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Ergonomic Recommendation for Optimum Positions and Warning Foreperiod of Auditory Signals in Human-Machine Interface

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Abstract. This study investigated the optimum positions and warning foreperiod for auditory signals with an experiment on spatial stimulus-response (S-R) compatibility effects. The auditory signals were presented at the front-right, front-left, rear-right, and rear-left positions from the subjects, whose reaction times and accuracies at different spatial mapping conditions were examined. The results showed a significant spatial stimulus-response compatibility effect in which faster and more accurate responses were obtained in the transversely and longitudinally compatible condition while the worst performance was found when spatial stimulus-response compatibility did not exist in either orientation. It was also shown that the transverse compatibility effect was found significantly stronger than the longitudinal compatibility effect. The effect of signal position was found significant and post hoc test suggested that the emergent warning alarm should be placed on the front-right position for right-handed users. The warning foreperiod prior to the signal presentation was shown to influence reaction time and a warning foreperiod of 3 s is found optimal for the 2-choice auditory reaction task.

Keywords: Ergonomic Interface Design, Control and Display, Auditory Display, Stimulus-response Compatibility.

1. INTRODUCTION

Controls and displays play an important part in almost every human task, ranging from simple computer and machinery operation to complicated cockpit operation, interactive driving simulation, and satellite positioning. Effective human-machine interfaces will obviously be advantageous in improving human performance, therefore it is becoming increasingly important to understand the interactions and relationships between display and control devices. Other than visual signals, the use of auditory signals has become more common in the design of information displays and warnings for reduction of high visual workload in many complex systems (Bronkhorst *et al.,* 1996; Nanthavanij and Yenradee, 1999). Industrial control systems, aircraft cabins, and computer interfaces often contain auditory signals that demand attention and action from control operators. It was shown that auditory signals can provide a means of conveying spatial information beyond the reach of visual field (Elias, 1995) and audible warning devices are also especially helpful in tracking mistakes by machines (Xiao and Seagull, 1999). The use of auditory signals also gives subjects a higher level of road sign information recall in a driving task (Mollenhauer *et al*., 1994). The unique features of auditory display systems give them advantages in signaling warnings and alarms and enhance the safety of, for example, the helicopter cockpit (Hass, 1998). It was reported that in some situations, auditory signals could be used to stimulate situational awareness and improve visual display effectiveness. Doyle and Snowden (1999) found that in a choice reaction task, the overall visual reaction time was facilitated by the use of auditory warning signals. The advantages of 3D-auditory displays in complementing existing visual displays were recently suggested by Chen and Carlander (2003). There are many control systems consisting of one or many auditory signals to be perceived and

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identified by operators (Chen, 2003). With the increasing use and importance of auditory signals in control consoles, there is an increasing concern to understand the interactions and relationships, and in particular the compatibility, between the displays and controls in such tasks. If appropriate spatial compatibility relationships are built between the control and display components in human-machine interface, the advantages may be faster learning, faster reaction time, fewer errors, and higher user satisfaction (Sanders and McCormick, 1993).

Fitts and Seeger (1953) introduced the concept of spatial stimulus-response (S-R) compatibility a long time ago and showed 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. This undoubtedly applies to situations where selection of a response is directly related to the position of a stimulus. The spatial S-R compatibility effect was widely studied using visual stimulus displays and manual response controls. For instance, the importance of spatial S-R compatibility for practical interface design has been demonstrated for the layout of the function keys on a keyboard and the corresponding labels for these keys on a screen (Bayerl *et al.*, 1988). Reaction times (RTs) were found shorter when the spatial positions of the control function keys and the display labels corresponded. A study on stove control-burner arrangements (Hsu and Peng, 1993) and another study on the use of a lever in response to a discrete stimulus (Chua *et al.*, 2001) also confirmed the significance of spatial compatibility for interface design in human-machine systems. Besides the aforementioned case studies, basic research aimed at fundamental understanding of spatial S-R compatibility with visual signals has been conducted with tasks involving 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 associated with spatially compatible S-R pairings were faster than those with incompatible S-R pairings (Roswarski and Proctor, 1996; Chan and Lau, 1999). The reduction of visual RT in spatially compatible S-R pairing was accounted for by the 'natural' tendency to respond in the direction of stimulation. The concept of spatial compatibility, however, has been explained by the coding hypothesis which proposes that there is a coding process of the spatial coding of positional information of the signal and response key (Umilta and Nicoletti, 1990). 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 (Chan *et al.*, 2001; Chan and Chan, 2004).

Although research has been conducted on the spatial compatibility using visual stimuli, the study of spatial compatibility with auditory stimuli is rare. Due to the fundamentally different nature of visual and auditory stimuli and the increasing importance of auditory stimuli in control consoles and other applications, the auditory spatial compatibility thus needs to be investigated. Chan *et al.* (2006) conducted a spatial S-R compatibility study with the auditory signals presented in transverse and longitudinal orientations relative to the listener. The results showed the inadequacy of the experimental setting as they found that such compatibility is restricted in some ways due to the difficulty of perceiving differences in auditory signals when the sound source is straight ahead or behind and there are no differences in intensity or phase of the sounds to be detected. Concerning the potential importance of relative stimulus-response positions and the limitation of sound perception in the longitudinal orientation, the current study was designed with sound sources located at the front-left, front-right, rear-left, and rear-right positions such that the auditory S-R compatibility effect in the transverse and longitudinal orientations could be analyzed simultaneously. Besides the spatial S-R compatibility effect, the effects of auditory stimulus position, response key position, and warning foreperiod were also examined. The results of this study were expected to help industrial designers to develop effective and user-friendly interfaces and provide practical recommendations for improving control consoles with auditory signals.

2. METHOD

2.1 Subjects

Fifteen male and fifteen female undergraduates of ages between 21 and 24 participated voluntarily in the experiment. They were all right-handed as tested with the Oldfield (1971) Handedness Questionnaire. All of them had normal or corrected-to-normal vision (Optical Co., Inc. Model 2000P orthorator), normal color vision (Ishihara Pesudo Isochromatic Plates), and passed a standard audiometric test (Peters Audiometer AP27) in which pure tones of 500, 1000, 2000 and 4000 cps were presented to each ear separately. No subjects had hearing loss greater than 20 dBA at any one of the four frequencies tested.

2.2 Apparatus and Stimuli

The experiment was conducted with the use of a personal computer and the computer language Visual Basic was employed for stimulus preparation and display, and data collection. Four speakers were located at the front-left, front-right, rear-left and rear-right positions, respectively with a distance of 500 mm from the nearest ear of the subject (Figure 1). They were placed at the ear level of the subject. The ambient sound level was less than 60 dBA and a tone of 790 Hz and 80 dBA was presented from a speaker to the subject in each trial.

The ambient sound level was less than 60 dBA and a pure tone ‘ding’ of 790 Hz and 80 dBA was presented from a speaker to the subject in each trial. The auditory stimulus was an attention tone selected from the Microsoft Windows’s sound library. The frequency of the selected tone was within human’s most sensitive range of 500 Hz to 3000 Hz and it was easily differentiated from the ambient environment. The intensity of the selected tone was sufficient high to avoid masking by the ambient noise and at the same time it did not cause subjects to be startled and affect their normal performance. The subject sat directly in front of a 15” color CRT monitor at a viewing distance of 500 mm. In a background of 5 cd/m^2, a green warning circle of 20 mm in diameter was filled to 135 cd/m^2 and placed in the centre of the screen for capturing subjects’ attention for the incoming auditory stimulus. With reference to the relative positions of sound sources, four response keys labelled as front-right, front-left, rear-right, and rear-left were provided on a control device and positioned on the same horizontal plane for inputting responses by the subjects. The results of this study were expected to give useful ergonomic recommendations for the design of computerized control consoles where auditory displays are utilized.

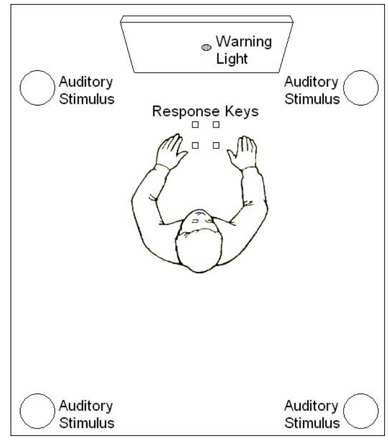
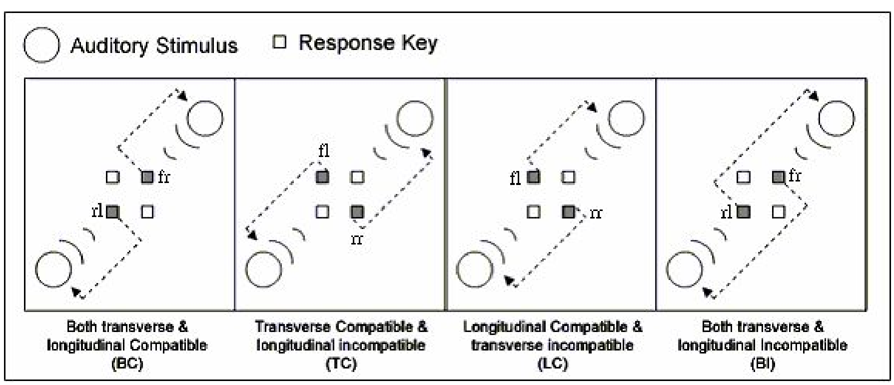


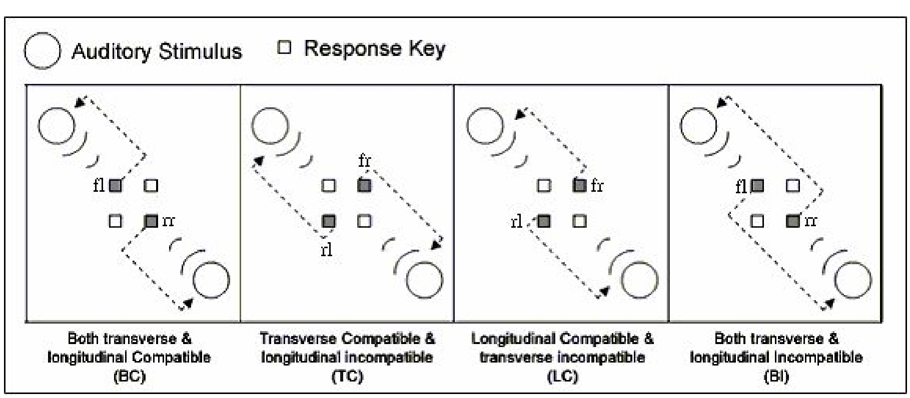
Figure 1. Experimental setup (not to scale)

2.3 Design

Two blocks of experiments with different sound orientations were tested. The front-right and rear-left positions of sound sources were tested in one block while the other two positions were tested in another block. For the block of front-right to rear-left sound orientation, four spatial S-R mappings were examined in



(a)



(b)

Figure 2. (a) The four S-R mappings tested in the block of front-right to rear-left sound orientation; (b) The four S-R mappings tested in the block of front-left to rear-right sound orientation (not to scale)

the transverse and longitudinal orientations as shown in Figure 2(a). They were: 'Both transverse and longitudinal Compatible (BC)', 'Transverse Compatible and longitudinal incompatible (TC)', 'Longitudinal Compatible and transverse incompatible (LC)', and 'Both transverse and longitudinal Incompatible (BI)'. In each mapping, a pair of auditory stimuli and a pair of response keys were positioned in such a way that the compatibility effects in the transverse and longitudinal orientations were studied. In the transverse orientation, subjects responded by pressing the left and right keys for the left and right tones, respectively under the compatible mapping condition. In the incompatible mapping condition, the left key was pressed for the right tone and the right key was pressed for the left tone. In the longitudinal orientation, subjects pressed the front key for the front tone and the rear key for the rear tone under the compatible mapping condition. The corresponding response keys for the tones were opposite in the incompatible mapping condition. In the BC mapping condition, auditory stimulus from a particular position was responded with the key on the corresponding side. In the BI mapping condition, stimulus was responded with the key on the opposite side. For example, when a stimulus from the front-right position was heard, the subjects would respond with the front-right (fr) key in the BC condition while they would respond with the rear-left (rl) key in the BI condition. In the TC and LC mapping conditions, compatible S-R mapping effect occurred in one orientation only. Similarly, four other S-R mappings were tested in the block of front-left to rear-right sound orientation as shown in Figure 2(b). Each subject performed all eight S-R mapping conditions and the order of testing of the conditions was counterbalanced across the subjects. There were eight practice trials and twenty trials in each mapping condition, within which the auditory stimulus was given randomly from one of the two auditory signal locations.

2.4 Procedure

Subjects were briefed with the objectives of the experiment and given verbal instructions at the beginning of testing. In each block of experiment, subjects were asked to place their left index fingers on the front left or rear left keys and their right index fingers on the front right or rear right keys in accordance with each spatial mapping condition. To ensure a reasonable level of competency, they had to complete the practice trials with no more than one incorrect response before they performed the test trials. Each trial started with the display of a green warning circle in the centre of the screen. After the warning light appeared, there was a 1 to 4 sec delay prior to the random presentation of an auditory tone from one of the two speakers. The subject pressed the appropriate key according to the specified spatial mapping condition upon detection of the tone. The green light remained on for 900 ms or until a response was captured by the computer. In all trials, subjects were asked to react as fast and accurately as they could. The time elapsed from the onset of auditory stimulus to successful detection of key response by the computer was taken as the reaction time. No feedback on the accuracy of their responses in testing trials was given to the subjects. There was a short break for subjects after testing of a mapping condition

3. RESULTS

A total of 4800 responses (30 subjects × 2 blocks × 4 spatial mapping conditions × 20 trials) were collected in the experiment. Among them, 118 (2.46%) responses were incorrect. All correct responses were subjected to successive filtering by removing reaction times lying beyond the $\pm 3\sigma$ control limits. Altogether 195 outliers (4.06%) were discarded from analysis. After this securitization, a total of 4487 (93.48%) responses remained for further analysis.

3.1 Reaction Time (RT)

Individual subject RTs ranged from 160 ms to 992 ms. The mean and standard deviation of RTs were 497 ms and 167 ms, respectively while the skewness and kurtosis of distribution were 0.73 and 0.21 respectively. Subjects' gender effect was found to be non-significant on mean reaction time [$F(1, 28) = 0.278$, $p > 0.05$]. The mean RTs for the factors of auditory stimulus positions and response key positions are summarized in Table 1. The shortest mean RT (426 ms) was found when the front-right auditory stimulus was responded with the front-right response key at the S-R congruous condition. The two longest RTs (564 ms and 573 ms) were noted when the auditory stimulus was placed on the rear-left with the response keys in the incongruous front-right and rear-right positions. In general, congruent settings of stimulus-response positions produced faster responses than incongruent settings. Furthermore, amongst the sixteen mean RTs, half of them were larger than the overall mean RT (497 ms) and another half were smaller than the overall mean RT. The eight smaller values were obtained when the left and right auditory stimuli were responded with the left and right response keys respectively, regardless of the front or rear stimulus positions. For instance, the front-left stimulus was better responded with the left response keys (i.e. front-left and rear-left) than the right response keys (i.e. front-right and rear-right). The results showed that the left-right correspondence but not the front-rear correspondence of the stimulus and response key positions strongly influenced subjects' reaction times.

Further analysis of RTs was conducted with a repeated measures analysis of variance (ANOVA) and the results are shown in Table 2. The effects of auditory stimulus position, response key position, and warning foreperiod of the green circle were considered. The results showed that the effects of auditory stimulus position [$F(3, 84) = 4.489$, $p < 0.01$] and warning foreperiod [$F(3, 84) = 3.169$, $p < 0.05$] were significant whereas the effect of response key position was non-significant ($p > 0.05$). Regarding the two-factor interactions, only the interaction of auditory stimulus position × response key position was significant [$F(9, 252) = 40.449$, $p < 0.001$].

Table 1. Mean reaction times computed for different auditory stimulus positions and response key positions

Auditory stimulus positions	Response key position	Mean reaction time (ms)	Average (ms)
Front-left	Front-left	435	502
	Front-right	550	
	Rear-left	466	
	Rear-right	562	
Front-right	Front-left	530	479
	Front-right	426	
	Rear-left	537	
	Rear-right	434	
Rear-left	Front-left	461	510
	Front-right	564	
	Rear-left	451	
	Rear-right	573	
Rear-right	Front-left	563	499
	Front-right	457	
	Rear-left	560	
	Rear-right	428	

The non-significant factor of response key position revealed that there was no significant difference in mean RTs collected from the four response keys, indicating that the four response keys functioned equally in the experiment. During testing, the right-sided response keys (i.e. front-right and rear-right) were manipulated with the right hands while the left-sided response keys (i.e. front-left and rear-left) were manipulated with the left hands. Subjects were allowed to rest their index fingers on the two designated response keys before each trial. The results of a paired-samples T test showed that there was no significant difference in mean RTs between the right and left hands [$t(29) = 0.603$, $p > 0.05$].

Regarding the significant factor of warning foreperiod, a zigzag curve was shown with a minimum noted at the 3s foreperiod (Figure 3). Post hoc Bonferroni multiple comparison tests revealed that the mean RT for the 3s foreperiod was significantly shorter than that for the 2s foreperiod ($p < 0.05$), but no significant differences were found between the 1s and 2s foreperiods and between the 3s and 4s foreperiods. The results revealed that the warning foreperiod given should be longer than 2s while 3s was optimal for fast responses in such configurations.

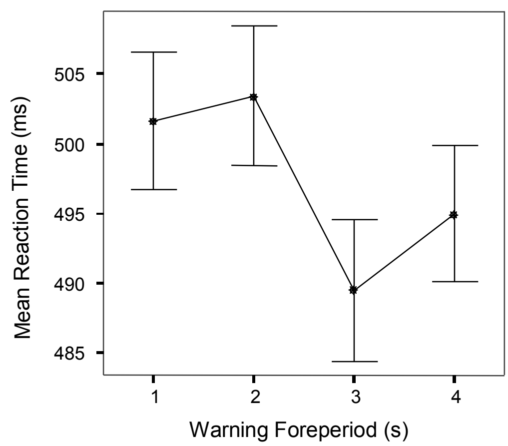


Figure 3. Mean reaction times for different warning foreperiods (error bars show mean +/- 1.0 SE)

Table 2. Results of ANOVA performed on mean reaction times

Source	Sum of Squares	*df*	Mean Square	*F*	*Sig.*	
Main Effect						
Auditory stimulus position	187905.870	3	62635.290	4.489	0.006	**
Response key position	6767.200	3	2255.733	0.282	0.838	
Warning foreperiod	61586.897	3	20528.966	3.169	0.029	*
Interaction Effect						
Auditory stimulus position × Response key position	6289260.757	9	698806.751	40.449	0.000	****
Auditory stimulus position × Warning foreperiod	35910.454	9	3990.050	0.496	0.877	
Response key position × Warning foreperiod	52480.369	9	5831.152	0.765	0.649	
Auditory stimulus position × Response key position × Warning foreperiod	181203.555	27	6711.243	0.842	0.697	

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

As shown in the ANOVA, the auditory stimulus position significantly influenced subjects' reaction times. The mean RTs for different auditory stimulus positions are shown in Figure 4. The shortest mean RT (479 ms) was obtained when the stimulus was presented at the front-right position whereas the longest value (510 ms) was observed for the stimulus coming from rear-left. Post hoc Bonferroni multiple comparison tests on auditory stimulus position revealed that no significant differences in mean RTs were found between the front-right and rear-right positions, between the rear-right and front-left positions, and between the front-left and rear-left positions; however, the mean RT for the front-right stimulus position was significantly different from that for the rear-left stimulus position ($p < 0.005$). The results indicated that subjects' performance with the front-right auditory stimulus was somewhat better than those with stimuli coming from the other three positions.

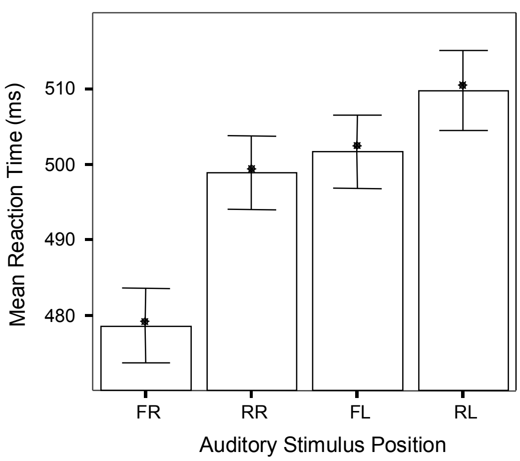


Figure 4. Mean reaction times for different auditory stimulus positions (error bars show mean +/- 1.0 SE)

The significant interaction of stimulus position and response key position revealed an apparent spatial stimulus-response compatibility effect in the current configuration (Figure 5). The responses were the fastest when the positions of auditory stimulus and response key were in correspondence. It can easily be perceived that the spatial relationship between the auditory stimulus and response key positions influenced reaction time under this diagonal setting of auditory stimuli. At each stimulus position, the four RTs collected from the four response keys are noted to exist in two separate groups; one group is above the overall mean RT level (497 ms) whereas another group is underneath, suggesting that performance with two designated response keys was better than that with the other two. With the square markers representing the left-sided response keys and the circle markers representing the right-sided keys, it is clear that the left and right auditory stimuli were better responded with the left and right response keys respectively, regardless of the front-rear correspondence.

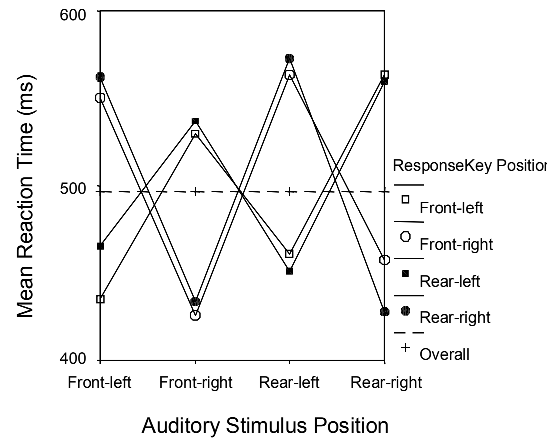


Figure 5. An interaction plot of auditory stimulus position and response key position

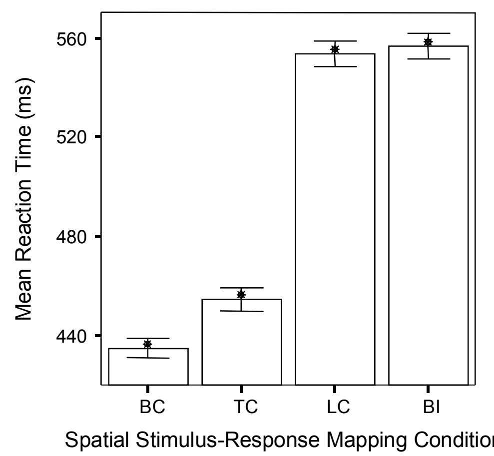


Figure 6. Mean reaction times for different spatial stimulus-response mappings (error bars show mean +/- 1.0 SE)

For better visualizing the effect of correspondence of stimulus-response positions, subjects' performance at four spatial S-R mappings viz. "Both transverse and longitudinal Compatible" (BC), "Transverse Compatible and longitudinal incompatible" (TC), "Longitudinal Compatible and transverse incompatible" (LC), and 'Both transverse and longitudinal Incompatible' (BI) are shown in Figure 6. The shortest RT value was found in the BC condition, followed by the TC, LC and BI mapping conditions. An one-way analysis of variance (ANOVA) with repeated measures confirmed that differences existed among the mean reaction times (RTs) for the four S-R mapping conditions [$F(3, 84) = 69.386$, $p < 0.001$]. Post hoc Bonferroni multiple comparison tests on spatial S-R mappings revealed that no significant differences were found between the BC and TC mappings and between the LC and BI mappings; however, the mean RTs for the BC and TC mappings were significantly different from those for the LC and BI mappings. The results showed that if the spatial S-R compatibility effect could only be established in one orientation, the condition of transverse compatibility had a higher priority than the longitudinal compatibility.

3.2 Response Error

Among the 4800 responses obtained from all subjects, 118 responses (2.46%) were incorrect. No significant effect was found between males and females on mean error percentage ($p > 0.05$, Mann Whitney test). The mean response error percentages (EPs) for different auditory stimulus positions and response key positions are shown in Table 3. The values ranged from 0.33% to 6%. Small EPs were observed when the response key was in the same transverse side (right or left) of the stimulus. That is, when an auditory stimulus was presented from the front-right direction, the front-right and rear-right response keys would be the more desirable choices for minimization of response errors.

Table 3. Mean response error percentages computed for different auditory stimulus positions and response key positions

Auditory stimulus position	Correct response key position	Mean response error percentage	Average
Front-left	Front-left	1.00%	1.75%
	Front-right	3.00%	
	Rear-left	1.33%	
	Rear-right	1.67%	
Front-right	Front-left	6.00%	2.58%
	Front-right	0.67%	
	Rear-left	3.00%	
	Rear-right	0.67%	
Rear-left	Front-left	1.00%	2.33%
	Front-right	4.00%	
	Rear-left	0.33%	
	Rear-right	4.00%	
Rear-right	Front-left	4.67%	3.17%
	Front-right	0.33%	
	Rear-left	6.00%	
	Rear-right	1.67%	

Further analysis of EPs was conducted with the non-parametric Friedman tests since the distribution of EPs was neither normal nor symmetric. Four main factors were considered. They were auditory stimulus position, response key position, warning foreperiod and spatial S-R mapping condition. The results showed significant spatial S-R mapping condition ($p < 0.001$) only. The significant S-R mapping effect revealed an apparent spatial S-R compatibility effect on response error. Figure 7 shows the mean EPs for different S-R mapping conditions. The smallest value was found in the TC mapping condition, followed by BC, BI and LC. Wilcoxon signed ranks tests further revealed that no significant differences in mean EPs were found between the TC and BC mappings and between the BI and LC mappings; however, the mean EPs for the TC and BC mappings were significantly different from those for the BI and LC mappings. Again, the results showed the transverse compatibility effect (EP = 0.83%) had a higher level of significance than the longitudinal compatibility effect (EP = 4.75%) as evidenced by the large difference of 3.92% in response accuracy.

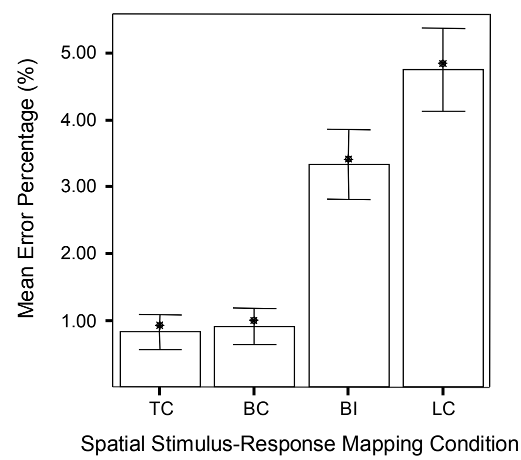


Figure 7. Mean error percentages for different spatial stimulus-response mappings (error bars show mean +/- 1.0 SE)

4. DISCUSSION

With this diagonal configuration of auditory signals and response keys, subjects responded faster to signals coming from the front-right than other directions. Hand preference is believed to be a contributing factor since all the subjects in the experiment were right-handed. It was reported that hand preference is related to the craniofacial and consequently aural asymmetries (Dane *et al.*, 2002). As Mondor and Bryden (1992) stated, when subjects were faced with a difficult dichotic task, there was a general tendency for right-handed subjects to bias their attention towards the right ear. Dane *et al.* (2002) evidenced this as the right ear advantage for right-handers. Right ear advantage refers to the phenomenon that the right-handers have more sensitive right ears and are more responsive to right-sided auditory stimuli. They further showed that the right-handers have a larger left craniofacial region. Previous researches reported that the left hemisphere is responsible for the sensation on the right side of the body while the right hemisphere receives sensation on the left side of the body owing to brain lateralization. Therefore, a larger left craniofacial region implies a more developed set of sense organs on the right side and thus a better perception for right-sided stimuli. In view of the right ear advantage and the larger left craniofacial region for right-handers, it was speculated that the right-handed subjects have then a directional preference for right-sided auditory stimulus. On the other hand, the responses obtained for the rear auditory signals were observed to be slower by Chan *et al.* (2001) who explained by the intrinsic structure of human ears. Compared to a signal from the front, the transmission and reception of the rear auditory signal is slightly shadowed by the ear pinnas, causing a lower intensity level to be perceived. The RT then tends to lengthen with a decrease of stimulus intensity, leading to slower responses. The right ear advantage for right-hander and the intrinsic structure of human ears account well for the results obtained here that subjects are more responsive to front-right auditory stimulus in the diagonal configuration of signals.

The significant two-way interaction of stimulus position × response key position revealed an apparent spatial S-R compatibility effect. It was not surprising that the BC mapping condition yielded the fastest response whereas the BI mapping condition yielded the longest RT. However, in a condition where either the transverse or longitudinal orientation was incompatible, it was repeatedly shown that the transverse compatibility effect overrode that of the longitudinal compatibility. In this study, subjects were found performing better in response speed and accuracy in the BC and TC mapping conditions than in the BI and LC mappings. There was no statistical difference found between the performance for the BC and TC mappings and between the BI and LC mappings. The superiority of the BC and TC mappings is believed to be due to the right-left prevalence of our right-left effectors. A similar study performed by Chan *et al.* (2006) revealed that auditory S-R compatibility effect existed in both transverse and longitudinal orientations when the transverse and longitudinal compatibility effects were examined separately. However, when the spatial S-R compatibility effects in these two orientations were tested simultaneously in this experiment, the results here showed that the performance for the TC mapping was better than that for the LC mapping. Furthermore, the performance for the LC mapping was as poor as that for the BI mapping in terms of response speed, and even worse than the BI mapping in terms of response accuracy. Therefore, the longitudinal compatibility effect is comparatively much weaker than the transverse compatibility effect, especially in a complex setting. In general, the auditory spatial S-R compatibility effect influences not only the reaction speed but also the response accuracy. For instance, faster responses were resulted in the BC and TC mapping conditions. As well, high accuracy of responses was guaranteed (Figure 6 and 7). The LC and BI mapping conditions, however, were unfavorable settings since they yielded comparatively longer reaction times and larger error values, which were resulted from the extra information coding demands, leading to lower efficiency and accuracy.

5. CONCLUSION

The spatial stimulus-response (S-R) compatibility effect for auditory signals in the transverse and longitudinal orientations was investigated in the experiment. Significant spatial S-R compatibility effects were found. For eliciting fast and accurate responses, the auditory signals and response keys should be paired in congruous positions. The right-left spatial correspondence between the signals and control keys yielded better performance in terms of speed and accuracy than the front-rear spatial correspondence. The auditory signal should be placed at the front-right position for right-handed users. The warning foreperiod prior to the signal presentation influenced reaction time and a warning foreperiod of 3s is optimal for the current two-choice reaction task. The results of this study provide important and useful ergonomics recommendations for interface design of auditory control consoles which will help improve the overall efficiency, accuracy and safety of man-machine systems.

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