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Author/s:
Nguyen, BN;Ramakrishnan, B;Narayanan, A;Hussaindeen, JR;McKendrick, AM

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# Perceptual Center-Surround Contrast Suppression in Adolescence

Bao N. Nguyen,[1] Bhavatharini Ramakrishnan,[2] Anuradha Narayanan,[2] Jameel R. Hussaindeen,[2] and Allison M. McKendrick[1,3,4]

[1]Department of Optometry and Vision Sciences, The University of Melbourne, Parkville, Victoria, Australia
[2]Elite School of Optometry, Medical Research Foundation, Chennai, India
[3]Division of Optometry, School of Allied Health, The University of Western Australia, Perth, Western Australia, Australia
[4]Lions Eye Institute, Perth, Western Australia, Australia

Correspondence: Bao N. Nguyen, C/O Department of Optometry and Vision Sciences, The University of Melbourne, Victoria 3010, Australia; bnguyen@unimelb.edu.au.

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**Purpose.** Center-surround contrast suppression—typically induced when a center pattern is surrounded by another pattern with similar spatial features—is considered a perceptual analogue of center-surround neurophysiology in the visual system. Surround suppression strength is altered in a range of brain conditions affecting young people (e.g., schizophrenia, depression, migraine) and is modulated by various neurotransmitters. The early teen years are associated with neurotransmitter changes in the human visual cortex, which could impact on excitation–inhibition balance and center-surround antagonistic effects. Hence, we predict that early adolescence is associated with perceptual changes in center-surround suppression.

**Methods.** In this cross-sectional study, we tested 196 students at every age from 10 to 17 years and 30 adults (aged 21–34 years) to capture the preteen, adolescent, and adult periods. Contrast discrimination thresholds were measured for a central, circular, vertical sinusoidal grating pattern (0.67° radius, 2 cyc/deg spatial frequency, 2 deg/s drift rate) with and without the surround (4° radius, otherwise same spatial properties as the center). Individual suppression strength was determined by comparing the perceived contrast of the target with and without the surround.

**Results.** After excluding unreliable data (7% of total), we found an effect of age on perceptual center-surround contrast suppression strength, $F(8,201) = 2.30$, $P = 0.02$, with weaker suppression in the youngest adolescents relative to adults (Bonferroni pairwise comparisons between adults vs 12-year-olds $P = 0.01$; adults vs 13-year-olds $P = 0.002$).

**Conclusions.** Our data demonstrate different center-surround interactions in the visual system—a key building block for visual perception—in early adolescence relative to adulthood.

Keywords: surround suppression, visual perception, visual cortex, development, psychophysics

The developmental trajectories of fundamental visual functions are generally well-understood. Characteristic features of visual cortical neurons such as orientation, spatial frequency, and direction selectivity are established during infancy, as inferred from clinical visual electrophysiology and behavioral studies.[1] Visual acuity improves gradually during childhood[2] (most studies report adult-like acuity by approximately 6–7 years of age[3–6]), whereas contrast sensitivity development is more protracted, continuing into late childhood[6–9] and adolescence.[10,11] However, most standard clinical tests of vision use uniform backgrounds that do not reflect the conditions that commonly occur in natural visual experience. In natural vision, objects are often present in nonuniform or cluttered backgrounds, giving rise to contextual effects. Contextual effects occur because of center-surround receptive field antagonism, where extraclassical receptive field stimulation modulates a neuron's response—a ubiquitous property of the primary visual cortex (V1),[12–15] but also present at precortical[16] and extrastriate levels of the visual system.[17] Center-surround antagonism is a fundamental building block of vision and critical for the processing and efficient coding of natural visual stimuli,[18,19] by reducing highly redundant information and serving an important functional role in daily visual tasks like object boundary identification,[20] figure–ground segmentation,[21] and collinear contour integration.[22]

A well-studied visual contextual effect is center-surround suppression of contrast, where the perceived contrast of a target is typically decreased (suppressed) by a surrounding pattern, provided the surround has similar spatial properties to the target stimulus.[23] The psychophysical properties of center-surround suppression, such as the stimulus parameters to elicit robust suppressive effects, are well-established and have a sound basis in convergent neurophysiological work.[24,25] Animal studies have discovered the neural circuitry responsible for center-surround suppres-

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sion, including intra-V1 horizontal connections, feedforward contributions from the lateral geniculate nucleus, and feedback from extrastriate areas V2,[26] V3,[19] and V5/MT.[19] Human studies point to a range of brain neurotransmitters—not solely inhibitory[27–32]—that regulate the fundamental neural computations of gain control and divisive normalization and are likely to underpin center-surround antagonistic effects

There are multiple sites and mechanisms by which brain disorder can result in perceptual changes to center-surround suppression and, as such, growing interest in measuring perceptual center-surround effects in conditions affecting young people like migraine,[33] schizophrenia,[34–38] bipolar disorder,[34] and autism spectrum disorder.[39,40] However, these studies have exclusively tested adults, despite global estimates that 1 in 7 (14%) adolescents experience mental health conditions[41] and almost 10% of adolescents suffer from migraine.[42,43] Adolescence, the transitional stage of life between childhood and adulthood, is a critical period for brain development, marked by changes in neurobehavioral function and neural circuitry.[44,45] Most studies of adolescent brain development focus on the association and prefrontal cortices as the "higher" brain areas involved in more complex cognitive and affective functions.[45–47] However, post mortem analysis of human visual cortex indicates that the early teen years are associated with rapid changes in neurotransmitter systems (e.g., the excitatory neurotransmitter glutamate and inhibitory neurotransmitter gamma aminobutyric acid [GABA])[48,49] that could plausibly impact on excitation–inhibition balance.

Developmental studies of vision typically compare pediatric age groups against adult performance, assuming a monotonic improvement with age. Not all studies systematically test vision during childhood, adolescence, and adulthood to determine the point at which visual function becomes adult-like,[2] and some studies omit testing adolescents altogether.[6,7,9,50–52] Here we measured center-surround contrast suppression in preteens, younger and older adolescents, and adults. We predicted that the strength of perceptual center-surround suppression might differ in early adolescence—when there are cortical neurotransmitter changes that could influence center-surround antagonism in visual cortex[48,49]—relative to adulthood. The results of this study may be used to inform future research aimed at better understanding the brain mechanism(s) underlying atypical visual performance in young neurotypical and clinical populations.

## Methods

### Participants

Students aged 10 to 17 years were recruited from a school eye screening program in Chennai, India.[53] Adult students (aged 21–34 years) were recruited from the Elite School of Optometry, India, and The University of Melbourne, Australia. All participants met the inclusion criteria of 6/9.5 or better unaided monocular visual acuity. The study adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board Ethics Committee of the Vision Research Foundation, India (ID #618-2017-P), and the Human Research Ethics Committee of The University of Melbourne, Australia (ID #1441571). Informed consent was obtained from all adults and parents, and children gave verbal assent.

A power analysis was conducted in G*Power[54] based on previous work investigating ageing effects on perceptual center-surround suppression (minimum effect size: Cohen's $d = 0.72$.[55]) Comparing across nine age groups with a conservative estimate of half the effect size (i.e., Cohen's $d = 0.36$), a total sample of 162 participants (i.e., $N = 18$ in each group) provided a power of 0.90 ($\alpha = 0.05$) for detecting a main effect of age. We therefore aimed to consecutively recruit 20 participants in each age group, with an additional 10%–20% sample to account for data attrition.

### Apparatus

For portable testing, we used the open-source application Psypad[56] (https://www.psypad.net.au/wiki/Main_Page) on an iPad 3 tablet (Apple Inc., Cupertino, CA, USA; 60 Hz frame rate, 2048 × 1536 pixel resolution) with a mean luminance of 173 cd/m$^2$ (gray background) under controlled device brightness conditions (i.e., autobrightness feature turned off and brightness set to maximum). Psypad runs custom thresholding procedures using a preloaded image library and saves date/timestamped test results on the local device and on the server. Gamma-corrected images were created in Matlab R2016b (Mathworks, Natick, MA, USA). Example tasks used in this study can be viewed in Psypad demo mode ("KIDS DEMO Drifting contrast matching task for children" and "KIDS DEMO Drifting surround suppression test for children").

### Experimental Procedure

Participants completed two tasks: a no surround and surround condition. For each task, two runs were completed. The first task was always the no surround condition (Fig. 1A), to estimate the matching contrast of the target stimulus without the influence of a surround. We also used the task to confirm that participants could reliably perform contrast judgments and check for systematic bias in button pressing (two alternative forced choice). The visual stimuli were two drifting vertically oriented sinusoidal gratings (0.67° radius, 2 cyc/deg spatial frequency, 2 deg/s drift rate), presented adjacent to one another for 500 ms duration. The application chose 1 of 10 pregenerated image variants to present each time to randomize drift direction and phase between trials. The left reference stimulus was fixed at 40% Michelson contrast, and the right stimulus contrast varied according to two interleaved one-down one-up staircases starting at 60% contrast and terminating after four reversals (step sizes: 8%, 4%, 2%, and 2% contrast). The starting contrast was chosen to be at a suprathreshold contrast level (sufficiently above the veridical contrast of 40%; i.e., the expected approximate contrast match) to ensure that participants could demonstrate the correct contrast discrimination judgment from the beginning of each test run. The final two reversals of each staircase were averaged to determine the matching contrast.

For the second surround task (Fig. 1B), procedures were identical to the no surround condition except that the left reference stimulus was a center-surround pattern (0.67° center radius, 4° surround radius, 40% center contrast, 95% surround contrast, gratings aligned in phase). For a 40% contrast center and 95% contrast surround pattern, the perceived contrast of the center was expected to be lower than the veridical contrast (40%) if there is perceptual suppression. In that case, at a starting contrast of 40%, the two stimuli will look different and so the first decision would be easy for most participants. We did not choose to start at 60% contrast like the no surround condition to accommodate participants who have a strong surround suppressive effect (i.e., perceived contrast closer to 0%). The final

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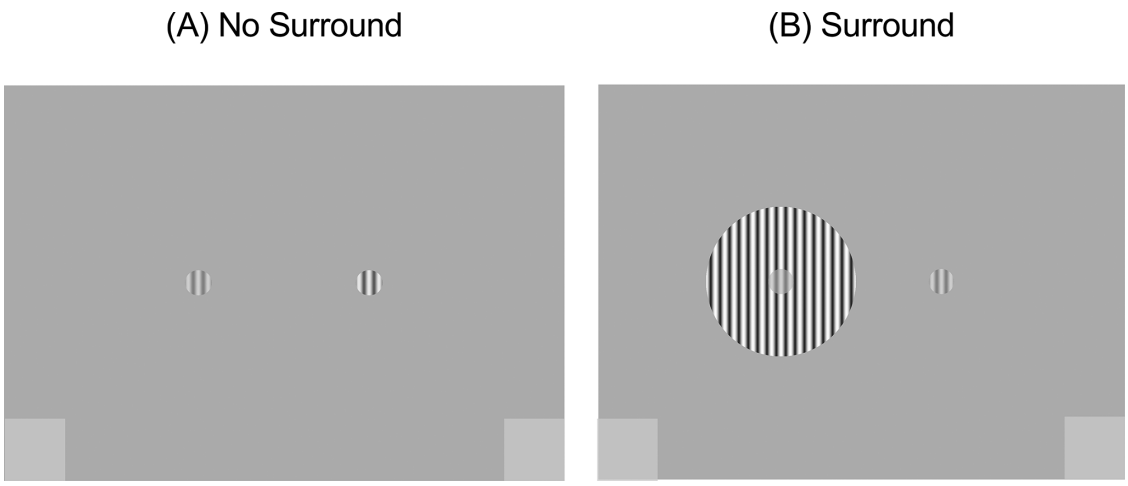



FIGURE 1. Example test stimulus presentation for the (**A**) no surround and (**B**) surround conditions. The stimulus on the left was the reference stimulus of fixed contrast (40% center, 95% surround). The stimulus on the right varied in contrast according to the staircase thresholding algorithm. Participants indicated their choice ("which center is higher in contrast?") by pressing one of the two touchscreen buttons (light gray squares) that appeared in the two bottom corners of the iPad.

two reversals of each staircase were averaged to estimate the perceived contrast of the center when surrounded. A decrease in perceived contrast for the surround condition, relative to the no surround condition, indicates suppression. Suppression indices were calculated according to Equation 1[24,57] where an index of 1 indicates maximal suppression and an index of 0 indicates no suppression.

$$1 - \frac{Perceived\ contrast\ with\ surround}{Perceived\ contrast\ with\ no\ surround} \quad (1)$$

Testing took place in a quiet room within each school or university, away from distractions (e.g., no other participants or adults other than the experimenter present in the room). The experimenters (B.R., B.N.N.) ensured there was no glare on the screen and participants viewed the stimuli binocularly in a comfortable, seated position. Instructions were consistent for all participants, only modified for the local language where necessary to ensure comprehension. For training purposes, images of zebras were shown to demonstrate differences in contrast. The task was presented as a game where participants chose the moving zebra with higher contrast, while looking through a little circular window. Initially, to familiarize the participant with the forced choice task, the participant was only asked to view the stimuli and respond verbally. Once the experimenter was satisfied that the participant understood the task, a practice trial was conducted to familiarize participants with button pressing. There was unlimited time for button pressing, and the next trial did not begin until 500 ms after a button response was registered. Participants were closely monitored to maintain the viewing distance (40 cm), and no substantive head movements or obvious lapses in concentration (eye closure) were observed. Participants generally required no more than 10 minutes to complete both tasks, including training, practice runs, and rest breaks between runs. Tests were not repeated unless there was an initial procedural error (e.g., the participant reported pressing the wrong button to begin with, and asked to start again).

### Statistical Analyses

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 27.0 (IBM Corp., Armonk, NY). Data were tested for normality and homogeneity of variances using a Kolmogorov–Smirnov test and Levene's statistic, respectively. For our main comparison of perceived contrast with and without the surround across age groups, we used a repeated measures ANOVA with age as the between-group factor and surround condition as the within-group factor. To compare across age groups for single within-group factor analyses, a one-way ANOVA was conducted for normally distributed data or a Kruskal–Wallis nonparametric test when the assumption of normality was violated. Post hoc two-sided Bonferroni tests were conducted for pairwise comparisons, with adjusted significance ($P$) values for multiple comparisons. A $P$ value of 0.05 was the criterion for statistical significance. Bland–Altman analyses were conducted to show test–retest variability between the two runs of each test condition.

## RESULTS

### Quality Control

All staircase data were checked for unreliable performance after each test session was completed and data uploaded to the server. For the no surround task (Fig. 1A), given a starting contrast of 60%, we discarded staircases where participants made an initial error that prolonged the staircase and/or sent the staircase on a divergent trajectory. For the surround task (Fig. 1B), because suppression is typically expected but facilitation is also possible, we could not be certain of an initial error in contrast discrimination judgment. As such, we only excluded staircases that did not converge with four reversals or were indicative of exclusively left or exclusively right button presses. Participants were excluded if both completed staircases for either the no surround or surround condition met the exclusion criteria. In total, 7% of data were discarded, leaving a total analysed sample size of 210 (Table).

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**Table.** Number of Participants Recruited, Excluded, and Resultant Sample Size Analysed for Each Age Group and in Total

| Age Group | Recruited (*N*) | Excluded (*N*) | Final Sample Size (*N*) |
|---|---|---|---|
| 10 years | 23 | 2 | 21 |
| 11 years | 24 | 2 | 22 |
| 12 years | 23 | 1 | 22 |
| 13 years | 27 | 0 | 27 |
| 14 years | 29 | 2 | 27 |
| 15 years | 25 | 3 | 22 |
| 16 years | 23 | 3 | 20 |
| 17 years | 22 | 2 | 20 |
| Adults | 30 | 1 | 29 |
| Total | 226 | 16 | 210 |

### Center-surround Contrast Suppression Task

Figure 2 shows the perceived contrast in the presence and absence of the surround. For the no surround condition, all age groups approximately matched to the veridical contrast (40%, *horizontal dotted line* in Fig. 2A), demonstrating that participants could consistently and reliably perform the contrast matching task across all age groups, one-way ANOVA main effect of age: $F(8,201) = 0.92$, $P = 0.50$, implying that participants understood and performed the contrast discrimination task as instructed.

To consider the effect of the surround, we conducted a repeated measures ANOVA with age as the between-group factor and surround condition as the within-group factor. As expected, the perceived contrast was generally lower in the presence of the surround, compared with without the surround (Fig. 2B), main effect of surround: $F(1,201) = 424.9$, $P < 0.001$, partial $\eta^2 = 0.68$. There was also a significant interaction between age and surround condition, $F(8,201) = 2.33$, $P = 0.02$, partial $\eta^2 = 0.09$, indicating that the magnitude of the suppressive surround effect was age-dependent. Supplementary Fig. S1 shows that these overall statistical results still hold when all collected data was analysed (i.e., without any exclusions).

To determine which age groups were different from each other in terms of the suppressive effect, we analysed the suppression indices (Fig. 2C; normalized value taking into account the no surround and surround perceived contrast for each individual) with a one-way ANOVA and post hoc Bonferroni pairwise comparisons between all age groups. This analysis revealed weaker suppression in the younger adolescents relative to adults (adults vs 12-year olds $P = 0.047$; adults vs 13-year-olds $P = 0.008$). All other pairwise comparisons relative to adult performance were not significant, and neither were there differences in surround suppression between the nonadult age groups ($P > 0.05$). Effect sizes (Cohen's *d*) were determined according to Equation 2:

$$d = (\mu_{adult} - \mu_{adolescent}) / \sigma_{pooled} \quad (2)$$

where

$$\sigma_{pooled} = \sqrt{\left(\frac{\sigma_{adult} + \sigma_{adolescent}}{2}\right)}$$

to compare the average magnitude of suppression strength (mean = μ) between adult and adolescent groups, taking into account measurement variability (standard

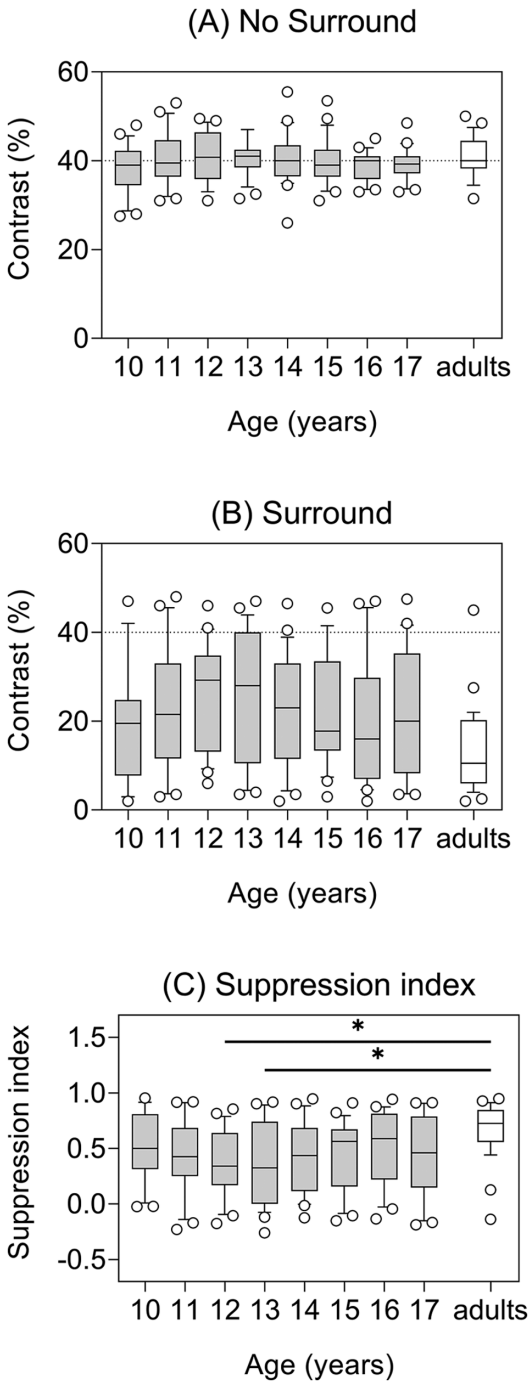



**Figure 2.** Results of the visual perceptual task. (**A**) Contrast matching thresholds as a function of age, relative to the 40% contrast no surround reference stimulus. (**B**) Contrast matching thresholds as a function of age, relative to the 40% contrast center 95% contrast surround stimulus. Perceptual surround suppression is demonstrated by a reduction in perceived contrast in the presence of the surround. (**C**) Suppression index (calculated from Equation 1) as a function of age. A higher suppression index means stronger suppression. In all panels, boxplots show the median and 25th and 75th percentiles, whiskers are the 10th and 90th percentiles, and symbols indicate the outliers for each group. The horizontal dotted line in (**A**) and (**B**) depicts the veridical contrast of the center pattern (40%). Asterisks indicate statistical significance ($P < 0.05$) of post hoc Bonferroni multiple pairwise comparisons of suppression index between each age group relative to adult performance.



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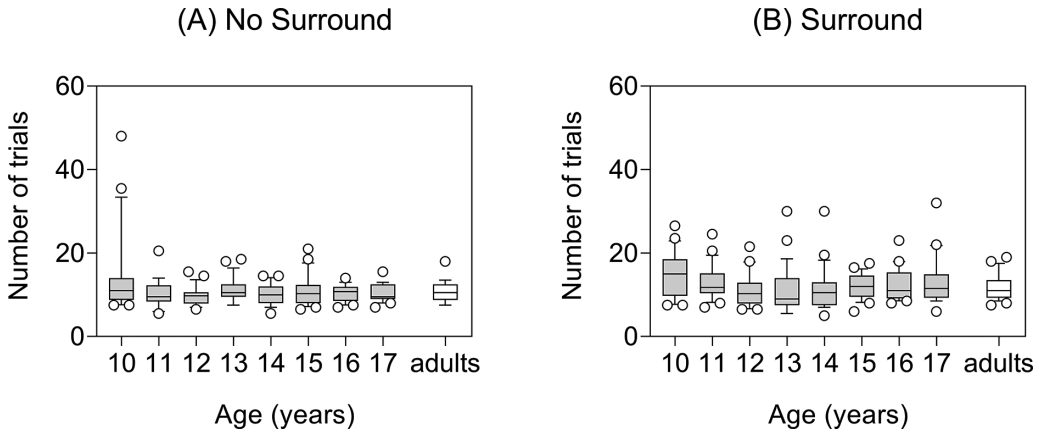



**Figure 3.** Number of staircase trials required to converge as a function of age for the (**A**) no surround and (**B**) surround conditions. Boxplots show the median and 25th and 75th percentiles, whiskers are the 10th and 90th percentiles, and symbols indicate the outliers for each group.

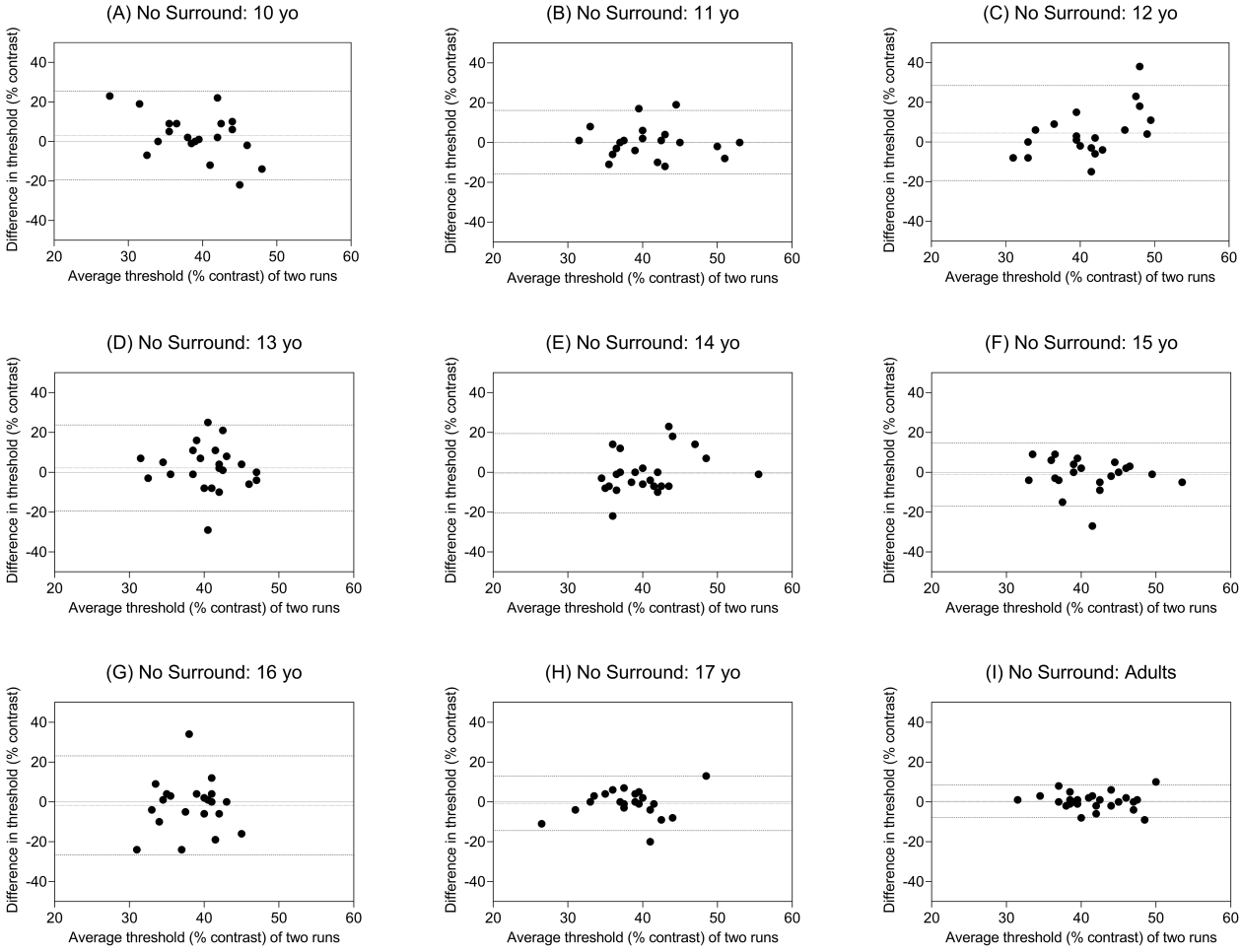



**Figure 4.** Bland–Altman plots of test–retest variability, showing the difference in contrast matching threshold (%) between two runs of the no surround condition as a function of average contrast matching threshold (%) of two runs. The bias (average difference) is indicated by the horizontal dotted line. The 95% limits of agreement are shown by the two horizontal dashed lines.

deviation = $\sigma$). The effect sizes observed in 12-year-olds and 13-year-olds were large and similar ($d = 1.07$ and $d = 1.05$, respectively).

These results could possibly arise from differences in task performance and reliability of responses rather than pure perceptual differences, hence we explored the staircase characteristics of the analysed data as a function of age. Staircase length varied between subjects as the termination criteria was based on reversals, but the number of staircase trials required for convergence was consistent across the different age groups for the no surround task (Fig. 3A), Kruskal–Wallis test: H(8) = 7.79, $P = 0.45$, and surround

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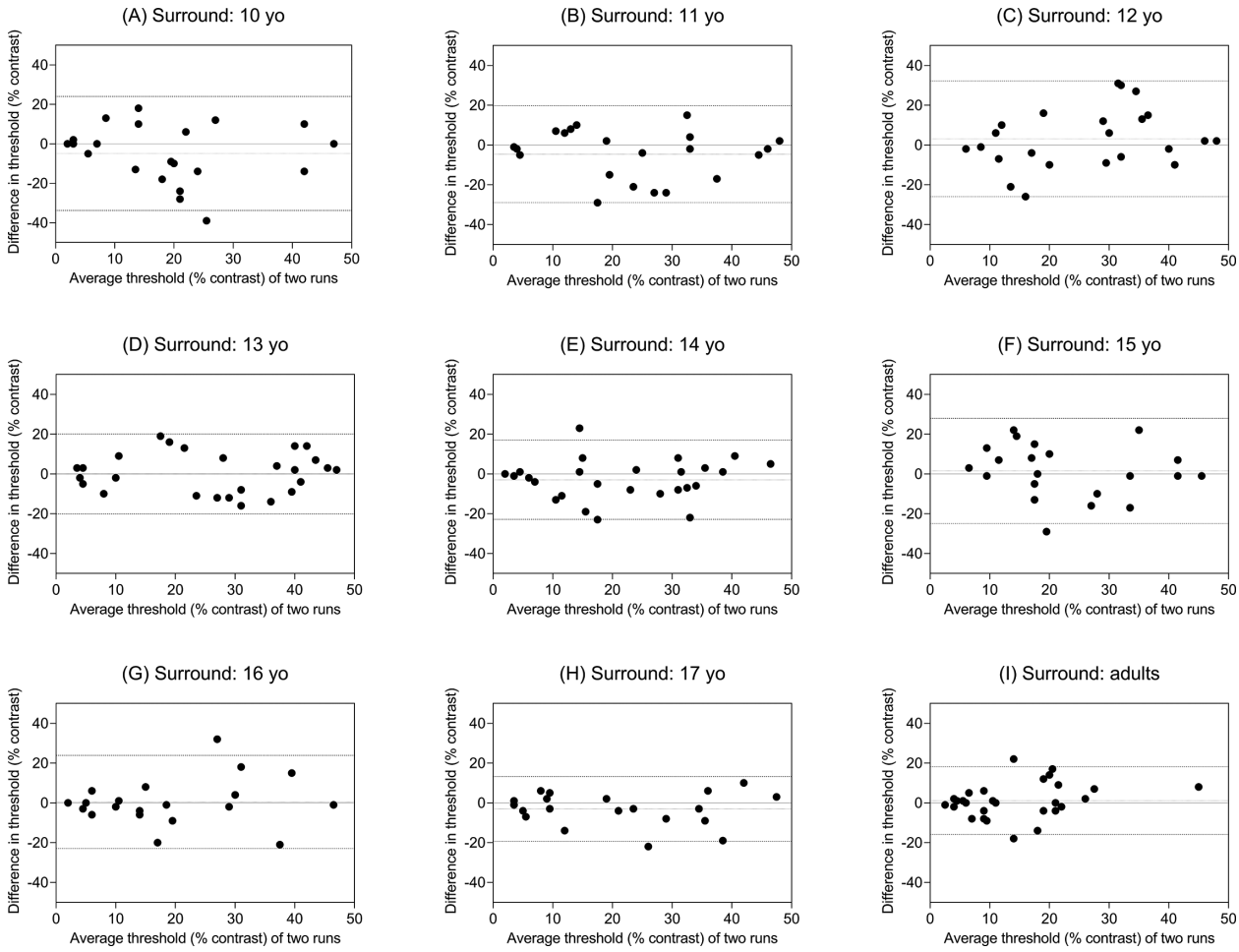



**Figure 5.** Bland–Altman plots of test–retest variability, showing the difference in contrast matching threshold (%) between the two runs of the surround condition as a function of average contrast matching threshold (%) of two runs. The bias (average difference) is indicated by the horizontal dotted line. The 95% limits of agreement are shown by the two horizontal dashed lines.

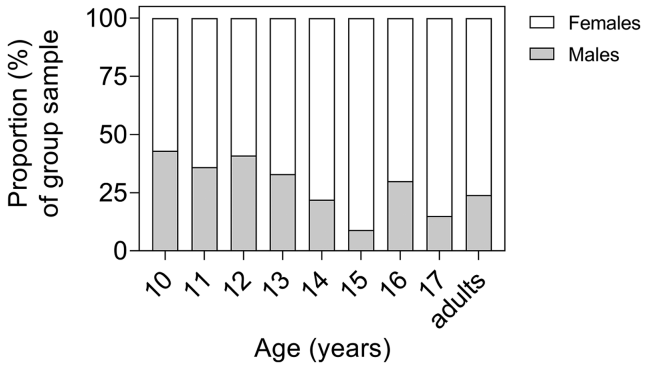



**Figure 6.** Proportion of females (*unfilled*) and males (*gray*) in each age group, according to self-reported gender identity.

task (Fig. 3B), one-way ANOVA: $F(8,201) = 1.34$, $P = 0.23$. Regarding test–retest variability between the two runs of each test condition, we found the narrowest limits of agreement for the adult participants for the no surround condition (Fig. 4I; Bland–Altman plot: 95% confidence limits of agreement of 8% contrast) compared with the nonadult age groups (Figs. 4A to 4H). Visual inspection of the Bland–Altman plots for the surround condition (Fig. 5) indicates relatively uniform limits of agreement across all age groups, including adults. Hence, we find no strong evidence for differences in staircase length (Fig. 3) nor test–retest variability (Figs. 4 and 5) between adolescents and adults to account for the differences in threshold measurements obtained in the 12- and 13-year-old participants relative to adults.

## Effect of Self-reported Gender Identity

Although we had more participants who self-identified as female than male overall (151 females, 59 males, 0 nonbinary), the relative proportions of females to males in each age group did not differ from adults (Fig. 6; $\chi^2$ tests of proportions, $P > 0.05$). Although our study sample size calculation was not powered to explore the potential influence of gender and age, we conducted a two-way ANOVA including gender as an additional factor. This analysis revealed no difference between males and females, $F(1,191) = 0.02$, $P = 0.90$, or an interaction between age and gender, $F(8,191) = 0.95$, $P = 0.47$. The main effect of age on perceptual surround suppression strength remained when gender was not pooled, $F(8,191) = 2.08$, $P = 0.04$, $\eta^2 = 0.08$.



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## Discussion

Our novel finding is that early adolescence is associated with weaker perceptual center-surround suppression when compared with adults. Several studies demonstrate altered perceptual center-surround contrast suppression with healthy adult ageing.[25,55,57–62] However, our understanding of normal changes to perceptual surround suppression across a lifetime is incomplete, with a dearth of information prior to adulthood. Our findings add to this body of literature by highlighting early adolescence as a unique period of development of center-surround interactions in vision.

Changes in center-surround contrast suppression have been associated with altered neurotransmitter levels in human visual cortex, notably the major inhibitory neurotransmitter GABA.[31,63,64] There is also evidence that other mechanisms play a role in determining center-surround suppressive effects, such as withdrawal of excitation not primarily driven by GABA-mediated inhibition[27] or cholinergic system involvement.[28,29] There is some evidence of discrete changes in components of excitatory (glutamate) and inhibitory (GABA) neurotransmitter systems that could impact on the circulating neurotransmitter levels—for example, receptor expression levels, synthesis, vesicular transport, and release of neurotransmitter.[48,49] However, it is difficult to predict center-surround visual perceptual effects based on the many molecular changes reported in post mortem visual cortex, and potential interactions thereof, across the range of ages tested here.

Although not studied here, another well-studied example of contextual effects in vision is surround suppression of motion, for which there is some evidence of its developmental trajectory in the literature. Perceptually, it becomes more difficult to discriminate the direction of motion of a high contrast drifting grating stimulus as it gets larger, which is typically measured using stimulus duration thresholds.[65] This increase in motion discrimination duration thresholds with size was originally explained by a model of increased suppression as the spatial extent of the stimulus encroaches on the suppressive surround,[65,66] although whether these perceptual effects are driven primarily by GABA-mediated inhibition has been contested more recently.[27] Contrast and motion surround suppression tasks are markedly different, and performance on one task does not predict performance on the other, at least in adults.[59,67,68] Nevertheless, we note partial developmental similarities between perceptual surround suppression of motion and contrast. Spatial surround suppression of motion is weak in infancy,[69] young children (5-year-olds),[70] and older adults,[32,60,67,71,72] when this task has been studied relative to younger adults at these discrete timepoints in the lifespan. Although we did not compare visual perceptual performance on two surround suppression tasks (motion vs contrast) directly, our study findings suggest that the differences between surround effects in contrast and motion observed previously in adults[59,67,68] extends to their developmental trajectories.

In the absence of explicit instruction, from informal observation and discussion with participants, the obvious strategy to adopt to complete the two-spatial forced choice task is to foveate on one stimulus and then make a single eye movement to the second stimulus within the fixed 500-ms stimulus interval. An alternate possibility is to fixate in between the two stimuli, effectively creating a peripheral (which generally produces stronger perceptual surround suppression[73]), rather than foveal perceptual task. Because, for logistical reasons, no eye tracking measurements were recorded, it is not possible to rule out the effect of different viewing behaviors on our perceptual results.

It is important to recognize that measured age-related differences in psychophysical threshold estimates might not solely reflect differences in visual processing, but may be due to nonvisual factors such as differences in attention, motivation, or understanding of the task.[74,75] Given that there were no direct ways to account for the potential confound of lapse rate on the second (surround) task, it is possible that our reported contrast matching thresholds for the surround condition were affected by increased lapse rates. Lapses in attention could lead to guessing, particularly when stimuli are close to threshold,[74] and contribute to substantial within-individual variability[75] and prolong staircases. We did not find evidence for either of these outcomes in our 12- and 13-year-old groups, compared with adult performance. The tasks were quick and only repeated twice to minimize total test duration. Furthermore, data indicative of strong response bias (where the same button was pressed throughout the test, possibly owing to disengagement with the task) were excluded. It is also unlikely that if participants chose to press buttons at random that this would probabilistically produce on average weaker suppression in specific age groups and not others.

Our data indicate that performance on the initial no surround contrast matching task (the same contrast discrimination judgement for all tests) was consistent and reliable (on average participants matched to the veridical contrast; see Fig. 2A) across all age groups, implying that participants understood and performed the task as instructed. We also adopted various ways to ensure that participants remained focused and motivated, including regular breaks, an engaging zebra analogy to explain the task, practice trials, frequent encouragement from the experimenter, and kept the tests brief. We, therefore, consider it unlikely that the weakened perceptual suppression in 12- and 13-year-olds relative to adults was purely an artefact of poor procedural performance. Nevertheless, we anticipated the possibility of some unreliable psychophysical performance and so *a priori* recruited more participants than indicated by the power analysis to account for post-testing data attrition.

Although other psychophysics studies have interleaved catch trials (i.e., stimuli that are expected to elicit 100% correct responses in all participants) within staircases to quantify lapse rates,[11,76] provided physical incentives,[11,74] or moved participants around to different locations for each new test to reduce boredom,[74] we chose not to implement these techniques for practical reasons. We preferred more efficient testing (given testing was typically limited to certain time periods during the day to fit into school schedules) and, for ethical reasons, did not offer rewards to any of our participants to minimize perceived inequality once students returned to their classrooms.

Interestingly, other psychophysical studies testing children on sensory discrimination tasks (e.g., auditory frequency discrimination[76]) report high lapse rates, particularly in younger children (<10 years of age) and those with a lower IQ. Such findings suggest that testing younger children may be more fraught with inattentiveness and response variability from some kind of cognitive immaturity,[76] hence our decision to constrain testing to older children and

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adolescents aged 10 years and over. We did not measure IQ in our study for logistical reasons, but note that some studies (but not all[77]) of visual contextual effects in adults have linked stronger perceptual surround suppression of motion to higher IQ (correlation $r \sim 0.4$[68,78] once extreme IQ scores >120 are removed that drive the strong correlation). However, there is conflicting evidence for whether stronger perceptual center-surround suppression of contrast is ($r = 0.87, N = 9$)[79] or is not ($r = -0.09, N = 46$)[68] correlated with higher IQ. On average, our 12- and 13-year-old participants showed approximately 54% of the suppression strength of the adult group (large effect sizes). Although not relevant to the specific task used here (contrast suppression), if we extrapolate from previous data on perceptual motion suppression,[68] our younger adolescents would need a major shift in IQ (approximately a 25-point IQ score difference) to effectively double their average suppression strength to match that of the adults in this study. We, therefore, consider any contribution of IQ to our results as unlikely, especially given no strong reason for why our youngest participants (aged 10 and 11 years old) would have higher IQs than the 12- and 13-year-olds to explain the difference in perceptual performance.

We only considered chronological age relative to each participant's date of birth in our analysis. Other than chronological age, the obvious biological difference between adults and 12- and 13-year-olds is puberty and the accompanying hormonal changes. Puberty influences the development of brain structure and function in adolescents (see reviews[80–82]), but whether pubertal changes in young adolescents can explain the weakened perceptual center-surround suppression observed in our study is an open question. Puberty involves several distinct but temporally overlapping, hormonally driven phases of development that extend over several years. Because individuals of the same chronological age can markedly differ in biological maturity[83,84]—up to 5 years difference in pubertal onset across individuals[80]—future work could consider assessing levels of sex steroid hormones and/or objective physical developmental characteristics to evaluate whether pubertal development may explain some of the age-related changes observed in the brain. We note, however, that these hormonal and physical measurements cannot solely be used as indicators of pubertal development, because other aspects of puberty (e.g., significant physical and psychosocial changes) might also influence the developing brain.[80] Biological sex may also need to be considered in a planned future study, because the timing and trajectory of puberty depends on sex hormones and differs between males and females. Although our study was not sufficiently powered for a smaller subset analysis, we found no strong evidence to suggest that our main results (weaker suppression in young adolescents) were driven by differences between self-reported male and female gender. Nevertheless, future studies relating pubertal development, vision and the brain should consider the issues of biological sex and pubertal development carefully.

In conclusion, our cross-sectional data in a large group of young people, across the ages of the pre-teen years, adolescence, and adulthood, indicate weaker perceptual surround suppression early in adolescence relative to adults. Because center-surround interactions are a key building block for daily vision tasks, our findings contribute to the understanding of normal human vision across a lifespan.

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