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The Development of Crowding and Interocular Interactions in a Resolution Acuity Task

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Purpose. To investigate the impact of interocular similarities of a surround stimulus on foveal resolution acuity in the normally developing visual system.

Methods. Liquid crystal shutter goggles synchronized with the monitor frame rate were used to present a Landolt C and surround bars to one or both eyes, in monocular, dichoptic, half-binocular, and binocular viewing conditions. Resolution acuity was measured under each condition in 56 normally sighted children (7 to 14 years of age) and 22 adults (21 to 38 years of age). The effect of the surround bars (crowding) was tested in a subgroup of nine children, and 10 adults.

Results. Across all age groups resolution acuity was significantly better in the binocular condition than in the other three viewing conditions (binocular summation), and was significantly better in the half-binocular (with target presented to the test eye and bars presented to both eyes) than in the dichoptic condition (target presented to test eye and bars presented to the nontested eye only). In children, but not in adults, resolution acuity was significantly better without than with bars.

Conclusions. The interocular similarities may explain the better visual resolution in the half-binocular condition than in the dichoptic condition for all age groups tested. The results suggest that interocular interactions underpinning resolution acuity under these viewing conditions are developed in early childhood. The foveal crowding effect was found to be apparent at the beginning of school age, and diminished with maturation. (*Invest Ophthalmol Vis Sci.* 2011;52:9452–9456) DOI:10.1167/iovs.11-8148

In binocular vision, signals from both eyes are combined into a single percept and visual performance may be superior or inferior to monocular performance, depending on the stimuli presented to each eye. In the case of dissimilar images presented to each eye, the right and left percept are said to be rivalrous, which may result in an alternation between percepts over time or in spatial location, the latter being known as piecemeal rivalry, and perceived as a patchwork of the two different images.[1] In children, piecemeal rivalry is more likely to occur than a temporal alternation between percepts, perhaps due to a lack of effective feature integration in childhood.[1]

However, when different regions in both retinas are stimulated simultaneously by different stimuli, a single binocular image is perceived because there is no spatial conflict between the two stimuli. When identical images are presented to both eyes at corresponding retinal locations, visual performance is better than if the image is presented to one eye only.[2] This phenomenon is called binocular summation and has been reported with various tasks including detection, recognition, and discrimination for visual acuity, contrast sensitivity, light detection, and reaction time.[3–5] However, it is not yet thoroughly understood how visual performance is affected in an intermediate state, when one eye views only part of a stimulus that is presented to the fellow eye (i.e., a half-binocular condition).[6]

Previous work suggests that binocular summation diminishes during maturation of the normal visual system.[7] Vedamurthy et al.[7] reported that binocular summation in contrast sensitivity was significantly higher in children aged 6 to 14 years than in adults. These findings pointed to a developmental change in interocular interactions of contrast sensitivity in children, and maturation in binocular summation for contrast sensitivity beyond 14 years of age.

On the other hand, Pott and van Hof-van Duin[8] measured visual acuity under monocular and binocular conditions using a C-chart in 180 5-year-old children and 24 young adults. They reported that binocular summation for acuity was lower in children than adults, but no statistical comparison was made.

Visual performance also can be affected by the spatial proximity of visual stimuli, and the effect may be facilitatory or inhibitory. Ehlers[9] coined the term "crowding" to describe the inhibitory effect of distractors presented close to a test letter. Several terms have been used to describe the reduced perception of a target stimulus surrounded by others, such as lateral masking,[10–12] surround suppression,[13] lateral inhibition,[14] surround masking,[15] and contour interaction.[16] Moreover, the crowding effect has been reported with various tasks including letter identification,[16] orientation discrimination,[17] face recognition,[18] and more recently has been linked to reading rate.[19,20]

Crowding at the fovea is immature at the beginning of school age,[21,22] with foveal acuity being adult-like for isolated optotypes but poorer than adult level for surrounded optotypes.[22] These findings indicate that crowding is stronger in childhood than in adulthood. Semenov et al.[21] investigated crowding in children using an approach in which the size of an isolated target (Landolt C) was set at the 75% correct level. Using this letter size, percentage correct levels were determined at a range of target-surround Landolt C-bar separations. They found that the critical separation (the maximum distance beyond which the surrounding features do not degrade performance) decreases during childhood reaching adult levels by 9 years of age.

However, another study suggests that crowding is not fully mature by this age, and that while the critical separation for Landolt C acuity is stable by around 10 years of age, the critical separation for a rectangular grating target decreases until 12 years of age.[23] In agreement with the immaturity of attentional factors in children, it was suggested that this differential devel-

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opment in the case of crowding reflects attentional factors related to target and surround features. However, a more recent study using an approach in which isolated and surround thresholds are obtained using identical methods, found that crowding remains immature at 11 years of age with higher critical separation in children than in adults.[22] Although these findings are equivocal the available evidence indicates that crowding is not fully developed until late childhood.

The crowding phenomenon is thought to be underpinned at least in part by cortical processing, because it is found not only when target and surround are presented to one eye but also when the target is presented to one eye and the surround to the other eye.[24] Moreover, the crowding effect has also been described in face recognition in which higher cortical levels are involved,[18] and recent evidence shows that the type and similarities of target and surround features may also play a role in crowding.[23] Therefore, it has been suggested that crowding occurs at multiple levels of visual processing from a low level at which binocular combination takes place to a higher level where feature integration and attention occurs.[19]

Research on the impact of interocular similarities in target and surround stimuli on spatial vision in normal adults suggests that while the major contribution to binocular enhancement is summation of the target, the similarity of surround features also plays a role in improving resolution acuity and contrast sensitivity.[6,25] These findings suggest that in adults spatial vision is enhanced when target and surround stimuli are interocularly similar. However, it is not known whether the immature visual system also depends on such interocular similarities. The present study investigates the impact of interocular similarity of a surround stimulus on resolution acuity. Children and adults with normal vision were tested, as an early step toward understanding how the mature and immature visual systems are affected by stimuli of this kind.

Methods

Subjects

Each adult subject or parent signed a declaration of informed consent before participating in accordance with the Declaration of Helsinki. Eligible subjects were aged 18 to 40 years (adults) or 7 to 15 years (children). Subjects included in the study had best corrected visual acuity (BCVA) of 0.0 log minimum angle of resolution (logMAR, measured using a Bailey-Lovie chart) or better in each eye; stereopsis of 40 arc sec (Titmus stereotest), normal ocular motility and normal ocular health. None of the children required refractive correction, while six of the 22 adults (27%) wore refractive corrections at mean spherical errors from 1.5 diopter (D) to −7.5 D (mean −3.69 D).

Apparatus

Stimuli were generated using a graphics card (VSG 2/5; Cambridge Research Systems, Rochester, UK) in a host computer. All stimuli were presented at the center of a 20-inch flat fast phosphor monitor (Monoray; Clinton Electronics Corp., Loves Park, IL) with a resolution of 1024 × 768 and dimensions of 2.6° × 1.94° at the viewing distance of 8 m. The monitor was gamma corrected. Liquid crystal shutter goggles were synchronized with the monitor frame rate so that alternate frames were presented independently to each eye. In this way, different images were presented on each frame, and each eye received only one of the two images. The fast phosphor decay time of the monitor minimized crosstalk (the persistence of the stimulus at one frame into the next frame) and no flicker was perceived. The stimulus was presented to each eye at a frame rate of 60 Hz, which was half of the full monitor refresh rate.

Subjects were tested wearing the goggles in all conditions, even if unnecessary (e.g., in the binocular condition) to maintain constant stimulus luminance level across conditions. The mean luminance level of the stimulus was 51.9 candela (cd)/m^2, but was reduced to 4.5 cd/m^2 when viewed through the goggles and via a front-silvered mirror. The mirror was employed to allow a sufficiently long viewing distance (8 m) to allow stimuli to reach and exceed adult acuity levels. The shutter goggles were worn over spectacle correction, if required.

Stimuli

Resolution acuity was measured using a Landolt C letter target with four possible gap orientations (right, left, up, or down). The Landolt C was constructed as an annulus in a 5 × 5 grid. A gap, one-fifth of the dimension of the square grid, was inserted into the annulus at the right, left, top, or bottom position. Four tangential bars of width equal to the gap in the letter C and length equal to its diameter were positioned around the letter C. The distance between the Landolt C and bars was 0.4 of the width of the letter, based on previous work showing maximum crowding at this separation.[16,26]

The target and surrounding bars were presented at the center of the display at −0.82 Weber contrast. High contrast was selected to simulate typical optotypes and because crowding has maximum effect at high contrast.[27] This particular contrast level was chosen because in pilot work it was found to be the highest level at which cross-talk was not perceived by subjects (some cross-talk was apparent at very high contrast, despite our use of a monitor with fast phosphor decay). Stimulus duration was brief (142 ms) to minimize any effect of change in fixation during stimulus presentation. In addition to the Landolt C (and surround bars), two vertical and two horizontal markers of −0.47 Weber contrast, width 0.1° and length 0.6° were presented with inner edges at 0.8° from fixation. These markers assisted in identifying the fixation point, and served as a check for suppression and fusion, because one vertical and one horizontal marker were presented to each eye. In the absence of suppression, the observer was aware of all four bars. In the absence of fixation disparity during fusion, the vertical and horizontal bars were perceived in alignment. The subjects were asked whether they could perceive both pairs of bars and whether the bars were in alignment before and during each test condition. Misalignment was not reported by any of the subjects during testing. Loss of perception of one pair of bars was reported by two adult subjects, and in these cases recording was continued only when all bars were visible.

Procedure

The following viewing conditions were used in the experiments:

- In the monocular condition, the Landolt C and bars were presented to the test eye, while the non-tested eye was occluded with a black opaque patch.
- In the binocular condition, the Landolt C and bars were presented to both eyes.
- In the dichoptic condition, the Landolt C was presented to the test eye, and the bars were presented to the nontested eye.
- In the half-binocular condition, the Landolt C was presented to the test eye and the bars were presented to both eyes.

The eye with poorer acuity was designated as the test eye to which the target would be presented for resolution measurement because previous work suggests a more pronounced effect of surround bars when presented to the eye with better resolution acuity.[24] For this reason, the monocular condition was applied first followed by the other three viewing conditions in pseudorandom order.

Resolution acuity was estimated using a single interval four-alternative forced-choice double staircase, with two down and one up rule (2/1) and step size of 0.05 logMAR. The subject's task was to indicate the orientation of the C gap (up, down, right, left) and enter their responses using a keyboard (adults) or joystick (children). To simulate a video game, the children's task was to move the joystick in the direction corresponding with the orientation of the gap in the Landolt C. To motivate them, children were informed that the video game has

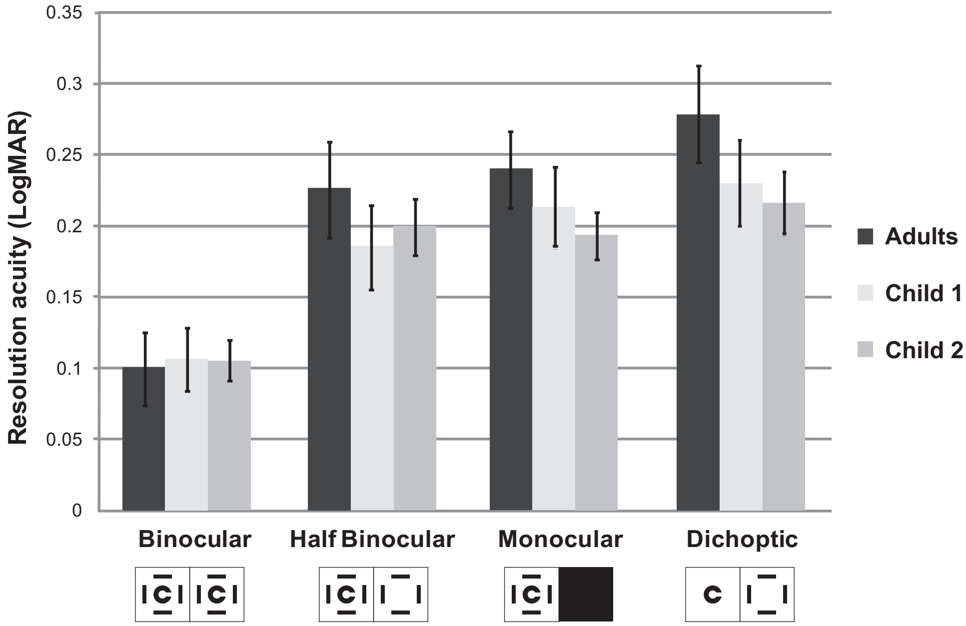

FIGURE 1. Resolution acuity (logMAR) under a range of viewing conditions. A dark square in the monocular condition represent an eye patch. Error bars represent 1 SEM.

four levels (the four conditions). Details of threshold calculation and procedure have been described previously.[25]

The effect of the surround bars was tested in a subgroup of 9 of the 56 children (7 to 14 years of age), and 10 of the 22 adults to determine whether a crowding effect would be elicited with our foveal stimulus. Crowding effects have been found to be small[10,16,28] or in some conditions nonexistent at the fovea in adults.[29] For this purpose, resolution acuity in monocular and binocular conditions was measured in these subjects with and without the surround bars.

Data Analysis

In the main experiment a repeated measures analysis of variance (ANOVA) was used to compare visual resolution across monocular, binocular, half-binocular, and dichoptic viewing conditions as within-subject factors and age group as a between-subjects factor. Mauchly's test of sphericity indicated that the data could not be assumed to be normal ($P < 0.05$) so the Greenhouse-Geisser correction factor was applied.

Visual resolution was compared across the conditions with and without surround bars using a nonparametric statistical test (the Wilcoxon Signed rank test) because the sample size was relatively small. Spearman's correlation coefficient (ρ) was used to look for relationships between variables (age and the difference between acuities measured with and without bars).

RESULTS

A total of 56 normally sighted children participated in the study. In the younger group (child 1) the mean age was 9.4 years ($n = 29$; 20 females; 7.8 to 11.6 years) and in the older group (child 2), the mean age was 12.8 years ($n = 27$; 17 females; 11.7 to 14.1 years). Twenty-two adults, with a mean age of 31.5 years (21 to 38 years; 12 females) also participated. Unreliable data from two children were not included in the analysis. During the experiment these two children showed poor attention on the task.

Figure 1 shows the mean logMAR resolution acuity measured in each viewing condition for each age group. Within each age group resolution acuity was statistically significantly different across viewing conditions ($P < 0.001$) (see Fig. 1). Within each viewing condition resolution acuity was similar across the age groups ($P = 0.649$). Bonferroni post hoc tests showed that resolution acuity was significantly better in the binocular condition than in the monocular condition ($P < 0.001$), the half-binocular condition ($P < 0.001$), and the dichoptic condition ($P < 0.001$), consistent with binocular summation. In addition, resolution acuity was significantly better in the half-binocular condition than in the dichoptic condition ($P < 0.001$).

Table 1 shows the mean logMAR resolution acuity under monocular and binocular viewing with and without surround bars in 9/56 (16%) children with a mean age of 11.7 years and 10/22 (45%) adults with a mean age of 31.7 years. In children, resolution acuity was significantly better without than with bars in monocular ($P = 0.012$) and binocular ($P = 0.04$) viewing conditions. No such difference was found in adults ($P > 0.05$). A significant negative correlation was found between the effect of surround bars and age in the monocular presentation (Spearman's correlation coefficient $\rho = -0.865$, $P = 0.003$) indicating that the magnitude of this effect decreases with age (see Fig. 2). However, no significant correlation was found in the binocular presentation (Spearman's correlation coefficient $\rho = -0.299$, $P = 0.434$).

DISCUSSION

The principal aim of the present study was to determine whether resolution acuity in children depends on interocular similarity of target and surround stimuli and whether any such relationship differs between age groups.

TABLE 1. Group Mean Resolution Acuity (LogMAR) Measured under Monocular and Binocular Viewing, with and without Surround Bars

	Children		Adults	
Viewing Condition	Mean LogMAR	Mean Difference	Mean LogMAR	Mean Difference
Monocular with bars	0.165	−0.092	0.199	−0.02
Monocular without bars	0.073		0.179	
Binocular with bars	0.057	−0.080	0.151	−0.016
Binocular without bars	−0.023		0.135	

A negative value indicates decrement in the condition with surround bars.

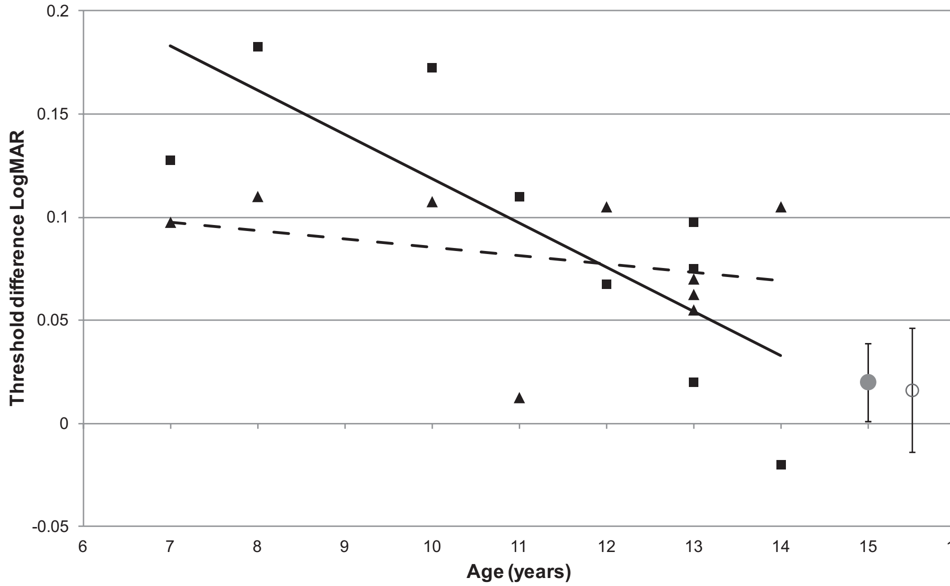

FIGURE 2. Difference in logMAR acuities with and without bars (*squares*, monocular; *triangles*: binocular) in children as a function of age, and in adults (*filled circle*: monocular; *open circle*: binocular). Errors bars at the adult data points indicate standard errors of the means. *Solid and dashed trend lines*: linear fit to the monocular and binocular data, respectively, from children.

While all subjects showed acuity of 0.0 or better on a logMAR chart, mean acuities in the test conditions are worse than this level. The relatively low acuities may be due to the low luminance of the stimulus.[30] Another plausible explanation could be the brief presentation of the stimuli.[31]

In all age groups tested in the present study resolution acuity was better under the binocular viewing condition than in any of the other three viewing conditions. Acuities measured in the four viewing conditions were consistent across all age groups, indicating that the interocular similarities and differences had similar effects in children and adults. This finding suggests that the interocular interactions underpinning resolution acuity in these viewing conditions are developed in early childhood. As outlined earlier (in the introductory section), previous work demonstrates relatively higher binocular summation in children than in adults, but here we find similar binocular and monocular acuities in these groups. The lack of summation may reflect the fact that the present study employed a resolution acuity task.[8] Previous work indicates that interocular interactions that occur in binocular summation and inhibition are less apparent in visual resolution than in detection,[32] and this relatively low effect may explain the insignificant difference in resolution acuity, across different age groups in the present study.

A further factor contributing to the lack of maturational change found in the present study could be the age range (greater than 3 years) of each group and the lack of an age gap between the groups of children.

The poorer performance in the dichoptic than the half-binocular condition may be considered in the context of binocular alignment, fusion, and similarities. As described above four markers were designed and presented at all times with the aim of ensuring binocular alignment. Therefore, a binocular misalignment seems unlikely to be a plausible explanation for worse performance in the dichoptic viewing condition. Moreover, the lack of significant difference between acuity in the monocular and dichoptic conditions suggests that in the dichoptic condition the target and bars were not closely adjacent or overlapping, as might occur if binocular alignment were lost.

In the present study, stimuli were presented briefly (142 ms). Perhaps the effects measured here vary with stimulus duration, such that crowding and interocular interaction effects may be different at longer or more brief durations. This possibility is supported by previous work demonstrating that binocular summation depends on stimulus strength, being greater for relatively weak (low contrast, brief duration) stimuli than for stronger (high contrast, longer duration) stimuli.[33] However, Meese and Hess[6] found that the effect of interocular interactions on contrast detection was similar across stimulus durations ranging from 33 to 200 msec. The effect of stimulus duration was not tested in the present study, but taken together these finding suggest that any contribution of binocular summation to our findings may be greater with a low contrast, shorter duration stimulus.[33] However, other types of interactions that reduce interocular inhibition[6] may not vary with stimulus duration. Further work would be needed to investigate this possibility.

Better acuity in the half-binocular compared with the dichoptic condition could be explained by enhancement due to interocular stimulus similarities (the bars were presented to both eyes in half-binocular viewing). One mechanism for this enhancement could be a release[6] of the inhibitory (crowding) effect due to the surrounding bars, when they are presented binocularly. The crowding effect was found in children but not in adults. However, the enhancement in half-binocular viewing was found not only in children but also in adults (in whom crowding was not apparent) suggesting that release of crowding is unlikely to explain this finding. Perhaps the interocular similarity in the half-binocular stimulus elicits a degree of summation, resulting in better acuity in this condition.

As discussed above, monocular and binocular visual resolution was affected by the presence of surrounding bars in a group of 9 children but not in adults. The present finding is in accordance with previous studies indicating that visual functions such as the crowding effect are immature at the initiation of schooling.[21,22] Furthermore, the present study shows that the crowding effect is reduced with age in the monocular condition, approaching adult levels by 14 years of age. In binocular viewing the children show crowding while the adults do not, indicating that the effect does decrease with maturation, but the trend is not significant, perhaps due to the small sample size.

Recent studies in children reported a decrease in the critical separation with age in school-age children[21,23] but disagree on the age at which it reaches adult levels. This disagreement could be partly due to the differences in the methodological approach in measuring crowding. A plausible explanation for the present and previous finding of foveal crowding in children but not in adults could be that the separation between target and bars used does not elicit crowding in adults.[22] Perhaps a smaller separation in adults than in children would allow foveal crowding to become apparent in both groups.

It has been suggested that crowding reflects inappropriate feature integration and/or grouping[20] The ability to integrate visual features across the visual field develops throughout childhood and early adolescence.[34,35] Thus, the present and previous findings of immature crowding in school age children are not surprising.

The age-related reduction of the crowding effect observed in children in the present study is in agreement with recent studies on the development of reading speed. Kwon, Legge and Dubbels[36] measured the developmental changes in the size of the visual span (i.e., the number of letters that can be read at each fixation, without moving the eyes) during school-aged years and found that the size of the visual span increased during these years and was correlated with reading speed. It has also been suggested that there may be an association between the improvement in reading rate and decrease in crowding during school-aged years.[36,37] Our findings are consistent with the aforementioned previous work, suggesting that the crowding effect is immature at the beginning of school age, and that adult level is reached at around 13 years of age.

The present and previous findings suggest that visual sensitivity is better with peripheral stimulation of both eyes than only with peripheral stimulation of the non-tested eye and that this is the case in children and adults. While the present study includes subjects with normal vision, our findings may have implications for the visual stimuli used in some forms of amblyopia therapy. In particular, binocular therapies involving the presentation of foveal stimuli to the amblyopic eye and nonfoveal stimuli to the fellow eye may allow enhanced sensitivity of the amblyopic eye.[38–41] Further work involving amblyopic subjects is needed to investigate whether dichoptic and half-binocular viewing conditions have similar effects in amblyopic children and adults.

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