar code names were also defined, which were O (Orthogonal)-C-S-C, O-C-S-I, O-C-D-C, O-C-D-I, O-S-S-C, O-S-S-I, O-S-D-C and O-S-D-I. 30 participants were recruited and randomly divided into five groups of six participants each, and the test sequence of each group was in a quasi-random order so that each participant was tested with all the sixteen testing conditions. In a trial, the visual stimulus was lit up in red randomly in one of the eight possible signal locations. Each signal position was tested four times in a random order for each testing condition. Participants needed to respond to the lit up signal with the two square response keys under the stimulus array. The 16 testing conditions were explicitly shown in Fig.1 and 2.

2.2 Apparatus and Stimuli

This experiment was carried out using a personal computer with a 17-inch touch-screen display. The computer language Visual Basic 2010 was employed for stimulus preparation and response data collection. The touch-screen display was tipped at an angle of 15 degree from horizontal for ensuring comfortable responses made by participants. Eight identical 15-mm diameter stimulus circles with each embedded in a square box were presented in two linear array types (continuous array vs. split field array) (Fig. 1). During the stimulus presentation, one of the stimulus circles would be lit up in red. Each stimulus array type was tested in both parallel and orthogonal orientations relative to two horizontally aligned response keys positioned underneath. A green square of 10-mm side length was shown at the center of the stimulus array serving as a fixation point as well as a warning signal before stimulus presentation. Two grey square-shaped response keys of 20-mm side length each were positioned below the stimulus array on the immediately left and right sides of the midline of the display, and to be responded by participants' index and ring fingers of their right hand, respectively.

2.3 Participants

Thirty Chinese students of City University of Hong Kong (22 males and 8 females) of ages 21-25 participated in this experiment. They were all right-handers as tested with the Lateral Preference Inventory [22]. All of them had normal or corrected-to-normal vision (Optical Co., Inc., Model 2000P Orthorator) and normal color vision (Ishihara Pseudo isochromatic Plates). They all gave informed consent before the start of the experiment and did not report any physical or health problems for the hands (fingers) they used for the test.

2.4 Procedure

There were 16 testing conditions for each participant. Each condition contained 15 practice trials and 32 test trials. Participants were required to have at least 13 correct trials in the practice session prior to the start of test trials in each test condition. Before testing, participants were asked to position their left index and right ring fingers of the right hand above the two virtual keys with their wrists supporting by a soft cushion. They were instructed about the spatial mappings being tested in that particular condition. At the beginning of each trial, the participant fixated a lit up green square signal. After a delay of 1-3 s, one of the eight visual stimuli lit up in red. Participants then touched the control key according to the condition being tested. The fixation green square and red stimulus remained lit for 1 s or until the participant made a response. Responses made with the wrong keys were counted as errors and those made before 150 ms or after 1100 ms were considered to be misses (errors). The green square was then reset and lit up again after 1 s, indicating the start of another trial. Participants were asked to react as fast and accurately as they could. No feedback on speed or accuracy was given. There was a 2-min break for participants after testing each mapping condition. Participants' reaction times and errors were recorded for further analysis.

3 Results

A total of 16,042 (30 participants x 16 conditions x 32 trials + 682 make-up trials) responses were collected in this study. Overall, 682 (4.25%) responses were incorrect or made after the time limit. Therefore, a total of 15,360 (95.75%) correct responses were thus used for further analysis.

3.1 Mean Reaction Time

The 15,360 correct RTs were within the range of 356-1014 ms, with a mean of 791 ms and a standard deviation of 118 ms. Individual participants' mean RT ranged from 654 to 918 ms. The mean RTs for different testing conditions are summarized in Table 1. Amongst the 16 testing conditions, the shortest value (745 ms) was obtained for the condition 'P-S-S-C', while the longest value (817 ms) was for the condition 'O-C-S-C'. The average mean RTs computed for orientations of 'Parallel' and 'Orthogonal' were 786 and 795 ms respectively. It can also be seen that the effect of grouping influenced RTs such that conditions with split field array had better RTs than with continuous array regardless of the stimulus orientation. As to the alignment effect, the single relative position alignment (781 ms) was responded to faster than the double one (791 ms) in the parallel orientation, while there was no marked difference between the two alignments in the orthogonal orientation. Interestingly, the effect of spatial compatibility existed only in the parallel orientation that compatible mappings were always responded to faster than incompatible mappings, whereas the opposite results were obtained in the orthogonal orientation.

Further examination of RT was performed with repeated-measures ANOVA. The main factors considered were stimulus orientation, grouping, alignment and S-R compatibility. The results showed that the main factors of orientation [$F_{(1, 29)} = 4.71$, $p < 0.05$] and grouping [$F_{(1, 29)} = 23.18$, $p < 0.001$] were significant, as were the two-way interactions of grouping x alignment [$F_{(1, 29)} = 43.89$, $p < 0.001$] and orientation x S-R compatibility [$F_{(1, 29)} = 19.32$, $p < 0.001$]. There were no significant differences for the effect of alignment and S-R compatibility as well as other two-way and three-way interactions (*p's* > 0.05). As suggested by the sparsity-of-effects principle that a system or process is driven primarily by some of the main effects and low-order interactions [23], only the interactions of up to three factors were considered here. Regarding the two significant main factors, responding to the parallel orientation was found to be significantly faster than to the orthogonal orientation, and the split array led to significant RT advantage than did the continuous one. In respect of the two-way interaction effects of grouping and alignment, an interaction plot is shown in Fig. 3. It shows that there was no obvious RT difference between the continuous and the split array for the double relative position alignment. However, for the single relative position alignment, with the split array, a marked reduction in RT was resulted. As for the interaction effect of orientation and S-R compatibility, Fig. 4 illustrates that the effect of spatial compatibility affected participants' response performance oppositely under the different stimulus orientations. For the parallel orientation, as expected, compatible mappings resulted in faster RTs, while incompatible mappings in slower RTs. However, for the orthogonal orientation, the opposite result was obtained that compatible and incompatible mappings contributed to slower and faster RTs, respectively. This somewhat unexpected result provides a good piece of evidence that mapping a right key to an up stimulus and a left key to a down stimulus does not always lead to better response performance or even degrades the performance, at least for the stimulus-response sets used here.

Table 1. Mean reaction times (RT) (ms) and error percentage (EP) (%) computed for different testing conditions

Orientation	Array	Alignment	Condition	Mean (SD)
Parallel (RT: 786, EP: 4.64)	Continuous array (RT: 797, EP: 4.92)	Single (RT: 800, EP: 5.42)	P-C-S-C	RT: 793 (118), EP: 2.60 (2.73)
			P-C-S-I	RT: 807 (109), EP: 8.23 (12.70)
		Double (RT: 794, EP: 4.43)	P-C-D-C	RT: 787 (123), EP: 1.98 (2.78)
			P-C-D-I	RT: 800 (113), EP: 6.88 (8.93)
	Split field array (RT: 775, EP: 4.35)	Single (RT: 762, EP: 1.67)	P-S-S-C	RT: 745^{A} (124), EP: 0.73^{A} (2.12)
			P-S-S-I	RT: 779 (108), EP: 2.60 (3.19)
		Double (RT: 788, EP: 7.03)	P-S-D-C	RT: 786 (129), EP: 5.00 (4.83)
			P-S-D-I	RT: 790 (116), EP: 9.06^{B} (8.06)
Orthogonal (RT: 795, EP: 4.23)	Continuous array (RT: 803, EP: 3.88)	Single (RT: 810, EP: 3.96)	O-C-S-C	RT: 817^{B} (116), EP: 5.42 (4.99)
			O-C-S-I	RT: 803 (105), EP: 2.50 (3.32)
		Double (RT: 795, EP: 3.81)	O-C-D-C	RT: 812 (120), EP, 4.90 (5.90)
			O-C-D-I	RT: 778 (108), EP: 2.71 (4.84)
	Split field array (RT: 788, EP: 4.58)	Single (RT: 777, EP: 3.07)	O-S-S-C	RT: 808 (120), EP: 3.33 (4.26)
			O-S-S-I	RT: 746 (112), EP: 2.81 (8.93)
		Double (RT: 799, EP: 6.10)	O-S-D-C	RT: 812 (120), EP: 7.19 (6.04)
			O-S-D-I	RT: 786 (116), EP, 5.00 (4.96)

^{A} The shortest RT / ^{B} The longest RT.

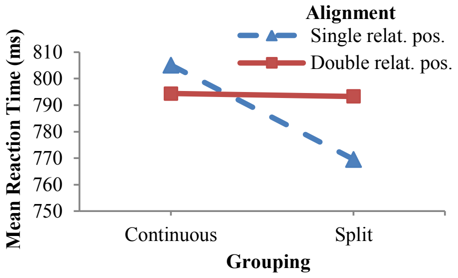

Fig. 3. Interaction plots of mean reaction times (RTs) for stimulus grouping and alignment

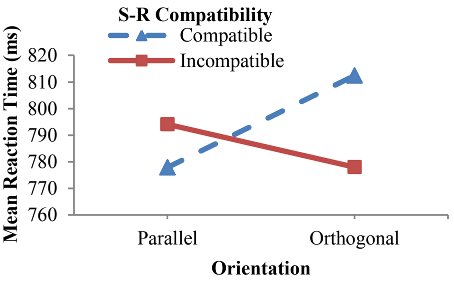

Fig. 4. Interaction plots of mean reaction times (RTs) for stimulus orientation and S-R compatibility

3.2 Mean Response Error

Altogether participants made a total of 682 (4.25%) incorrect or missing responses. The mean error percentages (EP) for the 16 testing conditions are shown in Table 1. The most accurate condition was 'P-S-S-C' (EP = 0.73%), while the least was 'P-S-D-I' (EP = 9.06%). Further analysis of the mean EP was performed with the non-parametric Friedman Test, and it showed there were significant differences among the 16 testing conditions (χ^2 (15) = 104.72, $p < 0.001$). Wilcoxon signed-rank test was then conducted to investigate the differences in EPs between each factor. The results showed there were no significant differences in EPs (*p's* > 0.05) between the parallel (EP = 4.64%) and orthogonal (EP = 4.23%) orientations, continuous (EP = 4.40%) and split (EP = 4.47%) groupings, as well as compatible (EP = 3.89%) and incompatible (EP = 4.97%) mappings. Only the factor of stimulus alignment was found to be significant ($p < 0.001$) that the EP for the double relative position alignment (EP = 5.34%) was significantly larger than that for the single one (EP = 3.53%). The results suggest that the conditions that provided salient relative spatial correspondence between stimulus and response were less prone to error responses, and although not significant, less error responses were made for mapping a left key with up stimuli and a right key with down ones.

4 Discussion

In this study, two control keys were used to respond to eight visual signals arranged in parallel and orthogonal orientations. It was found that participants responded significantly faster to the horizontally presented stimulus arrays than to the vertically presented ones. It may be due to the fact that the parallel orientation could provide congruent spatial dimension and obvious spatial correspondence between the stimulus and response sets, thereby resulting in faster responses. However, for the orthogonal orientation, the mapping between the stimulus and response sets depended upon their relative salience, requiring an additional translation step for stimulus-response mapping and thus resulting in longer reaction time. Moreover, faster reaction times were obtained for the conditions with the split field array than that with the continuous array in both parallel and orthogonal orientations. It is believed that the split field array could provide participants with more salient right-left and up-down reference frames for the parallel and orthogonal orientations, respectively, leading to better response performance. The main factor of alignment alone was nonsignificant, but its interaction effect with grouping was significant such that the single relative position alignment with the split grouping resulted in much faster RT than that with the continuous grouping, while no much difference in RT was observed for the double relative position alignment between the two different groupings. This finding suggests that if stimulus signals cluster together, the salience of left (up) and right (down) coding will be weakened, probably due to the influence of adjacent stimuli. Overall, the result showed that the condition 'P-S-S-C', which had the clearest relative spatial correspondence, yielded the best performance amongst all the test conditions. From the reaction time examination, it is noted that there was no significant differences between compatible and incompatible conditions. However, with the significant interaction effect of orientation and S-R compatibility, for the conditions with orthogonal orientation, the mean reaction times for compatible conditions (i.e. the left key for up signals and the right key for down signals) were significantly faster than that for incompatible conditions (i.e. the left key for down signals and the right key for up signals). This finding of preferable left-up and right-down mapping was consistent with the previous study of Bauer and Miller [17] (experiment 3) showing different mapping preferences for the left and right hands towards vertical stimuli and horizontal responses. They found that left-up and right-down mapping was preferable for the right hand, whereas right-up and left down for the left hand. However, the response preferences towards orthogonal mapping are rather mixed that some other studies reported that right-up and left-down mapping was of greater preference, seemingly due to salient features coding between the stimulus and response directions [4]. Nevertheless, the finding of this study demonstrated that left-down and right-up mapping relationship responding with right hand was very robust.

5 Conclusion

For the eight visual signals and two controls interacted horizontally and vertically with different S-R mapping types, it was found that the conditions in the parallel S-R orientation resulted in better response performance than in the orthogonal orientation. Besides, for stimulus grouping, visual signals split into two rather than four in a group could provide salient reference frames for the stimulus and response set and thus achieving faster reaction time. For the different stimulus alignments, the single relative position alignment was less prone to error responses than the double one, but no significant difference in reaction times was found between the two alignments. An interaction effect of grouping and alignment was observed that participants responded very differently towards the continuous and split arrays with the single relative position alignment. Also, with the orthogonal orientation, the left-up and right-down mapping yielded better response performance, which was different from the results of some previous studies showing the better response performance of right-up and left-down mappings, implying the intricate stimulus-response mappings here and cultural factors might affect the compatibility relations in this orientation [24].

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