

Grouping Effects on Foveal Spatial Interactions in Children

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PURPOSE. Grouping of flankers from the target can modulate crowding in adults. Visual acuity in children is measured clinically using charts with targets and different flankers to enhance spatial interactions. We investigated grouping effects on interactions using visual acuity letters, flanked by contours and letters, in children.

METHODS. Visual acuity for isolated and flanked letters was measured in 155 three- to 11-year old children and 32 adults. Flankers were one stroke width from the target and were a box or four bars and black or red letters. Magnitudes of interaction were flanked minus isolated logMAR acuities. Psychometric function slopes were also examined.

RESULTS. Magnitudes of interaction by contours did not change significantly with age. They were 0.047 ± 0.014 logMAR more with bars than a box. Interaction from flanking letters reduced with age, adults being not different from 9- to 11-year-olds for black and red letter surrounds. It was weaker by 0.033 ± 0.013 logMAR when a black letter was surrounded by red rather than black letters. Psychometric function slopes for visual acuity were steepest for the youngest children (3–5 years).

CONCLUSIONS. For contour and letter flankers, grouping effects on interaction magnitude are age independent. Grouping bars into a box forming a single object reduces magnitude of effect. Grouping letter flankers by color and ungrouping them from the target reduce interaction magnitude by ~8%, suggesting that luminance-defined form dominates. Differently colored letter flankers of high-luminance contrast on acuity charts could draw attention to the target but retain significant interaction strength.

Keywords: grouping, crowding, contour interaction, visual acuity, development

Foveal visual acuity measured with a target optotype surrounded by other features may be worse than when the optotype is presented on its own.^{1–4} This detrimental effect on target recognition could be the result of different types of spatial interaction, including contour interaction, the effect of nearby contours possibly encroaching upon inhibitory regions of the target's receptive field^{5–8}; lateral masking, the effect of overlapping or nearby objects similar to the target itself, thought to be processed within the same spatial channel as the target, thereby reducing discriminability^{9,10}; and crowding, the inability to recognize objects in clutter^{11,12} resulting from confusion between target and neighbor and thought to be due to excessive feature integration of target and flanker features at a second stage.^{13,14} Flom⁵ proposed that contour interaction is a component of crowding, together with eye movements and attention. At the fovea in adults, flanker effects on visual acuity for standard clinical optotypes (e.g., Sloan letters) are not thought to be due to crowding^{13,15} as the optotype size is larger than the critical spacing limit over which crowding occurs.¹⁶ Newly designed thin optotypes,¹⁶ or thin Vernier lines with flankers,¹⁷ can reveal crowding effects at the fovea in adults, but they are not currently used in clinics. Factors that affect spatial interactions leading to reduced acuity in children are currently unknown. The magnitude of spatial interactions (i.e., the difference between flanked and isolated acuity)

depends on the separation between target and flanking features,^{1,3,4,18} similarity of flankers to the target,¹⁹ similarity of flankers to each other, and their spatial arrangement (see review by Herzog et al.¹⁴). For example, in adults, the magnitude of interactions is reduced when flankers are different from the target in contrast polarity^{17,20} or when flankers group with each other.^{17,21–24} Grouping of flankers, as well as grouping, or ungrouping, of flankers from the target contributes to the appearance of the entire visual scene, which plays an important part in determining the strength of crowding.¹⁴

Vision charts in which a target is surrounded by flankers are recommended for children's vision screening programs to detect amblyopia,^{25,26} as crowding is exaggerated if strabismus is present.^{27–31} In currently available tests, targets are flanked by a box,^{32–34} bars,³⁵ or other letters,³⁶ but these flanking features can have different effects on visual acuity in adults⁴ and children.³⁷ Compared to effects of simple contours such as a box or bars, other letters placed around a target letter can lead to stronger interactions.^{4,37} Even contours can produce different effects. For example, in adults, placing a box around a target results in a smaller magnitude of interaction compared to bars.⁴ Although the box provides more contours overall than four bars, the fact that it is a single (grouped) object could help to explain this result.

Using Gestalt principles of similarity to group individual elements into patterns is evident in very young infants,^{38,39} but little is known about how grouping principles modulate spatial interaction magnitude in children. Ruttum and Covert⁴⁰ investigated effects of changing the color of flanking bars placed 0.5 and 1 optotype width away from the target on visual acuity in amblyopic children. Acuity measured with black letters surrounded by red and black bars was not significantly different. It is important to know how altering the color of the flankers affects interaction strength in nonamblyopic children and whether this changes with age. Clinically, presenting target and flankers in different colors could be used to draw attention to the target, as is sometimes done by pointing, to improve testability. However, this difference in color could lead to a reduction in spatial interaction strength (so an unwanted effect, particularly if greater in amblyopes). If the effects of grouping change with age, this may need to be taken into account when comparing visual acuity measurements obtained with different charts at different ages.

The aim of this study was to investigate the effects of grouping on the magnitude of spatial interaction (i.e., the difference between flanked and isolated acuity) in children and adults with normal foveal vision. Interactions by flanking contours were measured with a box and four bar flankers. A reduction was expected with a box, being a single object. Magnitudes were also measured with black and red flanking letters. Altering the surround letters to red allows the flankers to group together and also for the flankers and target to ungroup or “pop out,” so magnitude should reduce. Not being able to attend accurately to the target may contribute to greater interactions found for children than adults.^{36,37} If presenting the target and flankers in different colors allows the target to “pop out” and reduces attentional demand, reduction in effect may be greater for children than adults. The results of this study have implications for the design and use of bars, boxes, and color on charts for the measurement of visual acuity in children.

METHODS

Apparatus and Stimuli

The experimental routine was controlled by a custom-written MATLAB program and Psych Toolbox⁴¹ commands run on a MacBook Pro. The stimuli were displayed on the screen, which had a resolution of 2880 × 1800 pixels and a frame rate of 60 Hz. The background luminance was white (335 candela/m²), so target letters and flankers had 94% contrast if black, 75% contrast if red, and 54% contrast if blue (for color defectives).

Target optotypes were letters H, O, T, and V presented either in isolation (i.e., without flankers) or with flankers placed one stroke width away (measured from the edge of the target to the edge of the flanker). This is optimal for generating greatest magnitude of effect, while the target and flanker are resolvable from each other.^{4,27,42} Flanking features were (1) four black letters: A, C, L, and U (as in the Cambridge Crowding Cards³⁶); (2) four black bars; (3) a black box; or (4) four red letters: A, C, L, and U. The order of presentation of the target letter at a particular size was random. The position of the flanking letters surrounding the target was also random. Target optotypes and letter flankers were created by scanning Cambridge Crowding Cards, converting images to black and white matrices, and





Flankers	Example display
Black box	
Four black bars	
Black letters	
Red letters	

FIGURE 1. Examples of test stimuli with flanking features.

scaling those for the desired sizes. Examples of these configurations are shown in Figure 1.

Participants

Child participants were recruited from a primary school in Cambridge, United Kingdom. All children at the school were initially invited to take part in the study, giving a potential pool of participants aged 3 to 11 years. Participant information sheets and consent forms were distributed via the school. Only those children whose parent or legal guardian returned a signed consent form were invited to the testing room in small groups. The children were given a verbal briefing about the tests in an age-appropriate manner, and verbal assent was obtained from each child before testing. The data in this study were collected as part of a larger project on visual development. Data collection for this study took approximately 10 minutes per child; approximately 30 minutes per child was taken for all tests to be conducted in the larger project. Children were free to take breaks whenever they asked and had at least two breaks within the 30-minute session.

Thirty-two participants were also recruited from the staff and student population within the optometry discipline at Anglia Ruskin University to provide normative adult data. All adults were given a Participant Information Sheet and were required to sign a consent form before data collection began. A further 16 adults consented to participate in a contrast control experiment subsequent to the main experiments. The study was approved by the Faculty of Science and Engineering Research and Ethics Panel at Anglia Ruskin University and followed the Declaration of Helsinki.

Results of those children who were unwilling or unable to complete testing ($n = 2$), had a known history of strabismus

TABLE Number of Participants in Each Age Group

Age (y)	Bars vs. Box	Black vs. Red Letters
3–5	14	12
6–8	27	31
9–11	19	20
Adults	16	16
Total	76	79

and amblyopia ($n = 3$), or had a known ocular ($n = 1$) or systemic disorder ($n = 1$) were excluded from analyses. Refractive error was assessed with the SureSight Autorefractor or by performing retinoscopy without cycloplegia. Results from eyes with uncorrected refractive errors outside expected norms were not used. Habitual wearers of spectacles wore them during testing. Ishihara pseudo-isochromatic plates were used to screen for red-green color vision deficiency. The color of flanking letters was changed from red to blue for those children who failed the Ishihara test ($n = 3$). In total, the results of one eye from 155 child participants were used (Table). Adults with a known history of strabismus and amblyopia or a known ocular or systemic disorder were not tested. Tested adults wore habitual spectacle prescriptions, and eyes were screened to have normal visual acuity on the clinical logMAR test and normal color vision using Ishihara pseudo-isochromatic plates.

Procedure

Visual acuity was obtained using a two-down, one-up descending staircase. A catch presentation, with logMAR 0.3 above expected age acuity, was presented every sixth trial to improve motivation for children and to minimize predictability of the staircase for adults. For children aged 5 1/2 to 11 years (school year groups 1–6), the staircase terminated after six reversals, with the last four being used to compute threshold. For younger children (nursery and reception class), the number of reversals was reduced to four to reduce testing time and improve testability, with the last two reversals being averaged to calculate threshold. In separate studies,⁴³ we found that averaging the last two versus the last four reversals from a six-reversal staircase produced visual acuities that were not statistically different (two-tailed t -tests to follow, all $P > 0.80$). For 26 children (aged 4–16 years), means for four vs. two reversals were for isolated letter acuities measured with HOTV letters, -0.221 ± 0.023 and -0.224 ± 0.024 logMAR; for a box flanker, acuities were -0.108 ± 0.023 and -0.102 ± 0.024 logMAR. For 28 children (aged 4–15 years), means for four vs. two reversals were -0.211 ± 0.021 and -0.203 ± 0.025 logMAR for isolated HOTV acuities and 0.024 ± 0.024 and 0.032 ± 0.026 logMAR for letter flankers.

The task was explained to each child, and a matching card with the four target optotypes was provided. Printed cards showing the flanked letter configurations were also used (when needed) to demonstrate the task. Children could give their response by naming the target letter or pointing to it on the matching card. Viewing time was unlimited. The responses were input by the experimenter, after which the display changed to a white screen for 500 ms and a new target then appeared. A testing distance of 4 meters was used for children 5 1/2 to 11 years old. The distance was reduced to 2 meters for the younger children, to allow for larger letters

to be presented on the screen in anticipation of lower visual acuity and to encourage participation.^{36,44}

Participants wore their habitual correction, and testing was monocular with occluding glasses or a cling-on patch covering the unused eye. Initially, monocular visual acuity was measured for each eye, with either a target surrounded by four bars (for those allocated to the contour flanker experiment) or a target surrounded by four black letters (for those allocated to the letter flanker experiment). Each child then completed two further tests in random order, with the eye that had better visual acuity or the preferred eye if visual acuities were the same. For those children in the contour flanker experiment, these were an isolated target and a target flanked by a box (see Table). For those in the letter flanker experiment, these were visual acuity for an isolated target and a target flanked by red letters (see Table). The procedure for the adults followed that described for 5 1/2- to 11-year-old children, except that adults could input responses via a remote keyboard and visual acuity in the preferred eye only was measured.

Analysis

The magnitudes of spatial interactions with contours and letters were calculated as the difference in visual acuity (in logMAR) with flankers from without. To investigate the effects of grouping on contour flankers (box versus bars) and letter flankers (red versus black letters), data were grouped into four age groups (Table).

Slopes of psychometric performance functions sampled during each staircase were also estimated. Data were plotted as target size versus percent correct responses and fit with a Weibull function to estimate the slope parameter

$$P_{\text{correct}}(s) = 1 - (1 - g) \times \exp[-10^{\beta(s-th)}] \quad (1)$$

where g is the guess rate (25%), β is the slope parameter, s is the target size in logMAR, and th is estimated threshold in logMAR. As data were extracted from individual staircase steps and reversal points, more data contributed just above and below threshold (79% correct) than at other performance levels. To ensure acceptable fits in all cases, it was necessary to sometimes hold the threshold parameter or guide the fit by eye. However, the analysis was performed in the same manner for all staircases, without knowledge of the condition being analyzed or the age of the participant. We chose not to average staircase data across individuals before fitting, as this would have resulted in artificially flatter slopes if variability across individuals in that group was higher.⁴⁵

Statistical analyses were carried out using a mixed-design ANOVA, separately for contour flankers and letter flankers, with age group as a between factor. Any cross-experiment comparisons were made using two-tailed independent t -tests.

RESULTS

The magnitudes of spatial interaction for grouped data (as per Table) are shown in Figure 2. Overall, there is no statistically significant effect of age group on magnitude of interaction with contour flankers ($F(3, 72) = 0.774$; $P = 0.512$). Magnitude with bars appears to reduce with age for children from 0.18 ± 0.02 logMAR for 3- to 5-year-olds to 0.13 ± 0.02

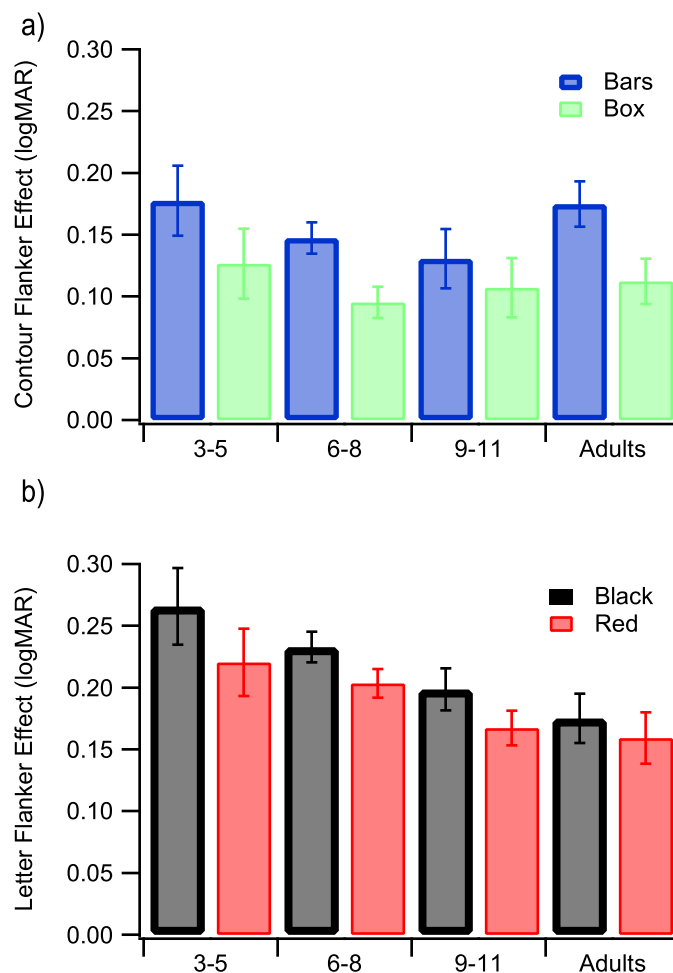


FIGURE 2. Magnitude of interactions with flanking contours (a) and flanking letters (b) for children aged 3 to 5, 6 to 8, and 9 to 11 years and adults. Error bar: ± 1 SEM.

logMAR for 9- to 11-year-olds but increases for adults to 0.17 ± 0.02 logMAR. For a box surround, interaction magnitude is 0.13 ± 0.03 logMAR for 3- to 5-year-olds and 0.11 ± 0.02 logMAR for adults. Interaction magnitude is 0.047 ± 0.014 logMAR greater with bars than a box ($F(1, 72) = 30.379$; $P < 0.001$). This effect is consistent across age groups as indicated by a lack of statistically significant interaction between age group and contour flanker type ($F(3, 72) = 0.973$; $P = 0.410$).

On average across age groups, $69\% \pm 7\%$ of participants obtained stronger interaction effects with bars than a box (by 0.09 ± 0.005 logMAR), $18\% \pm 8\%$ were stronger with a box than bars (by 0.06 ± 0.04 logMAR), and $13\% \pm 4\%$ had identical acuities with both. Visual acuity was worse when a letter was flanked by bars than when isolated in 73 of 76 participants and in 74 of 76 participants when flanked by a box than when isolated.

The magnitudes of spatial interactions with letter flankers are dependent on age group ($F(3, 75) = 3.95$; $P = 0.011$), reducing from 0.27 ± 0.03 logMAR for 3- to 5 year-olds to 0.18 ± 0.02 logMAR for adults with the black letter surround and from 0.22 ± 0.03 logMAR to 0.15 ± 0.02 for the red surround. Magnitude is 0.033 ± 0.01 logMAR greater when black rather than red letters are used as flankers. This difference is significant ($F(1, 75) = 17.87$; $P < 0.001$), and although

it is largest for the 3- to 5-year-old group at 0.045 ± 0.021 logMAR, overall it is independent of age group ($F(3, 75) = 0.25$; $P = 0.86$). Planned comparisons of means across age groups reveal that black and red letter surrounds produce interaction magnitudes significantly different for the 6- to 8-year-old age group compared with adults ($F(1, 75) = 4.44$; $P = 0.039$ for black; $F(1, 75) = 5.61$; $P = 0.0214$ for red), as well as for the 3- to 5-year-old age group compared with adults ($F(1, 75) = 7.99$; $P = 0.0060$ for black; $F(1, 75) = 6.11$; $P = 0.016$ for red).

On average across age groups, $58\% \pm 4\%$ of participants obtained stronger interaction effects with surrounding black than red letters (by 0.08 ± 0.01 logMAR), $15\% \pm 2\%$ were stronger with surrounding red than black letters (by 0.06 ± 0.004 logMAR), and $26\% \pm 4\%$ had identical acuities with both. Visual acuity was worse when a letter was surrounded by black or red letters than when isolated in every participant.

Different groups of participants contributed to experiments with flanking contours and flanking letters, however means across participant groups (3–5 years, 6–8 years, 9–11 years, and adults) were compared. Except for the adult group, magnitudes with flanking black letters were greater than those with flanking black bars or a box ($P < 0.001$ to $P = 0.015$). Magnitudes with flanking red letters were greater

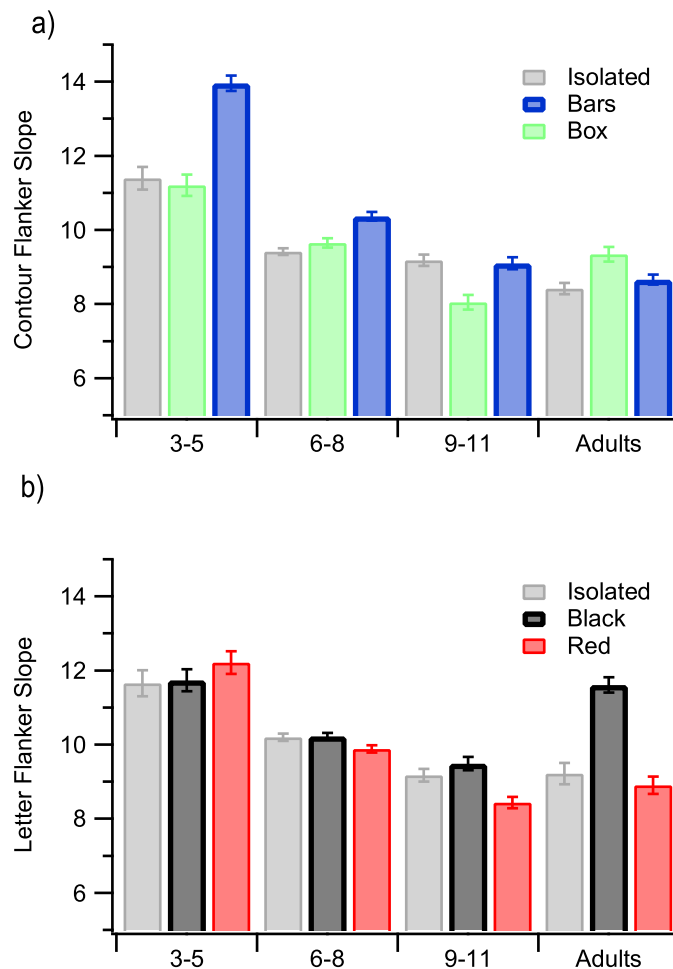


FIGURE 3. Psychometric function slopes for interactions with flanking contours (a) and flanking letters (b) for children aged 3 to 5, 6 to 8, and 9 to 11 years and adults. Error bar: ± 1 SEM.

than those with a black box ($P < 0.001$ to $P = 0.020$). For the adult group, a black letter surround degraded acuity significantly more than a box ($P = 0.026$).

Slope estimates of psychometric functions underlying visual acuity measures for grouped data (as per Table) are shown in Figure 3. Slopes are different across age group for both flanking contour ($F(3, 71) = 9.52$; $P < 0.0001$) and flanking letter ($F(3, 74) = 4.33$; $P = 0.0073$) groups. Slopes are significantly steeper for the 3- to 5-year-olds than for adults ($F(1, 71) = 21.38$; $P < 0.0001$ for flanking contour group; $F(1, 74) = 5.59$; $P = 0.021$ for flanking letter group). If younger (3–5 years and 6–8 years) and older (9–11 years and adults) groups are analyzed separately, contour flanker condition matters in the younger group ($F(2, 76) = 4.098$; $P = 0.020$). Bars produce steeper slopes than the box and isolated acuity conditions ($P < 0.001$ to $P < 0.03$) according to Fisher's least significant difference (LSD) test. The effect of flanking letters nears significance ($F(2, 68) = 2.704$; $P = 0.074$) in the older group. Black letters produce steeper slopes than red letters according to Fisher's LSD test ($P = 0.033$). For adults, slopes for black letter surrounds are steeper than those for bars ($P = 0.0056$) or for a box ($P = 0.050$). For the 3- to 5-year-old group, slopes for bars are not different from those for black ($P = 0.090$) or red letters ($P = 0.18$).

DISCUSSION

The aim of this study was to compare the effects of grouping on spatial interactions for flanking contours and letters on letter acuity in 3- to 11-year-old children and adults. The results show that grouping effects are largely independent of age, even though age affects magnitudes of interaction using flanking contours and letters on single-letter targets differently.

Development of Interactions With Flanking Contours and Letters for Single Target Letters

In the current study, the magnitude of interaction when bars or a box are placed one stroke width away from the target does not change significantly with development. For bars, the magnitude is 0.16 ± 0.02 logMAR, and for a box, it is 0.11 ± 0.01 logMAR. This lack of reduction in magnitude with development is consistent with data from previous studies that have measured effects of bars on single Landolt C versus O acuity in children aged 2 to 7 years and adults,⁴⁶ as well as the effects of a box placed around single picture, symbol, and HOTV letter targets in children aged 3 to 16 years and adults.⁴ For bars placed 2.5 stroke widths from the target, Fern et al.⁴⁶ found average contour interaction magnitude of

0.08 ± 0.01 logMAR (0.09 ± 0.01 logMAR for 2-year-olds to 0.08 ± 0.03 logMAR for 7-year-olds). For a box placed one stroke width from HOTV letters, Lalor et al.⁴³ found a magnitude of 0.11 ± 0.02 logMAR for 3- to 4-year-olds to 0.13 ± 0.03 logMAR for 12- to 16-year-olds. Data from Norgett and Siderov,³⁷ who used single Sloan letters with bars, showed a small (0.04 logMAR) decrease in the magnitude of contour interaction from ages 4 to 6 years to adulthood, consistent for separations of 1.25, 2.5, and 5 stroke widths (0.25, 0.5, and 1 optotype widths). This small change across age might in part be due to the choice of 10 letters being more challenging for the youngest children. The overall lack of change in interaction with contour flankers with development suggests that unlike the effects with flanking letters, this spacing limit is tied to acuity receptive field size changes. Similar explanations have been proposed to account for the effects of blur and anisotropic amblyopia on spatial interactions in adult foveal spatial vision.^{1,27,42,47}

The magnitude of effect with black and red letter surrounds placed one stroke width away from the target letter significantly reduces with age from 3 years to adult. With similar stimuli and procedures, Lalor et al.⁴³ also found a significant reduction from age 3 years to adult (0.40 ± 0.10 to 0.19 ± 0.01 logMAR), with two participants having only just turned 3. Atkinson et al.³⁶ measured the magnitude of interactions with flanking letters on groups of children (3–4 years and 5–7 years) and adults using Cambridge Crowding Cards, from which stimuli in the current study were derived. The position of surrounding letters was 2.5 stroke widths (0.5 optotype widths) from the target (HTOVX) letters. As expected for this greater separation,^{4,42} the magnitude of effect was lower (0.21 ± 0.03 logMAR for 3- to 4-year-old group) than found in the current study, and for the 5- to 7-year-olds (0.10 ± 0.03 logMAR), it was not statistically different from adults (0.07 ± 0.03 logMAR). In line with this, Norgett and Siderov,³⁷ who also used a 2.5 stroke width separation, found magnitudes of 0.17, 0.09, and 0.07 logMAR for 4- to 6-year-olds, 7- to 9-year-olds, and adults, respectively. The significantly heightened interaction magnitude for young children (less than 9 years of age) over that found for adults when using flanking letters³⁶ instead of flanking contours^{37,43} may reflect changes in a neural crowding component or another factor not dependent on acuity receptive field size. To test this more cleanly, targets specific for measuring crowding at the fovea could be used.^{16,48}

Grouping and Interactions by Flanking Contours

For children, like for adults,⁴ contour interaction for a target-flanker separation of one stroke width is weaker with a box than bars. The difference is 0.047 ± 0.014 logMAR or approximately two letters on an acuity chart. Although clinically this difference is small, the use of bars rather than a box should be considered if spatial interactions are to be maximized. The box is a separate object, and this may aid in separating it from the target, reducing the detrimental effects of contour interaction over when four flanking bars are used. A similar result was obtained with Vernier acuity when changing flanking features to be perceived as a reduced number of repeated objects resulted in reduced crowding.^{14,23,24} For the stimulus configurations used in this study, similar principles guide the ungrouping of the target from the flankers in children as young as 3 years old. For the youngest group, it is also possible that intrinsic observer

uncertainty, as revealed by steeper performance slope with bars, may have contributed to their increased magnitude.

Grouping and Interactions by Flanking Letters

The use of red rather than black letter flankers to surround the black target did not eliminate spatial interaction but reduced its magnitude by 0.033 ± 0.013 logMAR (one to two letters out of an overall crowding effect of two to three lines on an acuity chart). This reduction may be attributed to the grouping of flankers by color, the ungrouping of flankers from the target caused by a difference in color, or a loss in target-flanker similarity.¹⁹ All may contribute to engagement of attention for identifying the target letter. However, the reduction is relatively small (approximately 8%), suggesting that form definition of the flankers based on luminance information, and independent of color, was still strong enough to uphold most of this spatial interaction effect.

Colors were chosen from a standard computer palette, similar to those used in a clinic with commercially available vision tests. Therefore, our flankers when black or red (or blue) were not isoluminant, providing contrasts of 94% and 75% (54% for blue). The change in contrast of flankers could potentially explain our results with lower contrasts reducing interaction magnitude. We think this is unlikely as subjectively, color differences provided stronger grouping cues than contrast differences. Grouping by contrast effects on crowding for suprathreshold discrimination tasks, so that flankers of different contrast (rather than color) to the target might group and ungroup from the target to reduce crowding or contour interaction, has not been demonstrated in the periphery^{19,49} or at the fovea.⁵⁰ We have subsequently measured acuities with different black letter flanker contrasts in the preferred eyes of a group of normal adults ($n = 16$). Surrounding letters of 100% and 75% contrast (like the black and red letter flankers in the experiments) provided magnitudes of 0.19 ± 0.02 and 0.16 ± 0.02 logMAR, similar to results in our experimental adult group for black (0.18 ± 0.02 logMAR) and red (0.15 ± 0.02 logMAR) letter surrounds. However, for the three children (9.1 ± 2.3 years) who had black and blue letter surrounds, interaction magnitudes were minimally changed at 0.21 ± 0.06 (blue) and 0.20 ± 0.06 (black) logMAR. Pelli et al.¹³ have also demonstrated that although target-flanker contrast matters, to change crowding magnitude in the periphery, flanker contrast needs to be much lower. For 25% flanking letters, we found no significant magnitude of effect at the fovea (0.008 ± 0.02 logMAR).

The small reduction in the strength of effect as a result of grouping by color found in this study is in line with results of other studies examining parafoveal and peripheral vision in adults. Bouma⁵¹ reported in parafoveal vision (1 and 3 degrees) that when a black letter was flanked by two red letters, participants scored at a slightly higher performance level than for an all-black configuration. When a red letter was flanked by two black letters, percent correct letter identification due to spatial interactions reduced by $61\% \pm 7\%$; when a black letter was flanked by black letters, it reduced by $53\% \pm 5\%$. The small differences found in this study were interpreted as being indicative of the importance of contrast for form recognition and that form and color are dealt with separately by the visual system.⁵¹ Poder⁵² reported a small reduction (by approximately 8%) in crowding when the color of the flankers was different from that of the target

letter (red versus black) at an eccentricity of 3.3 degrees. Kooi et al.'s¹⁹ data, obtained at 10-degree eccentricity with red-green configurations of target and flankers, showed a small reduction in the strength of crowding in four of six observers compared to when all stimuli were of the same color. Rosen and Pelli⁵³ used black and white Sloan letters 1 degree in size (1.08 logMAR) in the same arrangement as the current study at 10 degrees in the lower visual field. Critical spacing for crowding for target letters reduced from 3.01 ± 0.27 degrees with same-polarity flanking letters to 1.99 ± 0.25 degrees with opposite-polarity flanking letters. Adding surround letters of same polarity, outwardly in the four directions, to an opposite-polarity target letter still reduced crowding. However, adding additional letters that alternated in polarity, thereby grouping target with flankers to form a pattern, returned stronger crowding. Ruttum and Covert⁴⁰ showed 0.01 to 0.02 logMAR increased contour interaction in amblyopic children (5- to 17-year-olds) for red compared with black bars about black letters, and this difference was not significant. Differences found between this clinical acuity study and the current study could be due to different flanker types (colored bars versus letters), the smaller target-flanker separation used in the current study (1 vs. 2.5 stroke widths or 0.2 vs. 0.5 optotype widths⁴⁰), psychophysical paradigms (computerized staircase versus clinical protocol⁴), and different participant groups (normal versus likely presence of strabismic amblyopia with associated stronger crowding effects⁴⁰). The small change in visual acuity caused by changing the color of the flankers in the current study is well within the repeatability of visual acuity measures in children.^{35,54} The use of high-contrast red flankers to surround a black target could therefore be useful clinically to highlight the target letter and direct attention, without eliminating the spatial interactions. The outcomes from the current study on normal children are based on statistical analyses of means, although not one child in our study had better flanked acuity (with red or black letter surrounds) than their isolated letter acuity. Still, the clinician should remain mindful when working with idiosyncratic cases for whom mean patterns, such as revealed here, may not be followed.

Performance Slopes

In clinical studies on adults, the slope of the psychometric function underlying visual acuity assessment has been proposed to reflect measure reliability, a steeper slope being associated with smaller confidence intervals, more accurate letter-by-letter logMAR visual acuity,⁵⁵ and better test-retest consistency.⁴⁵ Smaller confidence intervals about a threshold estimate also mean greater sensitivity to real change,^{4,45} perhaps due to development, disease, or treatment. Modifying acuity charts to steepen the underlying psychometric performance function is therefore desirable. In adults, flanked acuity measures produce steeper psychometric function slopes than do isolated acuity measures.^{4,56} Lalor et al.⁴ found that psychometric function slopes underlying visual acuity measures for letters surrounded by letters (for a two-stroke-width separation) were statistically steeper than for isolated letters and for single letters, symbols, or pictures surrounded by a box. Reich and Hoyt⁵⁶ found steeper slopes for Tumbling Es with flanking bars than without. Shallower psychometric function slopes might occur with disease and have been reported for blurred versus unblurred letter acuity⁵⁷ and low-contrast versus high-contrast letter acuity⁴⁵ in normal adults. In amblyopia, Vernier acuity (a

relative position discrimination task) is degraded more than in normal adults because psychometric function slopes are also shallower.⁵⁸

Steeper psychometric function slopes can also reflect high levels of intrinsic observer uncertainty (as well as stimulus uncertainty) in contrast detection and discrimination tasks, with steeper slopes indicating greater uncertainty.^{59–63} We suggest that when intrinsic uncertainty is high, small increases in visibility (or size in this acuity task) when compared to a blank screen could lead to larger improvements in performance and steeper psychometric function slopes than if the same increases were introduced when it is low. The stimuli used in the current study were known and constant across age. However, despite clear instructions, provision of matching cards, and a friendly environment, observer intrinsic uncertainty, especially in the youngest participants, could have existed about knowledge of where the target letter (signal) would appear and the possible alternatives, or participants might have been unable to apply that knowledge to the task.⁵⁹ To gain insight into the possible role of observer uncertainty in grouping for contour and letter flankers, slope estimates were extracted from staircase data and analyzed.

Steeper slopes are obtained for the youngest children (3–5 years), which we speculate may indicate higher levels of intrinsic uncertainty in that age group rather than improved reliability usually attributed to steeper slopes. This result is different from that obtained by Jeon et al.,⁶⁴ where slopes obtained for data were averaged across participants in a group and found to be shallower for the youngest children (5 years old). It is possible that a shallower slope may have resulted from averaging across a wider range of acuities⁴⁵ in the youngest group or may have been due to different methods used for extracting slopes or the different acuity tasks. Although grouping effects for contour and letter flankers are the same across age, slope data indicate that different levels of uncertainty may have contributed to results for different surrounds in young children and adults. For the youngest group (3–5 years), bars produced the steepest slopes. For this group, letters may be less familiar targets, with a greater number of bars in the surround increasing target uncertainty. Learning about letter construction from bars at this age may also lead to greater object categorization uncertainty, which might contribute to crowding magnitude.⁶⁵ In the adult group, steeper slopes were obtained for a surround of black letters than red letters, which through “pop-out” might have reduced target uncertainty. For adults, slopes were steeper for black letters than for bars or a box, in general agreement with Lalor et al.,⁴ suggesting that letters may add more complexity to the judgment than do bars or a box.

Other Factors Contributing to Spatial Interaction Effects

Attentional factors can affect crowding,^{5,66–69} and changes with age in children's ability to attend to a target may reduce the magnitude of spatial interactions, including crowding.^{36,37,70} The expectation was that young children would benefit more from “pop-out” induced by color and a greater reduction in spatial interactions than adults, but there was no statistically significant effect. Performance in a visual search task improves with age, but simple feature search⁷¹ and visual pop-out develop rapidly.⁷² Our acuity task had unlimited viewing time, so the reduction of visual

interactions with age is not likely due to improved visual search or pop-out effects. Other factors therefore contribute differently in children and adults to the specific neural components of crowding.

Eye movement control is less precise in young children (4–5 years) than in adults,⁷³ and the stability of fixation improves until adolescence (see review by Luna et al.⁷⁴). Eye movements were not measured in this study, but in a previous study of 90 normal children aged 4 to 11 years, the difference in visual acuities measured for a full letter chart and a repeat letter chart (which helps to reduce eye movement contributions) was consistent across age,⁷⁵ so gaze control is not likely to contribute to the increased interactions with flanking letters in normal children. Although it is still possible that eye movement control could contribute to greater crowding effects in normal healthy young children, especially when a line or a chart of letters needs to be read, for our simple target arrangement and task, we think it unlikely that eye movements limited spatial interaction magnitudes for flanking contours or letters.

CONCLUSION

Grouping modulates the magnitude of spatial interactions in a visual acuity task based on clinical measures to the same degree in children and adults. Flanking letter interactions are not eliminated when the color of flankers is changed from black to red, suggesting only a partial role of attention. Color with good luminance contrast, like pointing, could be used in clinical settings to ungroup and draw attention to the target letter from neighboring letters when measuring children's visual acuity, although, as with all clinical testing, caution should be taken when testing idiosyncratic individuals.

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