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**Research Report**
**Effects of spatial distribution of attention during inhibition of return (IOR) on flanker interference in hearing and congenitally deaf people**
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**ABSTRACT**

This study explored the interaction between the spatial distribution of attention during inhibition of return (IOR) and different levels of flanker interference in congenitally deaf subjects as compared with hearing subjects. Color (Experiment 1) and alphanumeric (Experiment 2) flanker interference effects were differentiated into the pre-response and the response levels. The spatial distribution of attention was manipulated through IOR. Subjects were asked to either make color or letter/digit discriminations to the central targets or detect the abrupt-onset peripheral targets. Deaf subjects were significantly faster than hearing subjects at detecting peripheral targets irrespective of the cue validity, while the two groups had comparable sizes of IOR. In the central discrimination tasks, deaf subjects showed significant response level, but not pre-response level, flanker effects irrespective of the type of stimuli and the spatial location of the flanker. For hearing subjects, however, spatial attention interacted with the pre-response and response flanker effects in different ways. While flankers at the cued location caused interference effects at the response level and facilitatory effects at the pre-response level, those at the uncued location caused different effects depending on the type of stimuli. Moreover, increasing the peripheral attention for hearing subjects, by increasing the proportion of peripheral detection trials, made hearing subjects behave like deaf subjects. These results demonstrate that deaf people possess enhanced peripheral attentional resources as compared with hearing people. The spatial distribution of attention modulates mainly the resolution of the pre-response flanker interference in hearing people, but affects neither the pre-response nor the response level interference in deaf people.

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## 1. Introduction

Recent behavioral and brain imaging studies on visual perception in congenitally deaf subjects provide increasing evidence that visual skills are enhanced in deaf people as compared with hearing people, especially when visual stimuli are presented in the peripheral visual field and the tasks are attention-demanding (e.g., Rettenbach et al., 1999; Stivalet et al., 1998). For example, Bavelier and colleagues (2000, 2001) found that deaf subjects were better at detecting peripheral than central motion changes, while hearing subjects showed the reverse pattern. Correspondingly, the posterior parietal cortex was more activated in deaf subjects than in hearing subjects (Bavelier et al., 2001), and the effective connectivity between the medial temporal/medial superior temporal cortex (MT/MST) and the posterior parietal cortex was stronger in deaf than in hearing subjects during the peripheral but not the central attention (Bavelier et al., 2000). By manipulating the perceptual load of visual search in the central display and by putting the interfering flanker either in the central or in the peripheral display, Proksch and Bavelier (2002) found that deaf subjects showed a smaller flanker interference effect in the central and a larger effect in the peripheral as compared with hearing subjects, demonstrating that early deafness alters the spatial distribution of attention. Attentional resources are more equally distributed across the visual field in deaf people than in hearing people whose attentional resources decrease sharply from the central to the peripheral visual field.

Most of the previous studies, however, focused on the static spatial distribution of attentional resources across the visual field in the deaf population. Only a few studies examined the more dynamic attentional orienting mechanisms in the deaf (Bosworth and Dobkins, 2002; Colmenero et al., 2004). Deaf people use the sign language to communicate in their daily lives, during which they have to pay attention to both the speaker's facial expressions in the central vision and hand shapes in the peripheral vision. Therefore, processing the sign language requires quick shifts of attention between different spatial locations. In the classical exogenous spatial cueing paradigm (Klein, 2000; Maylor and Hockey, 1985; Posner and Cohen, 1984), response times (RTs) to the target at a previously cued location are often faster than those to the target at an uncued location when the cue–target stimulus onset asynchrony (SOA) is less than 300 ms. This earlier facilitatory effect, however, turns to a later inhibitory effect at longer SOAs, with responses being slower to the target at the cued location than at the uncued location. The latter bias towards novel locations is called “inhibition of return (IOR)”. By using a motion direction discrimination task in conjunction with the spatial cueing paradigm, Bosworth and Dobkins (2002) compared motion thresholds obtained with and without a valid spatial cue at the short SOA and got a slight advantage for deaf subjects in their abilities to orient spatial attention. Similarly, Parasnis and Samar (1985) used the spatial cueing paradigm to measure RTs for detecting targets at the cued or the uncued locations. They found that deaf subjects were less impaired by invalid cues than hearing subjects. Thus, the attentional orienting ability during the earlier facilitatory phase in exogenous spatial cueing is enhanced in deaf people as compared

with hearing people. Furthermore, Colmenero et al. (2004) demonstrated that the IOR effect disappeared in deaf subjects when the SOA was long (850 ms), while it existed in hearing subjects at both the short (350 ms) and the longer SOAs. This finding suggests that deaf people have better abilities than hearing people in reorienting attentional focus to explore various (including the cued) locations.

An unresolved issue is whether the enhanced spatial orienting ability in deaf people affects different stages of cognitive processing in different ways from hearing people, resulting in differential patterns of behavioral performance between hearing and deaf populations. The attentional selection process may occur at different stages of information processing and the spatial orienting process may interact in different ways with the attentional selection at different stages. Moreover, the relative bottom-up perceptual saliency of the visual stimuli may also play a role in determining how attentional resources are distributed over space and which stage of information processing the attentional selection acts on. By “perceptual saliency”, we mean the feature contrast of one particular item to the various other items represented within the same dimension (or attribute). The more dissimilar an item is from the others, the greater its saliency is. This within-dimension saliency contrasts with the between-dimension saliency, which can be defined according to the relative efficiency in computing the within-dimension saliency. The faster the computation is, the more salient the dimension is (Wei and Zhou, 2006). Theeuwes (1991, 1992) found that the presence of a task-irrelevant form singleton had essentially no effect on the speeded search for an item with a unique color, while the presence of a task-irrelevant color singleton slowed down the searching for a unique form. This finding was taken as evidence that the relative perceptual saliency of a stimulus attribute (color vs. form) determines whether attention is directed towards its location. The more salient an item, the greater effect it has on attention allocation.

In the present study, to examine whether the enhanced spatial orienting ability in deaf people affects the attentional selection at different stages of cognitive processing, we combined the manipulation of IOR with the unilateral flanker paradigm in which a target is presented at the central location and is accompanied by a flanker either at the cued peripheral location or at the uncued, opposite peripheral location (see Fig. 4). Ro et al. (2002) and Fuentes et al. (1999) have used similar manipulations to investigate the impact of attentional orienting on the response activation, although somewhat different results were obtained. In the present research, we further differentiated the flanker interference into the pre-response level and the response level. We then applied the same experimental design to both hearing and deaf adults. Moreover, we compared subjects' performances on color and letter/digit stimuli and examined whether the perceptual saliency of stimuli could affect the possible interaction between spatial attention and the level of flanker interference. Peripheral target detection trials were also included in the experiments and mixed with the central discrimination task over trials. By using the peripheral detection trials, we can test whether deaf and hearing subjects differ in their peripheral attention and in the speed of responding to the peripheral targets on the one hand, and make sure that subjects pay attention to the

periphery and the normal IOR mechanisms function in the experiments on the other hand.

In Experiment 1, we manipulated levels of the pre-response and response conflicts (Eriksen and Schultz, 1979; Milham et al., 2001; van Veen et al., 2001) by using four stimuli (e.g., red, green, yellow, blue), with two of them (e.g., red, green) requiring one response and the other two (yellow, blue) requiring another response. A target and its flanker potentially requiring different responses (e.g., red, yellow) would constitute conflicts at both the pre-response and the response levels (“response-incongruent” condition, RI), while a target and its flanker requiring the same response (e.g., red, green) would constitute conflicts only at the pre-response level (“stimulus-incongruent” condition, SI). There was also a congruent condition in which the target and its flanker were the same (“congruent” condition, CO). Therefore, relative to the CO condition, the RI condition could produce conflicts at both the response and the pre-response levels, whereas the SI condition could generate conflicts mainly at the pre-response level. The comparison between RI and SI conditions would reveal conflicts only at the response level. Similar manipulations were also used in Experiment 2 in which two letters (A and B) required one response while two digits (4 and 5) required another response.

We do not assume that information processing from sensory encoding to response execution is in discrete stages, as evidence has shown that information flows continuously between levels of representation. Response activation can not only begin before the completion of perceptual processing, but also feedback to earlier levels of perceptual processing (e.g., Eriksen and Schultz, 1979). Nevertheless, by using the above manipulations we can examine, to a large extent, whether the possible interaction between flanker interference and spatial attention is at the response level or at the pre-response level and how this interaction is modulated by the availability of

attentional resources in hearing and deaf people. We also manipulated the allocation of attentional resources to the periphery by varying the percentage of peripheral detection trials for hearing subjects. If the peripheral attention is enhanced in deaf subjects as compared with hearing subjects, hearing subjects should show the same pattern of behavioral performance as deaf subjects when they are forced to allocate more attentional resources to the peripheral visual field.

## 2. Experiment 1

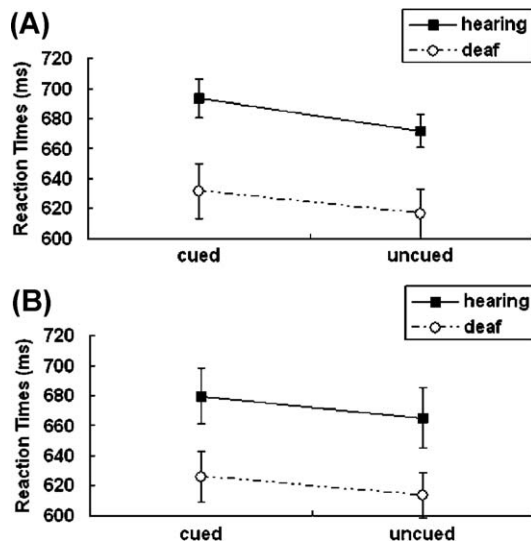
### 2.1. Results

Incorrect responses were discarded and RTs longer than 1500 ms or shorter than 200 ms (0.75% of total trials for hearing subjects and 1.21% for deaf subjects) were also discarded. Mean RTs and error rates were then calculated for each subject and experimental condition. Table 1 summarizes the mean RTs and error rates in all the conditions of Experiment 1 and Experiment 2.

RTs in the peripheral detection task from each subject group were entered into a 2 (subject group) × 2 (cue validity) ANOVA. Results showed that the main effect of cue validity was significant,  $F(1,36)=9.95$ ,  $p<0.005$ , indicating that, across the two groups of subjects, RTs were faster to targets at the uncued location (644 ms) than at the cued location (662 ms). The main effect of subject group was significant,  $F(1,36)=9.20$ ,  $p<0.005$ , suggesting that the mean detection RT to peripheral targets was much faster in deaf subjects (624 ms) than in hearing subjects (683 ms; see Fig. 1A). The interaction between cue validity and subject group was not significant,  $F<1$ , indicating that the IOR effects were equivalent across the two groups.

**Table 1 – Mean reaction times (ms) and error rates (%) as a function of cue validity and flanker congruency in Experiments 1 and 2**

		Cued			Uncued			Detection	
		RI	SI	CO	RI	SI	CO	Cued	Uncued
Experiment 1A	RT	776	729	744	769	760	741	694	672
Hearing	SD	88	83	74	79	79	80	59	54
(25% detection)	Error	4.7	2.0	4.3	4.4	2.7	3.6	0.9	0.7
Experiment 1B	RT	757	730	722	752	729	729	631	617
Deaf	SD	77	58	83	73	61	77	70	67
(25% detection)	Error	4.1	2.3	3.9	3.7	2.7	2.5	0.8	0.6
Experiment 2A	RT	744	701	720	724	726	729	680	665
Hearing	SD	101	89	98	98	94	95	82	88
(25% detection)	Error	1.9	1.7	1.9	2.7	2.7	2.9	1.4	1.9
Experiment 2B	RT	774	751	747	780	747	739	626	613
Deaf	SD	104	99	97	111	90	98	70	62
(25% detection)	Error	2.0	1.7	0.2	2.0	1.5	1.5	2.0	1.1
Experiment 2C	RT	682	666	666	685	661	666	521	500
Hearing	SD	68	66	64	66	64	64	73	75
(57% detection)	Error	1.1	1.7	1.4	1.4	1.4	1	0.3	0.3



**Fig. 1 – (A) Mean RTs with standard errors in the peripheral target detection task as a function of cue validity and subject group in Experiment 1. (B) Mean RTs with standard errors in the peripheral target detection task as a function of cue validity and subject group in Experiment 2.**

RTs in the central color discrimination tasks from each group were submitted to a 2 (subject group)  $\times$  2 (cue validity)  $\times$  3 (flanker congruency) ANOVA. Results showed that the main effect of flanker congruency was significant,  $F(2,72)=31.15$ ,  $p<0.001$ , with responses faster ( $p<0.001$ ) to congruent targets (734 ms) and SI targets (737 ms) than to RI targets (763 ms). The main effect of subject group was not significant,  $F<1$ . The interaction between cue validity and congruency was significant,  $F(2,72)=4.27$ ,  $p<0.05$ , so was the three-way interaction between subject group, cue validity and congruency,  $F(2,72)=4.49$ ,  $p<0.05$ . These interactions indicated that the pattern of interaction between cue validity and flanker congruency differed between the two groups of subjects. It is clear from Fig. 2 that these interactions were caused mainly by the variation in RTs to SI targets.

Separate ANOVAs were conducted for the hearing and the deaf subjects, with cue validity and flanker congruency as two within-subject factors. For the hearing group, the main effect of cue validity was not significant,  $F(1,21)=1.80$ ,  $p>0.1$ . However, the main effect of congruency was significant,  $F(2,42)=19.32$ ,  $p<0.001$ , so was the interaction between cue validity and congruency,  $F(2,42)=7.74$ ,  $p<0.005$  (see Fig. 2A). Further analysis on simple effects showed that RI flankers caused significantly longer RTs to the targets than SI flankers at the cued location,  $t(21)=5.46$ ,  $p<0.001$ , but not at the uncued location,  $t(21)<1$ . Compared with CO flankers, SI flankers caused significant pre-response interferences at the uncued location,  $t(21)=3.05$ ,  $p<0.01$ , but they caused significant facilitations at the cued location,  $t(21)=2.13$ ,  $p<0.05$ .

For the deaf group, the main effect of cue validity was not significant,  $F<1$ , nor was the interaction between the cue validity and the flanker congruency,  $F<1$ . However, the main effect of flanker congruency was significant,  $F(2,30)=12.93$ ,  $p<0.001$ , suggesting that, irrespective of the cue validity, RTs to targets accompanied by RI flankers (755 ms) were signifi-

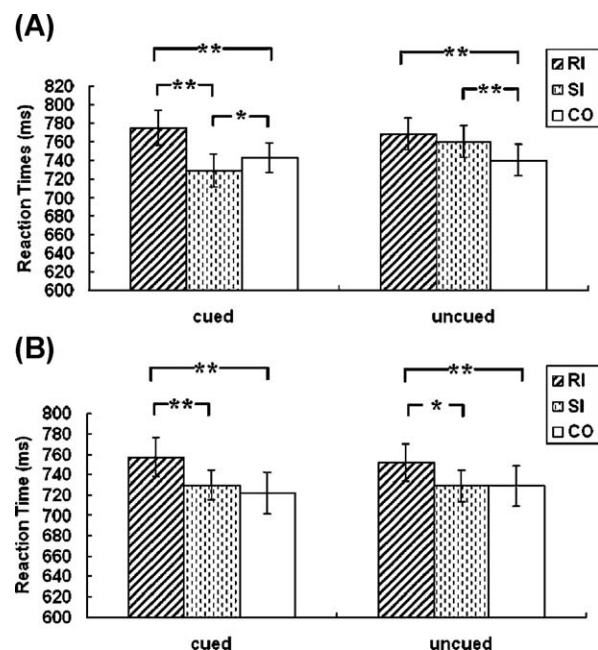
cantly slower than RTs to targets accompanied by either SI flankers (730 ms) or CO flankers (726 ms; see Fig. 2B).

A 2  $\times$  2  $\times$  2 ANOVA was also conducted for the combined pre-response and response conflict (RI vs. CO), with cue validity and subject group as the other two factors. This analysis found only a significant main effect of congruency (RI vs. CO),  $F(1,36)=75.24$ ,  $p<0.001$ , but no other significant main effects or interactions ( $p>0.1$ ). These results suggested that the combined flanker conflict was not affected by the spatial distribution of attention.

A 2 (subject group)  $\times$  2 (cue validity)  $\times$  3 (flanker congruency) ANOVA on error rates revealed only a significant main effect of flanker congruency,  $F(2,72)=6.17$ ,  $p<0.005$  (see Table 1). Further tests showed that the error rate in the RI condition was higher than that in the SI condition at both the uncued location,  $F(1,36)=4.32$ ,  $p<0.05$ , and the cued location,  $F(1,36)=12.91$ ,  $p<0.005$ , indicating the response level interference effects at both locations. The comparisons between the SI and the CO conditions showed a significant effect at the cued location,  $F(1,36)=12.44$ ,  $p<0.005$ , and a null effect at the uncued location,  $F<1$ . However, the error rates at the cued location were lower in the SI condition than in the CO condition, which was consistent with the SI facilitatory effect at the cued location found in RTs.

## 2.2. Discussion

In the peripheral detection task, the two groups of subjects showed significant and equivalent IOR effects. Deaf subjects,



**Fig. 2 – (A) Plots of mean RTs with standard errors as a function of cue validity and flanker congruency in the central color discrimination task of Experiment 1A (hearing group, 25% detection trials). (B) Plots of mean RTs with standard errors as a function of cue validity and flanker congruency in the central color discrimination task of Experiment 1B (deaf group, 25% detection trials) (\* $p<0.05$ ; \*\* $p<0.01$ ).**

however, were much faster (by 59 ms) at detecting peripheral targets than hearing subjects regardless of the cue validity. The latter result is in agreement with previous results showing that deaf subjects were faster and more accurate than hearing subjects at detecting (Loke and Song, 1991) and discriminating (Neville and Lawson, 1987a,b) stimuli presented in the periphery.

In the central color discrimination task, hearing and deaf subjects showed different patterns of interaction between cue validity and levels of flanker interference. For the response level interference (RI vs. SI), there were significant effects at both the cued and the uncued location in deaf subjects, while there was a significant effect only at the cued location but not at the uncued location in hearing subjects. For the pre-response level effect (SI vs. CO), there was an interference effect at the uncued location and a facilitatory effect at the cued location in hearing subjects. Deaf subjects, however, did not show any significant effects either at the cued or at the uncued location. For the combined pre-response and response conflict (RI vs. CO), there were equivalent and significant effects at both the cued and the uncued location in both groups of subjects (see Fig. 2).

The latter finding is consistent with Ro et al. (2002) who assumed that the flanker effect reflects the activation of response channel of the flanker. Thus, the equivalent flanker conflicts at the cued and the uncued locations suggested that response activation can occur independently of spatial attention. This argument, however, may need qualifications. It has been long established that the flanker interference does not occur when flankers are outside the focus of attention (Eriksen and Eriksen, 1974; Eriksen and Schultz, 1979). A more appropriate proposal is perhaps that the response activation needs a certain minimum level of attention. Above this limit, the response activation is not affected by the amount of attentional resources available. Taken together, results in the present central discrimination task suggested that the spatial distribution of attention during IOR modulates neither the pre-response nor the response level flanker effect in deaf people, while it does modulate the flanker effect (mainly at the pre-response level) in hearing people.

The facilitatory effect for the SI stimuli, as compared with the CO stimuli, at the cued location in hearing subjects (for both RTs and error rates) is perhaps surprising, but not without precedence. Flowers and Wilcox (1982; see also Grice et al., 1984; Grice and Gwynne, 1985) obtained a similar effect in the flanker task but without explicitly manipulating the focus of spatial attention. No detailed theories, however, have been proposed to account for this SI facilitatory effect. In General Discussion, we will propose a tentative account based on the interaction between the early token individuation process (Kanwisher, 1987, 1991) and the spatial distribution of attention.

### 3. Experiment 2

The purpose of Experiment 2 was to examine whether the pattern of effects observed for the color stimuli in Experiment 1 can be extended to the alphanumeric stimuli. Alphanumeric stimuli are less readily processed in deaf people than in

hearing people (Proksch and Bavelier, 2002). Moreover, a color flanker is more likely to attract attention than an alphanumeric flanker (Theeuwes, 1991, 1992; Wei and Zhou, 2006). Therefore, the distribution of attentional resources over space may interact with different levels of cognitive processing of alphanumeric stimuli, in a different way from the interaction with the processing of color stimuli. We also manipulated the proportion of peripheral detection trials such that a larger percentage of detection trials (57% of the total trials) were used in Experiment 2C for hearing subjects. The purpose of this manipulation was to force hearing subjects to put more attentional resources to the periphery in a way similar to deaf subjects, and to examine whether the pattern of flanker interference effects at the cued and the uncued locations in hearing subjects is now similar to that in deaf subjects.

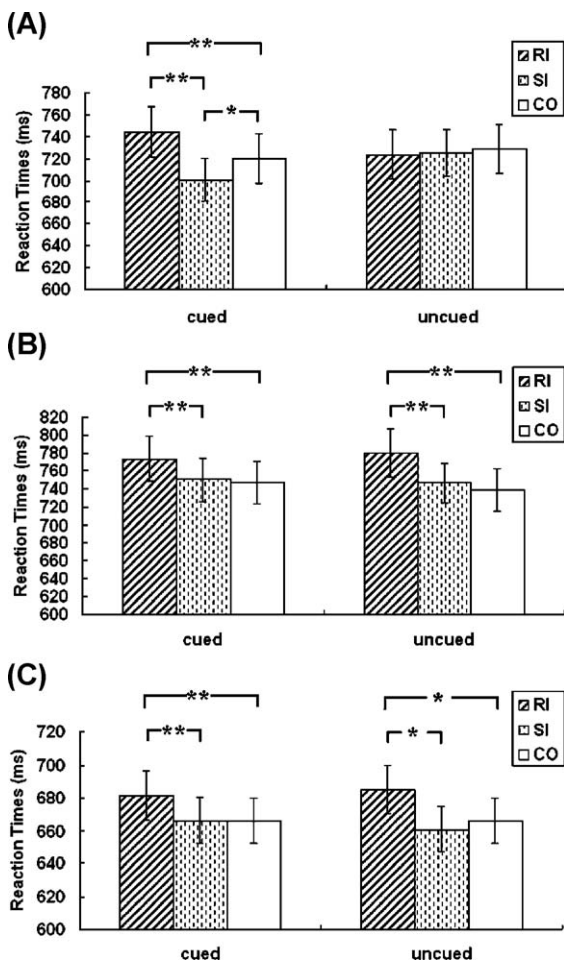
### 3.1. Results

#### 3.1.1. Experiments 2A and 2B

For the peripheral detection task, RTs from both groups were entered into a 2 (subject group)  $\times$  2 (cue validity) ANOVA. The main effect of cue validity was significant,  $F(1,34)=9.10$ ,  $p<0.01$ , indicating that RTs at the cued location (653 ms) were slower than those at the uncued location (639 ms), i.e. a typical IOR effect. The main effect of subject group was again significant,  $F(1,34)=4.43$ ,  $p<0.05$ , indicating that RTs in the peripheral detection task were faster in the deaf group (619 ms) than in the hearing group (672 ms) irrespective of the cue validity (see Fig. 1B). The interaction between subject group and cue validity was not significant,  $F<1$ , suggesting that the two groups of subjects had comparable IOR effects. Analysis of error rates in the peripheral detection trials did not find any significant effects.

RTs in the central letter/digit discrimination task were subjected to a 2 (subject group)  $\times$  2 (cue validity)  $\times$  3 (flanker congruency) ANOVA test. Neither the main effect of subject group nor the main effect of cue validity was significant,  $F(1,34)=1.03$ ,  $p>0.1$ ;  $F(1,34)<1$ . But the main effect of flanker congruency was highly significant,  $F(2,68)=20.01$ ,  $p<0.001$ , indicating that, collapsed over subject group and cue validity, RTs to RI stimuli (755 ms) were significantly slower than those to SI (731 ms) or CO (734 ms) stimuli. The interaction between subject group and flanker congruency was significant,  $F(2,68)=4.48$ ,  $p<0.05$ , so was the three-way interaction between subject group, cue validity and flanker congruency,  $F(2,68)=7.30$ ,  $p<0.005$ . These interactions indicated that the two groups of subjects had different patterns over the interaction between cue validity and flanker congruency (see Fig. 3).

Further ANOVAs were conducted separately for hearing and deaf subjects, with cue validity and flanker congruency as two within-subject factors. For the hearing group, the main effect of flanker congruency was significant,  $F(2,36)=6.92$ ,  $p<0.005$ , so was the interaction between cue validity and flanker congruency,  $F(2,36)=7.61$ ,  $p<0.005$  (see Fig. 3A). Further simple effect tests found that, at the cued location, RTs to the targets accompanied by RI flankers were significantly longer than RTs to the targets accompanied by either CO flankers,  $t(18)=3.75$ ,  $p<0.005$ , or SI flankers,  $t(18)=4.90$ ,  $p<0.001$ , indicating a response level interference effect. The 19 ms difference between the SI and the CO condition was also significant,



**Fig. 3 – (A) Plots of mean RTs with standard errors as a function of cue validity and flanker congruency in the central letter/digit discrimination task of Experiment 2A (hearing group, 25% detection trials). (B) Plots of mean RTs with standard errors as a function of cue validity and flanker congruency in the central letter/digit discrimination task of Experiment 2B (deaf group, 25% detection trials). (C) Plots of mean RTs with standard errors as a function of cue validity and congruency in the central letter/digit discrimination task of Experiment 2C (hearing group, 57% detection trials) (\* $p < 0.05$ ; \*\* $p < 0.01$ ).**

$t(18) = 2.38$ ,  $p < 0.05$ , but the reason for this effect was that subjects responded *faster* to the SI stimuli than to the CO stimuli, which replicated the SI facilitatory effect in Experiment 1A. At the uncued location, no significant effects were observed for hearing subjects.

For the deaf group, the main effect of flanker congruency was significant,  $F(2,32) = 16.36$ ,  $p < 0.001$ . No other main effects or interactions reached significance. Further tests on the congruency effect revealed significant differences between RI and SI conditions at both the cued location,  $t(16) = 4.07$ ,  $p < 0.005$ , and the uncued location,  $t(16) = 3.26$ ,  $p < 0.01$ , suggesting that there were equivalent response level interferences at both locations. However, there were no pre-response level interferences at either location, i.e. there were no differences between RTs to the SI and the CO stimuli ( $p > 0.1$ ; see Fig. 3B).

Analysis of error rates in the central discrimination task did not reveal any significant effects.

### 3.1.2. Experiment 2C

It is clear from Fig. 3 that the pattern of flanker congruency effects at the cued and uncued locations in hearing subjects was similar to that in deaf subjects of Experiment 2B, when hearing subjects allocated more attentional resources to the periphery because of the larger proportion of peripheral detection trials. Statistical analysis confirmed this observation. A 2 (cue validity)  $\times$  3 (flanker congruency) ANOVA revealed only a significant main effect of flanker congruency,  $F(2,40) = 21.40$ ,  $p < 0.001$ . Neither the main effect of cue validity nor the interaction between cue validity and flanker congruency was significant, both  $F < 1$ . Further tests on the congruency effects found significant differences between RI and SI conditions at both the cued location,  $t(20) = 3.39$ ,  $p < 0.005$ , and the uncued location,  $t(20) = 4.72$ ,  $p < 0.001$ . No differences were found between SI and CO conditions, both  $t(20) < 1$ .

A significant IOR effect (21 ms) was obtained in the peripheral detection task of Experiment 2C,  $t(20) = 8.34$ ,  $p < 0.001$ . The size of this effect was comparable with that in Experiment 2A (15 ms). A 2 (Experiment 2A vs. Experiment 2C)  $\times$  2 (cue validity) ANOVA on the detection data suggested that the main effect of cue validity was significant,  $F(1,38) = 22.18$ ,  $p < 0.001$ , but the interaction between experiment and cue validity was not,  $F(1,38) < 1$ . Moreover, the main effect of experiment was significant,  $F(1,38) = 42.3$ ,  $p < 0.001$ , indicating that the mean RTs to peripheral targets were significantly faster in Experiment 2C (510 ms) than in Experiment 2A (672 ms).

## 3.2. Discussion

Results in the peripheral detection task replicated the results in Experiment 1 by showing that deaf subjects were faster than hearing subjects at detecting peripheral targets irrespective of the cue validity and that hearing and deaf subjects exhibited comparable sizes of IOR effects. For the central letter/digit discrimination task, deaf subjects' performances had the same pattern as their performances in the central color discrimination task of Experiment 1B, with only the response level interferences at the cued and the uncued locations. Hearing subjects also showed the same pattern of congruency effects at the cued location in the two tasks, with interferences for the RI stimuli and facilitations for the SI stimuli. At the uncued location, however, hearing subjects did not show any congruency effects in the letter/digit discrimination task. When hearing subjects were forced to pay more attention to the peripheral visual field in Experiment 2C because of the larger percentage of peripheral detection trails, they behaved like deaf subjects in the central discrimination task and showed a similar improvement in RTs to the peripheral targets.

The significant response conflicts at the cued location and the absence of flanker interference effects at the uncued location in Experiment 2A may suggest that the flanker at the cued location received more attentional resources and caused more interferences than the flanker at the uncued location

(Lavie and Tsai, 1994). This suggestion obviously contradicts the beliefs that attention is pulled away from the cued location and oriented towards the uncued location during IOR and hence there are more attentional resources at the uncued than at the cued location. In the current experimental setting, however, most of the behavioral targets (75%) appeared at the central fixation. Subjects may strategically maintain attention at the central location and cease the attentional shifting to the uncued location. A consequence of this strategic blocking process is that more attentional resources are left at the cued visual field than at the uncued visual field. This could be especially true when the alphanumeric stimuli are adopted, because the letter/digit flanker at the uncued location is less likely to attract attention than the perceptually more salient color flanker. When the percentage of peripheral detection trials (57%) was increased in Experiment 2C, the alphanumeric flanker at the uncued location caused interferences with the processing of the central target, as in Experiment 2B (with 25% detection trials for deaf subjects). This demonstrated again the importance of peripheral attention in modulating the processing of the flanker and the flanker's interaction with the processing of the central target.

Note, the IOR effect in the peripheral detection task still existed in the presence of the above strategic blocking process. This result is in agreement with several recent studies showing that IOR is independent of the endogenous orienting of visual attention (Lupianez et al., 2004; Berger et al., 2005; Berlucchi et al., 2000). For example, Berger et al. (2005) presented endogenous and exogenous orienting cues in each single trial and orthogonally manipulated the cue validity of both types of cues. They found that exogenous and endogenous orienting mechanisms developed their typical and independent effects even when they were in conflict. The former yielded stable benefits at the cued location and costs at the uncued location, while the latter generated the biphasic pattern of early facilitation and late inhibition.

Comparing Experiment 2A with Experiment 1A, we found that the bottom-up perceptual saliency also plays an important role in deploying attention to the peripheral flanker. At the uncued location, both RI and SI flankers caused interferences in Experiment 1A, while they did not cause any effects in Experiment 2A. The crucial difference between the two experiments was in the perceptual saliency of color stimuli in Experiment 1A and that of alphanumeric stimuli in Experiment 2A. The spatial distribution of attentional resources in the present experimental settings could be determined in two stages, i.e. before and after the presentation of the target. Before the actual appearance of the target, the presentation of the peripheral and the central cues leads to a certain distribution of attentional resources over space. This distribution is independent of the properties of the targets. After the appearance of the target, the target display itself further modulates the distribution of attentional resources, with the perceptual saliency of the flanker playing a significant role here. According to Theeuwes (1991, 1992), the color dimension is more likely to automatically capture attention than the shape dimension; the higher perceptual saliency an item has, the greater effect it has on attentional allocation. Therefore, it is possible that at the uncued location, the color flanker in Experiment 1A received more attention

than the alphanumeric flanker in Experiment 2A, and the flanker interference for the former, but not for the latter, was hence incurred.

#### 4. General discussion

Results from the two experiments can be summarized as below. In the peripheral detection task, hearing subjects and deaf subjects in both experiments showed significant IOR effects. Deaf subjects, however, were significantly faster than hearing subjects at detecting the peripheral target in general, irrespective of the cue validity. In the central discrimination tasks, for deaf subjects, spatial attention did not modulate either the pre-response or the response interference effects. There existed significant response level, but not pre-response level, flanker interferences irrespective of the type of stimuli and the spatial location of the flanker. For hearing subjects, while the flanker at the cued location caused interference with the processing of the central target at the response level and facilitation at the pre-response level when the proportion of peripheral detection trials was low (25%, Experiments 1A and 2A), the flanker at the uncued location showed different patterns of congruency effect for different types of stimuli. The color flanker caused interference (Experiment 1A), but the alphanumeric flanker did not (Experiment 2A). Increasing the peripheral attention for hearing subjects, by increasing the proportion of peripheral detection trials (57%, Experiment 2C), could make hearing subjects behave like deaf subjects, such that the SI facilitation effect at the cued location disappeared and the alphanumeric flanker at the uncued location caused interference. Additionally, the combined pre-response and response level interferences (i.e. RI vs. CO) prevailed in all the conditions of the two experiments, with the exception at the uncued location in Experiment 2A. This finding is generally consistent with Ro et al. (2002). In the following discussions, we focus on two issues: (1) the superiority of peripheral attention in deaf people; (2) a possible mechanism underlying the SI facilitation effect at the cued location.

##### 4.1. The superiority of peripheral attention in deaf people

Earlier studies have suggested that deaf people are superior to hearing people in peripheral vision and attention (Neville and Lawson, 1987a, 1987b; Parasnis and Samar, 1985; Proksch and Bavelier, 2002; Rettenbach et al., 1999). The superior performance is supported by higher activities in corresponding brain regions (Bavelier et al., 2000, 2001). The present study produced results generally consistent with these findings.

Firstly, in both experiments, deaf subjects were about 56 ms faster than hearing subjects in responding to the peripheral target, while the IOR effects were equivalent for the two groups of subjects. This result suggests that there is dissociation between the early perceptual processing and the attentional (re)orienting. Although deaf and hearing people may differ in the availability of peripheral attentional resources and its impacts upon the early perceptual processing, they do not differ in the higher inhibitory processes of exogenous attentional orienting. This finding is at variance with earlier studies showing that deaf subjects performed

better than hearing subjects in tasks tapping into the early, facilitatory process of exogenous attentional orienting (Bosworth and Dobkins, 2002; Parasnis and Samar, 1985). Also, we did not observe a reduction of IOR effects for deaf subjects as reported by Colmenero et al. (2004) at a comparable SOA.

Secondly, the superiority of the peripheral attention in deaf subjects also manifested in their responses to the central target accompanied by the flanker at either the cued or the uncued peripheral location. Differing from hearing subjects, deaf subjects showed flanker interference effects at the response level irrespective of the type of stimuli and the location of the flanker. Only when attentional resources were forcefully distributed to the periphery because of the increase of the proportion of peripheral detection trials, did hearing subjects perform in the same way as deaf subjects. These results strongly suggest that the peripheral attention in deaf people is enhanced as compared with hearing people.

Finally, results from the central discrimination tasks suggested that the spatial distribution of attention during IOR modulates mainly the resolution of the pre-response, but not the response conflict in hearing subjects, while it does not modulate either the pre-response or the response conflict in deaf subjects. The perceptual load theory of attention (e.g., Lavie and Tsai, 1994) emphasizes the role of the amount of available attentional resources in determining the locus of attentional selection. If there are spare attentional resources being allocated to the task-irrelevant distractors, late attentional selection occurs. If all or most of the attentional resources are spent on the processing of the task-relevant information, early attentional selection occurs. The fact that deaf subjects showed flanker interference effects at the response level irrespective of the type of stimuli and the location of the flanker may imply that deaf people are capable of distributing more attentional resources to the periphery and processing the flanker there to higher levels.

#### 4.2. A possible mechanism underlying the SI facilitation effect at the cued location

The surprising finding of facilitatory effects at the cued location for the SI stimuli as compared with the CO stimuli in Experiments 1A and 2A needs an explanation that can be tested further. Our tentative and perhaps speculative account is based on the interaction between the earlier token individuation process (Kanwisher, 1987, 1991) and the spatial distribution of attention.

The token individuation theory assumes that object recognition includes two staged processes, i.e. type identification and token individuation. During the type identification, the type node of a perceived object is accessed. This provides information regarding what object is present. Token individuation refers to the formation of an episodic representation containing information about individual encounters of a particular object. This process provides information regarding which instance of the object is perceived. This two-stage theory can account for the repetition blindness effect which refers to a relative inability to detect or recall repetitions of items that occur in a rapid serial visual presentation.

We suggest that the SI facilitatory effect at the cued location for hearing subjects was caused by both the relatively

easier token individuation process for the SI stimuli than for the CO stimuli and the amount of spatial attention allocated to peripheral locations. To respond correctly to the central target, subjects have to firstly perceptually discriminate which one of the two simultaneously presented stimuli is the target. This discrimination can be carried out by using the differences in perceptual representations and/or by using the differences in spatial locations of the target and the flanker. In the SI condition, the target and the flanker differ in both the location and the color (alphanumeric) dimensions, while in the CO condition they differ only in the location dimension. Thus, the perceptual representations of the CO stimuli would be less helpful in this token individuation process than those of the SI stimuli. Whether the location dimension plays a dominant role in the token individuation process depends to a large extent on the amount of attentional resources allocated to the location of the flanker. When the flanker receives a relatively smaller amount of attentional resources, as in Experiments 1A and 2A in which most targets appeared at the central location, the token individuation for the SI stimuli is faster than that for the CO stimuli because the former is supported by information from both the feature and the location dimensions. When the flanker receives more attentional resources, as in Experiments 1B, 2B or 2C, the location dimension becomes dominant in accomplishing the token individuation process and the differences in the efficiency of the token individuation process for the SI and the CO stimuli disappear, so does the facilitatory effect. Indeed, when the flanker at the cued location received even more attentional resources, e.g., when 75% of the targets were the peripheral detection targets (unpublished data), the perceptual differences between the flanker and the target in the SI condition could lead to a flanker interference effect at the pre-response level.

In conclusion, by combining the manipulation of the IOR process in the exogenous spatial cueing with the differentiation of levels of interference in the flanker task, we investigated the interaction between the spatial distribution of attention and levels of flanker interference in deaf and hearing people. Results from both the peripheral detection task and the central discrimination tasks demonstrated the superiority of deaf people in the peripheral attention. Moreover, the spatial distribution of attention modulates mainly the resolution of pre-response flanker interference in hearing people, but has no effects on either the pre-response or the response level interference in deaf people.

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## 5. Experimental procedures

### 5.1. Experiment 1

Both deaf and hearing subjects were asked to discriminate the color of the central targets in Experiment 1. The manipulation of pre-response and response conflicts was carried out by asking subjects to make one response to the colors *red* and *green* and to make another response to the colors *yellow* and *blue* following van Veen et al. (2001). We called the target and its flanker congruent at both the pre-response and the response levels (“congruent” condition, CO) when they were identical. We called them incongruent at the stimulus level but



congruent at the response level (“stimulus-incongruent” condition, SI) when they had different colors, but were mapped to the same response. If the target and the flanker were of different colors and were mapped to different responses, they were considered incongruent at both the stimulus and the response levels (“response-incongruent” condition, RI). Peripheral target detection trials were also added into the experiment, in which a white dot appeared with equal probabilities at either the cued (inhibited) or the uncued (non-inhibited) peripheral location and subjects were asked to detect it as quickly as possible.

### 5.1.1. Subjects

Twenty-two (10 female, mean age:  $21 \pm 2$  years) hearing subjects were tested in Experiment 1A. Sixteen congenitally, genetically deaf subjects (8 female; mean age:  $20 \pm 1.5$  years) participated in Experiment 1B and had a binaural hearing loss of  $>90$  dB. All the subjects had no history of neurological disorders, gave their informed consents and were paid for their participations. They were all right handed and had normal or corrected-to-normal vision without color weakness or color blindness. All subjects were paid for their participations after the experiment. This study was approved by the Academic Committee of the Department of Psychology, Northeast Normal University, China.

### 5.1.2. Stimuli and procedure

Each trial consisted of a series of displays (see Fig. 4). A row of three white boxes appeared on the computer screen with black background for 1300 ms. The outline of one of the peripheral boxes then became thicker and brighter for 300 ms to attract attention. After an interval of 200 ms with the three white boxes, the outline of the central box became thicker and brighter for 300 ms and was followed by another interval of 100 ms before the target appeared. Hence, the SOA between the peripheral cue and the target was 900 ms. The target was presented until a response was made. Each white box extended  $1^\circ$  in the horizontal and the vertical directions. The center-to-center distance between the central box and one of the peripheral boxes was  $3^\circ$ .

There were two types of targets. For the peripheral detection task, a white dot appeared at the center of a cued or an uncued peripheral box with equal probabilities. There were 64 peripheral target detection trials in total. For the central color discrimination task, the target and the flanker appeared simultaneously in the central box and one of the two

peripheral boxes. Subjects were required to discriminate the color of the stimulus in the central box. The peripheral distractor could have one of the three kinds of relation with the central target, i.e. the same (CO), stimulus incongruent and response congruent (SI), and both stimulus and response incongruent (RI). The flanker appeared in either the cued or the uncued peripheral box with equal possibilities. Each condition at the cued or the uncued location had 32 trials.

Subjects sat about 50 cm from the computer screen in a dimly lit room, with their heads stabilized on a chin rest. They were instructed to respond as quickly and as accurately as possible to targets in the central box by pressing one button on the response pad if the color of the target was *red* or *green* and the other button if *yellow* or *blue*. Subjects used their index and middle fingers of their dominant hand to respond. To minimize the potential influence of the Simon effect (Lu and Proctor, 1995; Simon, 1969), we arranged the two response buttons in an up-down position. The color-to-button mapping was counter-balanced over subjects, such that half of the subjects pressed the upper button for *red* and *green* and the other half pressed the bottom button. For the peripheral detection trials, subjects were asked to simply press the upper button if they detected the appearance of a white dot in a peripheral box. Although eye movements were not monitored, many previous studies have shown that there are few trials contaminated by eye movements if the task is the simple detection of the target (e.g., Müller and Rabbitt, 1989; Fischer et al., 2003).

The presentation of stimuli and the recording of RTs and errors were controlled by the DMDX software package (Forster and Forster, 2003). All the trials in each experiment were pseudo-randomly mixed. Before the formal test, each participant performed 60 practice trials which had the same composition of different types of trials as the formal experiment.

### 5.1.3. Design

A  $2 \times 3$  design was used in each experiment in which the flanker could appear at either the cued or the uncued peripheral location. The congruency between the central target and its flanker had three levels: CO, SI and RI.

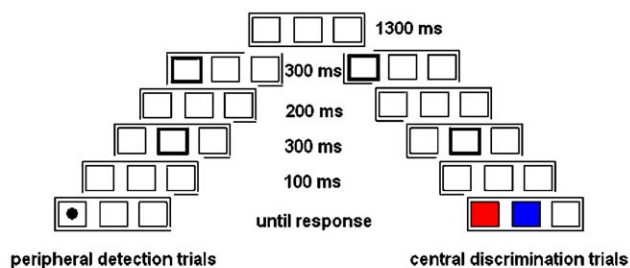
## 5.2. Experiment 2

### 5.2.1. Subjects

Forty normal hearing subjects were tested for the experiments, 19 for Experiment 2A (10 male, mean age:  $21 \pm 1.5$  years), 21 for Experiment 2C (11 male, mean age:  $21 \pm 1.5$  years). Seventeen congenitally, genetically deaf subjects (9 male; mean age:  $20 \pm 1.5$  years) participated in Experiment 2B and had a binaural hearing loss of  $>90$  dB. All the subjects had no history of neurological disorders. They gave their informed consents and were paid for their participations. They were all right handed and had normal or corrected-to-normal vision. All the subjects did not participated in Experiment 1. This experiment was approved by the Academic Committee of the Department of Psychology, Northeast Normal University, China.

### 5.2.2. Stimuli and procedure

The experimental design was the same as Experiment 1. We asked both deaf and hearing subjects to classify letters and



**Fig. 4 – Sequence and timing of a trial in the central discrimination task (right) and the peripheral target detection task (left).**

digits. The manipulation of the pre-response and the response conflicts was carried out by asking subjects to make one response to letters A or B and to make another response to digits 4 or 5. There were three levels of congruency between the central target and its flanker: CO, SI and RI. If the target and its flanker were identical (e.g., both A), they were congruent at both the stimulus and the response levels (CO). If the target and its flanker were two different letters (and two different digits) (e.g., target A, flanker B), they were incongruent at the stimulus level but congruent at the response level (SI). If the target and the flanker were one digit, one letter (e.g., target A, flanker 5), they were incongruent at both the stimulus and the response levels (RI). We also included the peripheral detection trials in Experiment 2. The peripheral detection trials would measure the effectiveness of peripheral cueing. More importantly, the percentage of them would build up an attentional set for the distribution of attentional resources to the peripheral and the central locations. The higher percentage the peripheral detection trials, the more attentional resources subjects allocate to peripheral locations. Therefore, we tested hearing and congenitally deaf subjects separately with 25% peripheral detection trials in Experiment 2A and 2B. And we tested another group of hearing subjects in Experiment 2C with 57% peripheral detection trials to simulate the enhanced peripheral attentional resources in deaf subjects.

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