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Perceptual salience of global structures and the crowding effect in amblyopia

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Abstract *Background:* The crowding effect refers to stronger deficits in linear acuity (e.g., letters in a line) than in single letter acuity in amblyopia. The current work investigated whether the salience of a global structure in which the target for identification is embedded influences the crowding effect in amblyopia. *Methods:* Compound shapes were presented to the amblyopic and fellow eyes respectively of 12 anisometropic amblyopes. The compound stimuli were presented on either a blank or a cross background so that the salience of global structures were manipulated. Reaction times (RTs) and response error rates were recorded when subjects identified global or local shapes, respectively. *Results:* RTs were shorter to global than local shapes for both the amblyopic and the fellow eyes. The global RT advantage was larger for the amblyopic than the fellow eye. Interestingly, when viewing the stimuli with the amblyopic eye, subjects made more errors to local targets when the compound stimuli were presented against the blank than the cross background. *Conclusion:* The results suggest that the salience of global structures of visual stimuli contributes to the crowding effect in amblyopia.

Introduction

The crowding effect refers to the phenomenon that visual acuity for a letter surrounded by bars or by other letters can be impaired relative to the acuity for a single letter [1]. The crowding effect is more pronounced in people with low vision, such as amblyopes, than those with normal vision [1, 9, 13]. Several interpretations of the crowding phenomenon have been proposed [2]. For example, the concept of contour interaction suggests that lateral spatial masking caused by the proximity of contours near the target decreases visual acuity, possibly resulting from lateral inhibition in the cortex. Alternatively, the surrounding distractors may result in high attentional demand to separate the target from distractors and thus lead to reduction of visual acuity. Variation of physical features of stimuli such as shifts of the most relevant spatial frequency band of letters to higher spatial frequencies may also contribute to the crowding effect [10].

The current work examined whether the salience of a global structure in which the target for identification is embedded influences the crowding effect. For instance, since proximity dominates similarity in grouping local elements [3, 5, 6], the global structures of stimuli shown in Fig. 1 are perceptually more salient than those in Fig. 2 because proximity and similarity of shapes determine local element grouping into a global structure in Figs. 1 and 2, respectively [5]. If the salience of a global structure in which the local shape is required to be identified significantly contributes to the crowding effect, we would expect that the identification of a local arrow becomes worse for stimuli in Fig. 1 than those in Fig. 2. However, if contour interaction or attention factors determine the crowding effect, we would expect worse performance of identifying local arrows for stimuli in Fig. 2 than those in Fig. 1 because the background crosses surrounding local

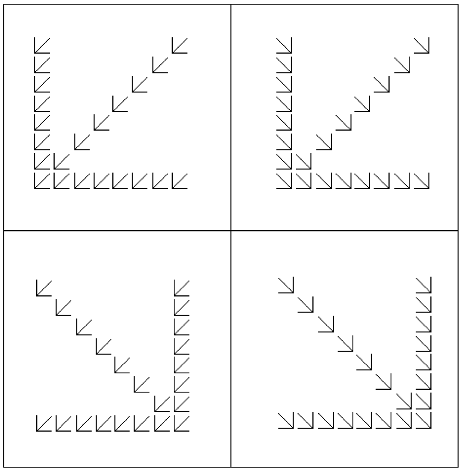

Fig. 1 Proximity-grouped compound stimuli. Global arrows made up of local arrows are presented on a blank background

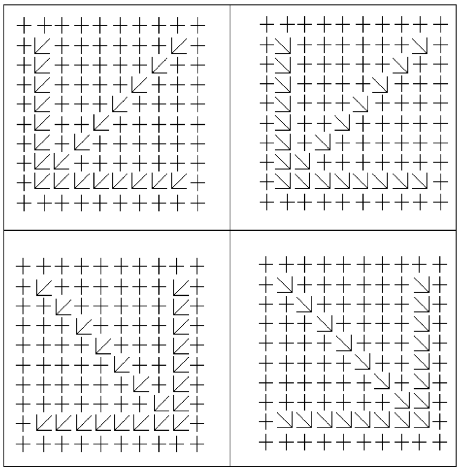

Fig. 2 Similarity-grouped compound stimuli. Global arrows made up of local arrows are presented on a background of crosses

arrows increase contour interaction and the difficulty of selection of a local arrow.

We recruited anisometropic amblyopes in the current study[1]. Compound shapes shown in Figs. 1 and 2 were presented to the subjects' amblyopic and fellow eyes, respectively. Performances of identifying global and local shapes were compared between the conditions when global structures are formed by proximity and perceptually salient or formed by similarity of shapes and perceptually less salient.

Materials and methods

Subjects

Twelve anisometropic amblyopes with central fixation were recruited in the current study. The clinical details of each of the subjects are given in Table 1. All tests were performed monocularly with the amblyopic or the fellow eye occluded. Informed consent was obtained from all subjects.

Stimuli

Two sets of compound stimuli were black on a white background, as shown in Figs. 1 and 2. Each compound stimulus consisted of a global arrow made up of local arrows pointing down left or down right. The directions of local arrows were either consistent or inconsistent with that of the global arrow. Local arrows of the stimuli in Fig. 1 were presented on a blank background so that proximity dominated local element grouping. Local arrows of the stimuli in Fig. 2 were embedded in crosses so that similarity of shape dominated local element grouping. The local arrows were arranged in an 8×8 matrix. The global figure was 3.5×3.0 cm (height × width), and the local figure was 0.3×0.25 cm. At a viewing distance of about 40 cm the global and local figures subtended a visual angle of 5.0×4.2° and 0.43×0.36°, respectively. The height and width of each background cross was the same as that of each local arrow. The stimulus used in the control condition was only one small arrow displayed at the center of the screen, which was as big as the local arrows composing the global shapes.

Table 1 Visual characteristics of amblyopes in the current work

Observer	Age (years)	Sex	Eye	Rx	Acuity
H.L.	5	F	OD	−0.25	20/15
			OS	+3.25/+1.00×60	20/100
L.H.	10	F	OD	+0.75	20/20
			OS	+5.75/+1.50×115	20/200
X.K.	7	F	OD	+1.50/+0.50×100	20/15
			OS	+7.00/+0.50×110	20/200
X.Z.	12	M	OD	−1.50	20/15
			OS	+1.00/+0.50×90	20/30
J.T.	12	M	OD	+2.00/+0.75×90	20/15
			OS	+1.00/+4.00×90	20/30
Z.Z.	6	F	OD	+1.00/+0.50×110	20/20
			OS	+5.00/0.75×85	20/40
C.F.	10	F	OD	+0.50/+0.75×185	20/20
			OS	+3.75/+2.00×180	20/50
S.M.	7	F	OD	+6.00/+0.50×60	20/60
			OS	+3.50	20/25
W.J.	8	M	OD	+0.50/+3.00×85	20/40
			OS	+1.75/+1.50×90	20/20
G.H.	13	F	OD	+3.00/+2.00×80	20/40
			OS	+2.00	20/20
M.X.	11	M	OD	Plano	20/15
			OS	+5.50	20/40
C.Q.	26	F	OD	Plano	20/15
			OS	+6.50/+1.00×90	20/200

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[1] Minor degrees of eccentric fixation are usually seen in strabismic amblyopia. Thus the difference in behavioral performances of the amblyopic eye with eccentric fixation and the fellow eye with central fixation may arise from the discrepancy between foveal and nonfoveal vision. To exclude this possibility, the current work recruited only anisometropic amblyopes whose both amblyopic and fellow eyes used central fixation. This may simplify the explanation of our results.

Procedure

The experiment employed a four-factor within-subject design with the factors being: Grouping (local elements were grouped by proximity or similarity, i.e., stimuli in Figs. 1 and 2); Eye (the amblyopic or the fellow eye); Globality (discrimination of global or local level); and Consistency (the global and local levels are consistent or inconsistent). Each trial began with a 1000-ms warning beep and the presentation of a fixation cross located at the center of the screen, which was 0.4×0.3 cm subtending 0.58×0.43° of visual angle. After another 1000 ms, the fixation cross was replaced by the stimulus, which was presented at the center of the screen and stayed on until subjects responded. While maintaining fixation, subjects were required to identify the orientation of global or local arrows in separate blocks of trials by pressing one of two keys on a standard keyboard with the right and left middle fingers. The presentation sequence of stimuli in Figs. 1 and 2, the order of presentation for the two eyes, and the order of the global and local tasks were counterbalanced across subjects. For each stimulus condition, there were 16 practice trials followed by 48 trials in one block for the identification of the global or local shapes. Subjects were encouraged to respond as quickly and accurately as possible. In the control condition, subjects discriminated orientations of a small arrow presented at the center of the visual field. There were 60 trials, of which the first 12 were for practice. Stimuli were presented on the screen until subjects made a response.

RTs and error rates were subjected to a repeated-measure analysis of variance (ANOVA) with Grouping (proximity vs similarity), Eye (amblyopic vs fellow eye), Globality (global vs local), and Consistency (consistent vs inconsistent) as independent variables.

Results

Error rates

The mean error rates under each condition are given in Table 2. The error rates were higher for the amblyopic than for the fellow eye [4.6% vs 2.2%, F(1,11)=6.18, *P*<0.03]. Subjects made more errors in responses to the local than global stimuli [4.5% vs 2.3%, F(1,11)=6.07, *P*<0.03]. The interaction of Grouping × Globality was significant [F(1,11)=10.02, *P*<0.009] due to the fact that the error rates were higher in the local compared to the global conditions when local elements were grouped by proximity whereas no difference was observed between global and local conditions when local elements grouped by similarity. There were also reliable interactions of Grouping × Eye × Globality [F(1,11)=6.55, *P*<0.03], suggesting that the effect of amblyopia on differential global/local responses was stronger when local elements were grouped by proximity than by similarity shapes. Post-hoc analyses showed that, for the amblyopic eye, error rates to the proximity-grouped stimuli were higher in the local than global conditions, whereas error rates to the similarity-grouped stimuli did not differ between the global and local conditions [F(1,11)=18.29, *P*<0.002]. Moreover, subjects made more errors in responding to local targets when local elements were grouped by proximity than by similarity [F(1,11)=6.98, *P*<0.022], whereas error rates to the global targets did not differ between the two conditions [F(1,11)=2.73, *P*>0.1]. For the normal eye, however, the error rates did not differ between proximity- and similarity-grouped stimuli regardless of whether subjects identified global or local stimuli (*P*>0.2).

Reaction times

The average RTs for correct responses to proximity- and similarity-grouped stimuli are shown in Table 3. The analysis of RTs indicated significant main effects of Grouping [F(1,11)=5.74, *P*<0.034], Eye [F(1,11)= 9.56, *P*<0.01], Globality [F(1,11)=26.68, *P*<0.001], and

Table 3 Reaction times (ms) in each stimulus condition

	Global		Local	
	Consistent	Inconsistent	Consistent	Inconsistent
Proximity-grouped stimuli				
Amblyopic eye	660	664	1164	1168
Fellow eye	640	680	877	948
Similarity-grouped stimuli				
Amblyopic eye	920	952	1071	1122
Fellow eye	749	920	809	912

Table 2 Error rates (%) in each stimulus condition

	Global		Local	
	Consistent	Inconsistent	Consistent	Inconsistent
Proximity-grouped stimuli				
Amblyopic eye	2.4	1.3	6.8	11.2
Fellow eye	2.7	1.6	3.5	4.5
Similarity-grouped stimuli				
Amblyopic eye	2.6	4.4	4.3	3.5
Fellow eye	0.0	3.3	0	2.3

Consistency [F(1,11)=10.52, *P*<0.008]. Subjects responded faster to proximity- than similarity-grouped stimuli (850 vs 932 ms). RTs were longer to the stimuli presented to the amblyopic eye than to the fellow eye (965 vs 817 ms). For both sets of stimuli, responses to the global shape were faster than those to the local shape. RTs were shorter when global and local shapes were consistent than when inconsistent.

There were reliable interactions of Grouping × Globality [F(1,11)=10.61, *P*<0.008], Eye × Globality [F(1,11)=8.74, *P*<0.013], and Grouping × Consistency [F(1,11)=8.29, *P*<0.014]. The interaction of Eye × Consistency was marginally significant [F(1,11)=4.14, *P*<0.06]. The global RT advantage was more salient for proximity- than for similarity-grouped stimuli and stronger for the amblyopic than for the fellow eye. The interference effect was stronger for similarity- than proximity-grouped stimuli and more pronounced for the normal than the amblyopic eye. Post-hoc analyses showed that the responses to the global similarity-grouped stimuli were slower than those to the proximity-grouped stimuli [F(1,11)=39.7, *P*<0.001], whereas the responses to the local stimuli did not differ between the two conditions (F<1).

In the control condition, subjects responded slower and with more errors to the identification of orientations of a single small arrow presented to the amblyopic eye than to the fellow eye [817 vs 651 ms, t(11)=2.71, *P*<0.02; 6.8% vs 1.7%, t(11)=2.82, *P*<0.02].

As visual acuity of amblyopic eyes was distributed over a wide range, we further analyzed the correlation between visual acuity of amblyopic eyes and error rates (and RTs) to examine the influence of visual acuity on the performance of the amblyopes. The analyses did not show any significant correlation between visual acuity and the performance of the amblyopes (*P*>0.25 for all analyses), suggesting that the effect of perceptual salience of global structures on behavioral performances could not be accounted for simply by the variation of visual acuity.

Discussion

Subjects responded faster to global than local targets when viewing the stimuli with both the amblyopic and the fellow eye. These results are consistent with the results of previous studies on healthy subjects [5, 14], indicating a global RT advantage. The global RT advantage was reduced when the local elements were grouped by similarity of shapes (stimuli in Fig. 2) compared with when local elements were grouped by proximity (stimuli in Fig. 1). These findings are in agreement with the previous work [5] and support the proposal that grouping by proximity occurs earlier than grouping by similarity and dominates the perception of global structures. The global RT advantage was more pronounced for the amblyopic eye than for the fellow eye, mainly because of the prolonged RTs to the local stimuli presented to the amblyopic eye. Moreover, for both proximity- and similarity-grouped stimuli, the RT difference between the amblyopic and fellow eyes was larger in the local condition, in which multiple local elements were displayed simultaneously, than in the control condition, in which a single local shape was presented. Therefore the local perception of compound stimuli was impaired by amblyopia, reflecting a strong crowding effect for the amblyopic eye.

Interestingly, responses to the local stimuli showed more errors when local elements were grouped by proximity than by similarity. However, this is true for responses to the stimuli presented to the amblyopic eye but not to the fellow eye. Response speeds to local shapes also tended to be slower for proximity than similarity-grouped stimuli, though the difference did not reach significance. These results could not be interpreted by the account of contour interaction or attentional demand [2]. Since there were crosses around each local arrow in the similarity-grouped stimuli, whereas each local arrow was adjacent to only two arrows in the proximity-grouped stimuli, the contour interaction should be stronger, and selection of an individual local arrow should be more difficult, for the processing of local shapes of similarity- than proximity-grouped stimuli. Thus, according to the concept of contour interaction or attentional demand, the crowding effect for the amblyopic eye should be stronger for the local processing of similarity- than proximity-grouped stimuli. However, our results contradict this prediction.

It is also difficult to explain the better local performance of similarity- than proximity-grouped stimuli presented to the amblyopic eye by variation of spatial frequency spectrum induced by the background crosses. Monkey studies have shown that contrast sensitivity of amblyopic eyes reaches the peak amplitude at a lower spatial frequency than fellow eyes [12], indicating that the amblyopic eye is less sensitive to high spatial frequencies than the fellow eye. Hess et al. [10] also found evidence that the most relevant spatial frequency band for detecting the orientation of an unflanked Landolt C is lower than for detecting the orientation of a flanked Landolt C; thus, the crowding effect of the amblyopic eye can be interpreted by its lower sensitivity to high spatial frequencies and the requirement for sensitivity to high spatial frequencies when the target letter is flanked by other letters or bars. According to the above analysis, high spatial frequency noise should produce stronger crowding effect for the amblyopic eye. However, although the background crosses used in the current study induced mainly high spatial frequencies (see [5] for the results of spatial frequency analysis), subjects' performance in the local condition was better for similarity- than for proximity-grouped stimuli presented to the amblyopic eye, which is opposite to the prediction of the spatial frequency concept.

The results of our current work are in line with a proposal that the salience of a global structure in which local elements are required to be identified contributes to the crowding effect in anisometropic amblyopia. Our previous work has shown that the perception of global shapes is weaker when local element grouping is dominated by similarity of shape than when it is dominated by proximity [3, 5]. Grouping of local elements interacts with selection of individual local elements and determines which level, global or local, dominates the processing of hierarchical patterns [4, 5]. Given that the global structure was more salient for proximity- than for similarity-grouped stimuli, it may be proposed that, at least to a certain degree, the salience of the global structure in which local items are required to be identified contributes to the impairment of local processing of proximity-grouped stimuli. It is possible that a salient global structure, which has been supposed to be mediated by low-spatial-frequency channels [11, 15], dominates the perceptual processing of hierarchical stimuli and competes with the process of segmenting an individual local element for identification. This effect may be particularly strong for the amblyopic eye, since neurons in the visual cortex that receive inputs from the amblyopic eye are more sensitive to low than to high spatial frequencies [12]. However, as the global shape salience could be weakened by the background crosses, the effect of global structure salience on local processing was reduced and thus local responses were facilitated. In other words, the crowding effect observed for the amblyopic eye in the current experiment may partially reflect the interaction between global and local perception.

Previous studies have attributed the crowding effect in amblyopia to lateral inhibition, high attentional demand, or variation of the most relevant spatial frequency. The present findings indicate that identification of local shapes in hierarchical patterns could be worse when the global structure of hierarchical stimuli is salient than when it is ambiguous. The results can not be explained by the lateral inhibition, attentional demand, or the spatial frequency concepts, but are consistent with a proposal that the salience of a global structure contributes to the impairment of local processing in amblyopia.

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