The Effect of Spatial Distance and Anatomical Distance on Finger Compatibility

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***Abstract*— Many studies have proofed that spatial coding is a dominant factor attributing to spatial S-R compatibility effects. However, anatomy-related factor is seldom studied. For exploring the possibility of separating spatial factor from anatomical factor in two-finger choice reaction, this study proposed a distinction between anatomical and spatial finger distances for testing. Testing of two pairs of fingers with differences in anatomical distance and spatial distance of response keys was conducted. The results showed that if spatial distance of response keys did not match with anatomical distance of fingers, slower response time (RT) and higher response error percentage (EP) were shown. Therefore, the spatial and anatomical relation should be considered carefully for the spatial S-R compatibility effects.**

***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 operation to the complex cockpit operation, interactive driving simulation, 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. 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 [5]. 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 [6]. 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 [7] – [9]. 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 [10]. 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.

Early spatial S-R compatibility studies on fingers were reported by Katz, Heister and his colleagues. Their studies indicated that spatial compatibility effects exist not only on hands, but also on fingers. Katz [11] 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.* [12] studied the effect of finger compatibility with participants using middle and index fingers to respond to 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.

Heister *et al.* [13] 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's experiment and tested with a larger number of participants for improve the reliability of results.

In this study, 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,

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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. Conditions a and b were different in both spatial and anatomical distance. Conditions a and c and conditions b and c were different in anatomical distance and spatial distance, respectively. It was hypothesized that with a similar design to that of Heister *et al.*'s [13] 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

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 [14] 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

Two spatial S-R mapping conditions (compatible and incompatible) and three different responding finger conditions were tested in this experiment for all participants. The finger 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 three finger conditions were tested for examining whether finger compatibility effect changed with different spatial and anatomical distances between responding fingers. 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 finger and fourth finger in condition a and first finger and fifth finger in condition c. The wide keys were operated by first finger and fifth 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 trails 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

The mean reaction time ranged from 319 ms to 340 ms for different test conditions. Participants had the fastest average RT for condition b and slowest average RT for condition c. For condition a, the right visual signal responded by right hand and right finger was the fastest with a mean RT of 304 ms. The slowest response was the left signal responded by right hand and right finger (338 ms). Similar to condition a, the fastest response for conditions b and c was obtained for the situation of right visual signal responded by right hand and right finger with mean RTs of 302 ms and 319 ms, respectively. Different from condition a, the slowest responses for condition b (343 ms) and c (359 ms) were obtained for the situation of left signal responded by left hand and right finger. Compatible mapping (319 ms) was 4.8% faster than incompatible mapping (335 ms).

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Further examination of RTs was performed with analysis of variance (ANOVA). 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. The results showed that there was no significant difference of mean RTs between conditions a and b ($p > 0.05$). Mean RT of condition c showed significantly longer mean RT than conditions a ($p < 0.001$) and b ($p < 0.001$) with the mean difference of 19 ms.

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

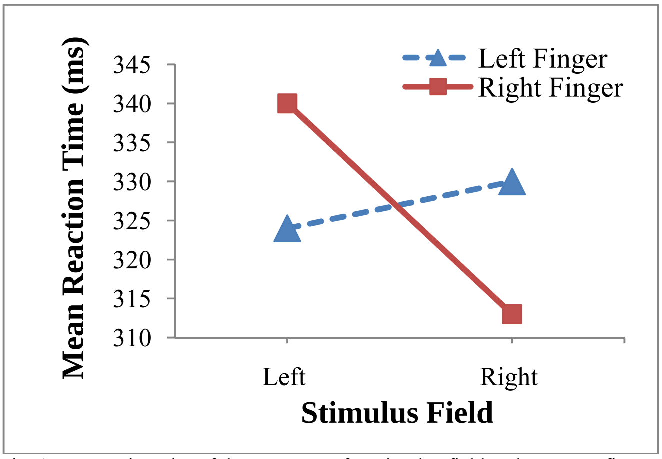

Fig. 1. Interaction plot of the mean RTs for stimulus field and response finger.

B. Response Error

The mean error percentages (EPs) for conditions a and b were similar. Condition c was with the highest mean EP (20.81%) amongst the three experimental conditions. Right response hand showed smaller mean EP than left response hand disregarding of the experimental conditions. The difference in response error between left and right hand response was the smallest in condition b (0.27%). Comparing compatible with incompatible S-R mapping, the mean EP of the compatible mapping was 3.94% smaller than the incompatible mapping. Again, right hand was with lower mean EP than left hand in both S-R mapping conditions.

Analysis of variance (ANOVA) was performed and 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 interaction effects were found ($p > 0.05$).

IV. DISCUSSIONS

Amongst the three finger conditions, conditions a and b differed in both spatial and anatomical distance. Conditions a & c and conditions b & c were different in anatomical distance and spatial distance, respectively. However, only conditions a & c and conditions b & c showed significant difference in mean RTs. In conditions a and b, the distance of the response keys corresponded to the anatomical distance of the fingers. Thus 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 of fingers. As a result, participants had to bend their fingers inwards in order to operate the narrow keys and the unnatural posture of the fingers may account for the slower response time obtained. The result indicated that the size of the spatial S-R compatibility effect depends on both spatial and anatomical relation which is different to Heister et al.'s [13] finding that only spatial relations affected the spatial S-R compatibility effect 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 of fingers, it may cause difficulty in operation and result in slower RT and higher EP.

For the main factor of stimulus field, without surprise, 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 [15]. 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 [16]. Umilta & Nicoletti [17] 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 [18, 19]. Similar to some previous studies, spatial S-R compatibility effects exist not only between visual stimuli and responding hands, but also between visual stimuli and responding fingers [12, 20, 21].

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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