Correspondence and Non-correspondence of Spatial and Anatomical Finger Distance on Spatial Compatibility

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Abstract— **This study investigated the effects of correspondence and non correspondence of anatomical distance and spatial distance on spatial compatibility using a unimanual two-finger choice reaction time task. The task was to respond for visual stimuli appearing either on the left or right side of a central fixation point under different finger responding conditions. The finger responding conditions involved three different matchings between anatomical finger distance and spatial key distance. Within the three finger responding conditions, two pairs of fingers with different anatomical distances were assigned to two different sets of response key differing in spatial distance for response. The results showed that if the anatomical distance between fingers did not correspond to the spatial key distance, the size of spatial compatibility effects would be decreased.**

Index Terms— **finger compatibility, spatial distance, anatomical distance**

I. Introduction

Displays and controls are important to almost every human activity today, ranging from relatively simple computer and machinery operations to complex cockpit operations, interactive driving simulations, and satellite positioning [1] – [3]. Displays and controls may refer to stimuli and responses, respectively, where displays give operational status information of the systems to operators and controls enable them to take the necessary action to change or affect system states. It was shown that people are generally fairly consistent in their choice of responses for specific stimuli and there are preferred pairings between elements in the stimulus set of a display with those in the response set of a control device. Population stereotype is a term to describe such phenomenon [4]. In human-machine studies, population stereotype is usually expressed as the probability with which a response is chosen, whereas stimulus-response (S-R) compatibility is illustrated by the speed and accuracy with which a response is elicited. The term compatibility was firstly introduced by A. M. Small and was later refined by Fitts and Seeger [5], which states that human performance relies not only on the type of signal or response arrays used but also on the pairing of individual signals with responses, and the reaction times (RTs) to a stimulus relies on the relation between the stimulus and response sets. 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 [6, 7]. An illustration of the importance of spatial compatibility for practical interface design consideration is noted in the layout of the functional keys of a keyboard and the corresponding labels for these keys on the screen [8]. The result showed that when the labels on the screen are arranged in a manner physically similar to the keys on the keyboard, obvious reaction-time advantage was shown.

A typical example of spatial S-R compatibility study with visual signals involved the pressing of a right or left key in response to a light appearing to the right or left of a fixation point on a screen. Reactions for the spatially compatible S-R mappings were always faster than those with incompatible S-R pairings [6, 9, 10]. The decrease in visual RT for compatible S-R pairing has been accounted for by the 'natural' tendency to respond in the direction of stimulation. The concept of spatial compatibility, however, has also been explained by the coding hypothesis which proposes that there is a coding process for spatial positional information of the signals and the response keys [11]. The higher efficiency and accuracy of a compatible S-R combination is probably due to lower coding demands and higher rates of information transfer. The incompatible pairing of signal and response positions requires an additional translation step in reversing the spatial codes and thus reaction time is increased and more errors are committed.

Given the importance and prevalence of auditory displays in control rooms, more recent spatial S-R compatibility studies were conducted with testing of auditory signals [12]. Some recent studies showed that spatial S-R compatibility effect exists not only in hand controls but also in foot controls. Chan & Chan [13, 14] recently conducted an experiment on spatial S-R compatibility for foot controls with visual displays and found that a significant improvement of reaction time with the correspondence of the stimulus and response key in both transverse and longitudinal orientations. With the increasing complexity of human-machine systems, designs of control console become more complicated. Most of the previous studies have been limited to situations where visual signals and controls are each positioned on two-dimensional planes, which are either parallel or orthogonal to each other [13, 15]. In order to have a more in-depth study of the human-machine systems, Chan & Chan [14] have recently conducted a research on spatial compatibility relationships between three-dimensionally spaced visual signals and response devices concurrently manipulated by both hands and feet. A significant interaction of visual signal position and response

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device position was shown indicating the existence of S-R compatibility effects in the task. The findings may give an implication for designing visual displays and control devices in three-dimensional space for improving overall human-machine system performance.

Studies concerning spatial S-R compatibility effects have mostly been done with hand or foot responses. Little work on finger spatial S-R compatibility has been conducted. Among the few exceptions is that by Bradshaw and Perriment [16], Katz [17], Heister and his colleagues [18, 19, 20]. Their studies indicated that spatial compatibility effects exist not only on hands and feet, but also on fingers. Bradshaw and Perriment [16] studied laterality effects and choice reaction time in a unimanual two-finger task. Participants were asked to respond for one of two stimulus lamps appearing on either left or right visual field in a presentation. Their results showed that reaction time for compatible condition was faster than that of incompatible condition with a 20 ms mean difference. Katz [17] found that spatial S-R compatibility effect existed between stimulus locations and responding fingers. It was shown that compatible pairings between visual stimulus and response finger obtained RT advantages than incompatible pairings disregarding the hand used for responding. Heister *et al.* [18] studied the effect of finger compatibility with participants using middle and index fingers to respond towards a left or right visual stimulus in prone and supine hand orientations. The results showed that strong compatibility effect between left and right stimulus field and spatially left and right finger was obtained in both hand orientations. Ehrenstein *et al.* [19] studied the effect of spatial orientation between response keys and stimuli on finger spatial compatibility. The experiment tested with unimanual two-finger choice reactions in an orientation of response keys parallel or perpendicular to the orientation of the stimuli with both palm-up and palm-down positions. The results showed that spatial S-R compatibility was found not only for horizontal S-R relationship but also for different orthogonal S-R mappings.

In a more recent work, Heister *et al.* [20] studied the change in compatibility effect with different relative distance of responses keys and responding fingers and they found that size of the spatial compatibility effect depends only on the spatial distance of the responding fingers, but not the anatomical distance of different pairs of fingers. However, they did not give any reasons to account for the results. In order to have a clearer understanding of the effect induced by difference between spatial distance and anatomical finger distance on spatial S-R compatibility, we replicated Heister *et al*.'s [20] experiment on one hand to identify the possible reasons for the results obtained by them and on the other hand to improve the reliability of results with a larger number of participants being tested.

In this study, the spatial distance is the separation of response keys on a control box. A wide (110 mm) and a narrow (45 mm) spatial distance were tested. Two anatomical distances of fingers, between the second (index) and fourth (ring) fingers, and between the first (thumb) and fifth (little) fingers, were examined. Varying the combinations of spatial distance and anatomical distance, three different finger responding conditions; a) second and fourth fingers operating narrow keys, b) first and fifth fingers operating wide keys, and c) first and fifth fingers operating narrow keys were tested in this experiment. Condition a and condition b were different in both spatial key (finger) distance and anatomical finger distance. For condition a and condition c, the difference between conditions was the anatomical distance between finger pairs, while it was the difference between spatial key (finger) distance for condition b and condition c. We hypothesized that with a similar design to that of Heister *et al.*'s [20] experiment, the results here should be similar. That is, the spatial S-R compatibility effect for two-finger choice reactions depends on the purely spatial rather than anatomical relations of the responses. If different findings are shown, there might be some factors contribute to the difference for consideration.

II. METHOD

A. Participants

Twelve male Chinese from the City University of Hong Kong between ages of 20-30 (median = 23) participated in this experiment. They were all right-handers as tested with the Oldfield [21] Handedness Questionnaire. All of them had normal or corrected-to-normal vision (Optical Co., Inv. Model 2000P orthorator) and normal color vision (Ishihara Pesudo Isochromatic Plates). They gave informed consent and were provided with a clearly set of instructions before the start of the experiment.

B. Design

Three different finger responding conditions were examined in terms of spatial compatibility effects in this experiment for all participants. These test conditions were a) second and fourth fingers operating narrow keys, b) first and fifth fingers operating wide keys and c) first and fifth fingers operating narrow keys. Participants were instructed to respond by pressing the left response key for left visual signal and right response key for right visual signal in the compatible mapping condition (C). The mapping for signal-key positions was reversed in the incompatible mapping condition (I) so that the left and right keys corresponded to right and left signals, respectively. The purpose of the three test conditions were to test whether finger compatibility effect changed with different spatial and anatomical distances between responding fingers. The spatial key distance and anatomical distance between responding fingers were matched with each other in condition a and condition b. In condition c, however, the anatomical distance between responding finger pair did not match with the spatial key distance needed to response with. The purpose of finger condition c was to evaluate the compatibility effect in a situation that participants used their first and fifth fingers to operate the narrow keys which were normally for second and fourth fingers. A total of 12 blocks of test (2 response hands x 2 compatibility conditions x 3 finger conditions) was conducted for each participant. The order of testing of the main factors was randomized across the participants. Each block consisted of ten practice trials followed by 30 test trials (15 random presentations in each of the right and left stimulus fields). There was a one minute break between two blocks of test.

C. Apparatus and Stimuli

A personal computer running the Visual Basic language was used to develop an application program for stimulus presentation and data collection. The visual stimulus was presented at a viewing distance of 600 mm from participants. It was delivered from one of the two red light-emitting diodes positioned at 10^{o} of visual angle to the left and right of a black circle for centre fixation. The stimulus presentation duration was 100 ms. The "←" and "→" keys (45 mm separation) on the keyboard were regarded as the narrow keys for the left and right responses, respectively. For the wide keys testing, the "Ctrl" and "0" keys (110 mm separation) were for the left and right responses, respectively. The narrow keys were operated by second and fourth fingers in condition a and first and fifth fingers in condition c. The wide keys were operated by first and finger in condition b only. An adjustable chair was provided to participants to make sure the line of sight was nearly perpendicular to the centre of the stimuli.

D. Procedure

Before the test, visual and verbal instructions of the tests were given to participants. All participants attended the two sessions of tests on two different days. They responded with their right hands in the first session and left hands in the second session. 10 practice trials were given at the beginning of each session, and then 30 test trials were presented. A visual signal was presented randomly from either left or right side in each test trial. Subjects were asked to press the left and right response keys for the left and right visual signals, respectively, in the compatible conditions and press the left and right keys for the right and left visual signals, respectively, in the incompatible conditions. Before the presentation of a stimulus, participants had to fixate their eyes to the black fixation point at the centre. Once the stimulus was presented, participants responded with the corresponding fingers pressing the appropriate keys according to the test conditions. Subjects were asked to react as fast and accurately as they could. The reaction time and accuracy were recorded for analysis.

III. Results

A. Mean Reaction Time

Table I shows different reaction times computed in the experiment. Participants had the fastest average RT for condition b (319 ms) and the slowest average RT for condition c (340 ms). For condition a, the right visual stimulus responded by right hand and right finger was the fastest with a mean RT of 304 ms. The slowest response was the left stimulus responded by right hand and right finger (338 ms). Similar to condition a, the fastest responses for condition b and c were obtained in the situation of right visual stimulus responded by right hand and right finger. The mean RTs were 302 ms and 319 ms for condition b and c, respectively. Different from condition a, the slowest responses for condition b (343 ms) and c (359 ms) were obtained when the left stimulus were responded by left hand and right finger. For the effect of S-R mapping, RT of compatible mapping (319 ms) was 5.3% faster than incompatible mapping (336 ms). The RT difference between compatible mapping and incompatible mapping were 19 ms, 11 ms and 22 ms for conditions a, b and c, respectively (Table II).

TABLE I
MEAN REACTION TIMES (RTS) IN DIFFERENT TEST CONDITIONS.

Condition	Stimuli Field	Response Hand	Response Finger	Mean RT (ms)	Overall Average (ms)
a	L	L	L	313	321
			R	325	
		R	L	312	
			R	338	
	R	L	L	336	
			R	318	
		R	L	323	
			R	304	
b	L	L	L	330	319
			R	343	
		R	L	322	
			R	322	
	R	L	L	317	
			R	305	
		R	L	313	
			R	302[a]	
c	L	L	L	336	340
			R	359[b]	
		R	L	328	
			R	354	
	R	L	L	348	
			R	332	
		R	L	343	
			R	319	

L: Left R: Right
[a] The shortest RT
[b] The longest RT

TABLE II
MEAN REACTION TIMES (RTS) IN DIFFERENT S-R MAPPING CONDITIONS.

S-R Mapping	Condition	Mean RT (ms)	Overall Average (ms)
Compatible	a	312	319
	b	315	
	c	329	
Incompatible	a	331	336
	b	326	
	c	351	

Further examination of RTs was performed with the analysis of variance (ANOVA), and the results are presented in Table III. The main factor considered were finger condition (a, b and c), stimulus field (left and right), response hand (left and right) and response finger (left and right). The results showed significant finger condition effect ($F_{(2, 144)} = 9.71$, $p < 0.001$) and stimulus field effect ($F_{(1, 144)} = 7.41$, $p < 0.001$). The main factors of response hand and finger were not significant ($p > 0.05$). For two way interaction effect, only the interaction of stimuli field x finger ($F_{(1, 144)} = 18.22$, $p < 0.001$) was significant. No significant effects were found for three, four and five way interactions between factors. Post-hoc analysis was conducted to examine the significant difference between the levels of the main factors. The effect of stimulus field showed that participants responded significantly shorter ($p < 0.001$) to right visual signal than left visual signal with a mean RT difference of 10 ms. Fisher's LSD test was used to test the main factor of experimental condition (Table IV). The results showed that there was no significant difference of mean RTs between condition a and b ($p > 0.05$). Mean RT of condition c showed significantly longer mean RT than condition a ($p < 0.001$) and b ($p < 0.001$) with the mean difference of 20 ms.

TABLE III
RESULTS OF ANALYSIS OF VARIANCE ON MEAN REACTION TIME.

Source	SS	df	MS	F
Main effect				
Condition	22967.36	2	11483.68	9.71***
Stimuli Field	8763.07	1	8763.07	7.41***
Hand	2490.08	2	2490.08	2.10
Finger	53.61	1	53.61	0.05
Two-factor Interaction				
Condition * Stimuli Field	5359.08	2	2679.54	0.108
Condition * Hand	197.62	2	98.81	0.08
Condition * Finger	69.07	2	34.54	0.03
Stimuli Field * Hand	526.08	1	526.08	0.44
Stimuli Field * Finger	21559.71	1	21559.71	18.22***
Hand * Finger	11.27	1	11.27	0.01
Error	170349.6	144	1182.98	
Total	347721.42	287		

**p* < 0.05, ***p* < 0.01, ****p* < 0.001

TABLE IV
POST-HOC ANALYSIS WITH LSD TEST ON TEST CONDITIONS.

	Condition (I)	(J)	Mean Difference (I) – (J)
Mean RT (ms)	a	b	0.73
		c	-18.57***
	b	c	-19.30***

**p* < 0.05, ***p* < 0.01, ****p* < 0.001

Interaction plot of the mean RT for stimulus field and response finger was shown in Figure 1. The interaction plot shows that when responding to left visual signal, the mean RT of left finger response (324 ms) was shorter than that of right finger response (340 ms). On the contrary, if right visual signal was displayed, participant's mean RT with right finger response (313 ms) was shorter than that with left finger (330 ms).

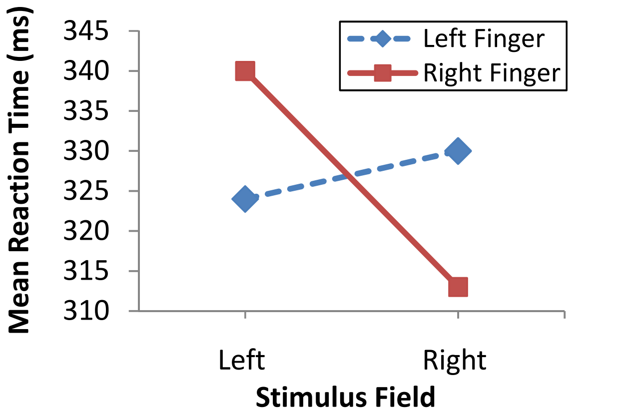

Fig. 1. Interaction plot of the mean RTs for stimulus field and response finger.

The interaction plots between stimulus field and responding finger of each finger responding condition are shown in Figures 2, 3, and 4. The interaction of different conditions shows that RT of compatible mapping was shorter than that of incompatible mapping.

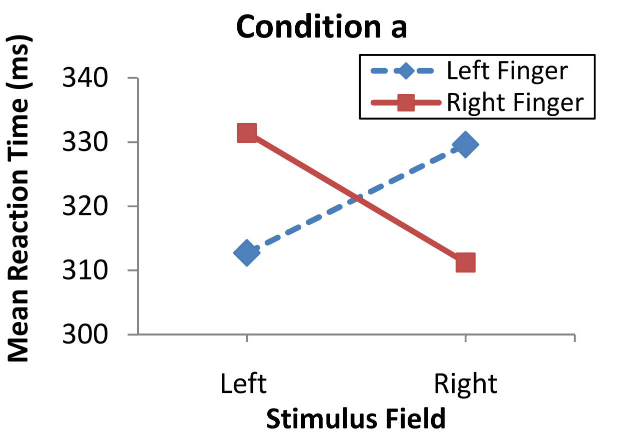

Fig. 2. Interaction plot of the mean RTs for stimulus field and response finger in condition a.

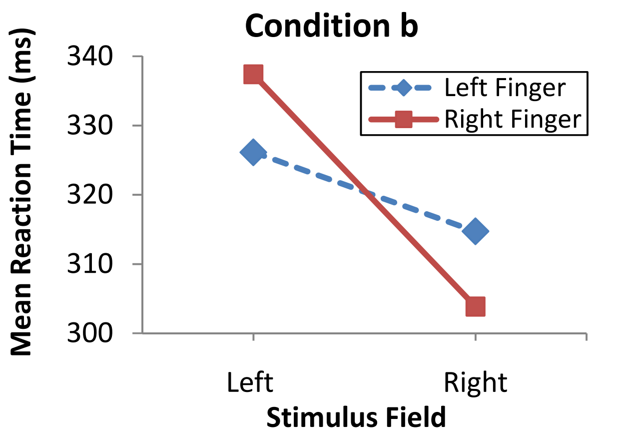

Fig. 3. Interaction plot of the mean RTs for stimulus field and response finger in condition b.

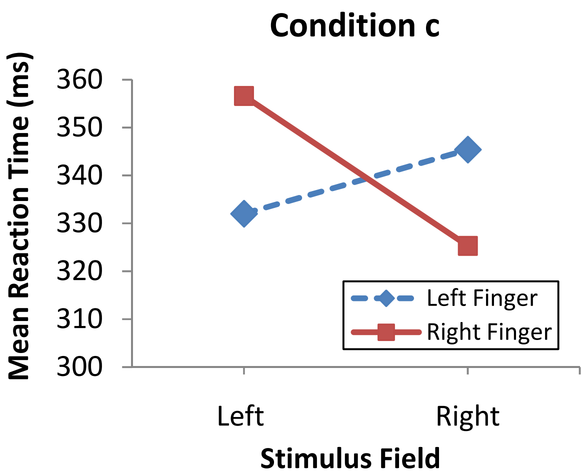

Fig. 4. Interaction plot of the mean RTs for stimulus field and response finger in condition c.

B. Response Error

Error percentages of different finger responding conditions are summarized in Table V. The mean error percentages (EPs) for conditions a and b were similar. Condition c was with the highest mean EP (20.81%) among the three finger responding conditions. Right response hand showed smaller mean EP than that of left response hand disregarding of the conditions tested. The difference in response error between left and right hand response was the smallest in condition b (0.27%). Comparing compatible mapping to incompatible mapping, the mean EP of the compatible mapping was 3.94% smaller than the incompatible mapping. The EP difference between compatible mapping and incompatible mapping were 2.71%, 3.47% and 5.65% for condition a, b and c, respectively (Table VI).

Analysis of variance (ANOVA) was performed and the results are summarized in Table VII. It showed that only the main factor of the compatibility mapping exhibited significant effect on mean error percentage ($F_{(1,132)} = 6.12$, $p < 0.05$). The mean EP of compatible mapping was significantly smaller than incompatible mapping ($p < 0.05$). No significant two-factor and three-factor interaction effects were found ($p > 0.05$).

TABLE V

MEAN ERROR PERCENTAGES (EPS) IN DIFFERENT TEST CONDITIONS.

Condition	Response Hand	Mean Error (%)	Overall Average (%)
a	Left	18.40	17.19
	Right	15.97	
b	Left	17.01	16.88
	Right	16.74	
c	Left	21.60	20.81
	Right	20.01	

TABLE VI

MEAN ERROR PERCENTAGES (EPS) IN DIFFERENT S-R MAPPINGS

S-R Mapping	Condition	Mean Error (%)	Overall Average (%)
Compatible	a	15.83	16.32
	b	15.14	
	c	17.98	
Incompatible	a	18.54	20.26
	b	18.61	
	c	23.63	

TABLE VII

RESULTS OF ANALYSIS OF VARIANCE ON MEAN ERROR PERCENTAGES.

Source	SS	df	MS	F
Main effect				
Condition	0.05	2	0.02	2.51
Mapping	0.06	1	0.06	6.12*
Response Hand	0.01	1	0.01	0.81
Two-factor interaction				
Condition* Mapping	0.01	2	0.00	0.30
Condition*Response Hand	0.00	2	0.00	0.15
Mapping *Response Hand	0.00	1	0.00	0.34
Three-factor interaction				
Condition*Mapping *Response Hand	0.00	2	0.00	0.21
Error	1.21	132	0.01	
Total	1.33	143		

$p < 0.05$, $**p < 0.01$, $***p < 0.001$

IV. DISCUSSIONS

This study demonstrated the effect of correspondence between anatomical distance and spatial distance of responding fingers on a unimanual two-finger choice reaction task [27]. Among the three finger responding conditions, conditions a and b were different in both spatial key (finger) distance and anatomical finger distance. For conditions a and c, the difference between conditions was the anatomical distance between finger pairs, while it was the difference between spatial key (finger) distance for conditions b and c. From the obtained results, it showed significant differences in mean RT between conditions a and c, and between conditions b and c, but not between conditions a and b. In conditions a and b, the anatomical distance between the finger pairs corresponded to the spatial key distance during operations; Therefore, it was more natural and comfortable for participants to press the keys. However, in condition c, the distance of the response keys did not match with the anatomical distance between the finger pair for responses. As a result, participants had to bend their fingers inwards in order to operate the narrow keys and such unnatural posture of the fingers may account for the slower response time obtained. The results indicated that the size of spatial S-R compatibility effect depends on both spatial and anatomical relation which is different to Heister et al.'s [20] finding that only spatial relations affected the size of spatial S-R compatibility effects for two-finger choice reactions. The results of this study give an implication of the importance of the correspondence between anatomical finger distance and spatial distance of response keys. If the spatial distance of the response keys was far less than the anatomical distance between the responding finger pair, it may cause difficulty in operation and result in slower RTs and higher EPs.

For the main factor of stimulus field, mean RT of the right stimulus field was shorter than the left stimulus field. The right field advantage can be explained by a left-hemispheric specialization for choice reactions [22]. In fact, the left hemisphere of right-handed people is dominant in recognizing the global properties of an environment. Thus the stimulus displayed to the right visual field (perceived by left hemisphere) was responded faster than those displayed to the left visual field (perceived by right hemisphere) for right handers [23]. Umilta & Nicoletti [24] explained the right field advantage as a general directedness of attention to the right visual field.

Strong interaction of stimulus field and finger showed a strong spatial compatibility effect for fingers. For compatible S-R mapping (right finger responds to right stimulus field and left finger responds to left stimulus field), the mean RT and EP were faster and more accurate than incompatible mapping (right finger responds to left stimulus field and left finger responds to right stimulus field). Compared with the incompatible S-R mapping, the mean RT and EP obtained were 4.8% faster and 3.9% more accurate for compatible mapping. The higher efficiency and accuracy of a compatible S-R combination is probably due to lower coding demands and higher rates of information transfer. The incompatible pairing of signal and response positions requires an additional translation step in reversing the spatial codes and thus reaction time is increased and more errors are committed [25, 26].

V. Conclusions

The spatial stimulus–response compatibility effect for visual signals and responses with fingers was investigated in this study. The experiment findings are summarized and some ergonomic recommendations are made to improve the overall performance of operators on human-machine systems.

a) Strong spatial S-R compatibility effect for fingers was shown which implies that designs of human machine interface should be compatible between displays and controls in order to achieve a faster response time and higher accuracy.
b) Response time for visual signal on right visual field was shorter than left visual field. This suggests that important and critical information should be displayed on the right visual field for right-handed operators in order to obtain the response time advantage.

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