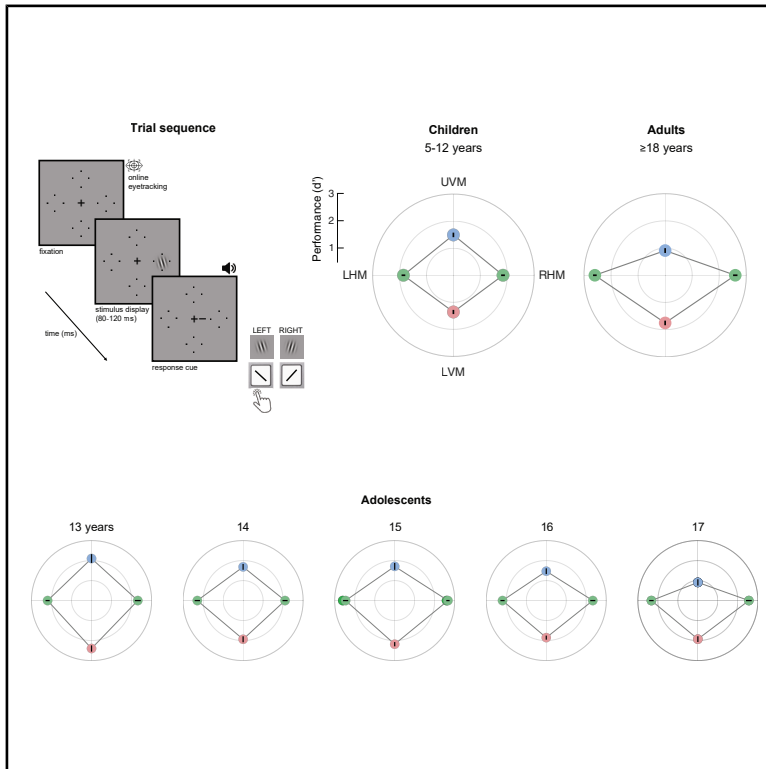# Visual field asymmetries develop throughout adolescence

Graphical abstract

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In brief

Developmental neuroscience; Sensory
neuroscience; Psychology

Highlights

- Human visual perception varies with polar angle at equal
  distances from gaze

- Adults and children perform better on the horizontal than the
  vertical meridian

- Adults–but not children–perform better on the lower than
  upper vertical meridian

- These asymmetries develop gradually, reaching adult levels
  in late adolescence

CellPress

Article

Visual field asymmetries develop throughout adolescence

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SUMMARY

For human adults, visual perception varies with polar angle at isoeccentric locations from the center of gaze. The same visual information yields better performance along the horizontal than vertical meridian (horizontal vertical anisotropy, HVA) and along the lower than upper vertical meridian (vertical meridian asymmetry, VMA). For children, performance is better along the horizontal than vertical meridian (HVA) but does not differ between the lower and upper vertical meridian. Here, we investigated whether the extent of the HVA varies and whether the VMA emerges and develops during adolescence, or whether the VMA only emerges in adulthood. We found that both the HVA and VMA develop gradually throughout adolescence and become as pronounced as those of adults only in late adolescence.

INTRODUCTION

Visual perception in human adults varies throughout the visual field. It decreases across eccentricity –distance from the center of gaze– and also differs around isoeccentric locations, varying with polar angle (the counterclockwise angle from the x-axis at which a point in the x y-plane lies) at a constant distance from the center of gaze. The same stimuli yield better performance along the horizontal than the vertical meridian (HVA) and along the lower than the upper vertical meridian (VMA). In adults, these perceptual polar angle asymmetries, and their retinal and cortical correlates, have been well characterized (see review[1]).

For adults, polar angle asymmetries are pervasive. They are evident in basic dimensions such as contrast sensitivity (e.g.,[2–8]) and acuity.[9–11] These asymmetries become more pronounced with increasing stimulus spatial frequency and eccentricity, and when the target appears amidst distractors (e.g.,[2,12]). They are present across stimulus properties –including luminance, contrast, orientation, size, and spatial frequency,[2,4,13] whether stimuli are viewed monocularly or binocularly,[2,9] masked or unmasked,[2,14] and across stimulus orientation and tilt angles,[9,12,15] as well as across head orientations. Both HVA and VMA are retinotopic: when observers rotate their head, the asymmetries shift with the retinal location of the stimulus rather than its spatial location.[16]

The extent of these asymmetries increases with eccentricity from the center of gaze[2,15,17,18] and with spatial frequency.[2,4,9] Furthermore, these asymmetries are strongest at the cardinal meridians and diminish gradually with angular distance, disappearing at the intercardinal meridians (the meridians midway between the cardinal meridians; e.g., at 45 and 225 deg and 135 and 315 deg).[2,9,15,19]

Recently, we directly compared the extent of both the HVA and VMA in an orientation-discrimination task using horizontal and vertical stimuli. We found that the HVA is more pronounced for horizontal than for vertical stimuli, whereas the magnitude of the VMA is similar for both orientations.[20] The stronger HVA for horizontal stimuli reflects a radial bias[21–23]: Horizontal stimuli enhanced performance along their radial (horizontal) meridian, whereas vertical stimuli enhanced performance along their radial (vertical) meridian, thereby potentiating and diminishing the HVA, respectively.

These asymmetries are also evident in mid- and higher-level vision, including texture segmentation,[2] illusory contours,[24] letter recognition,[25] perceived size,[26] face perception,[27] and numerosity processing,[28] as well as in visual short-term memory.[10]

Optical quality and retinal factors (e.g., cone density and midget retinal ganglion cell density) account for only a small fraction of these perceptual asymmetries.[29,30] Instead, they are better accounted for by the distribution of cortical surface area in primary visual cortex (V1), which is larger for the horizontal than the vertical meridian and for the lower than the upper vertical meridian.[31–35] Moreover, individual differences in contrast sensitivity at the cardinal meridians correlate with the V1 surface area representing those meridians.[33]

Remarkably, pronounced systematic differences in visual performance between adults and children indicate that visual perception continues to develop beyond childhood. In children (5–12 years), visual performance shows an HVA —though less pronounced than in adults—but no VMA.[36] Correspondingly,
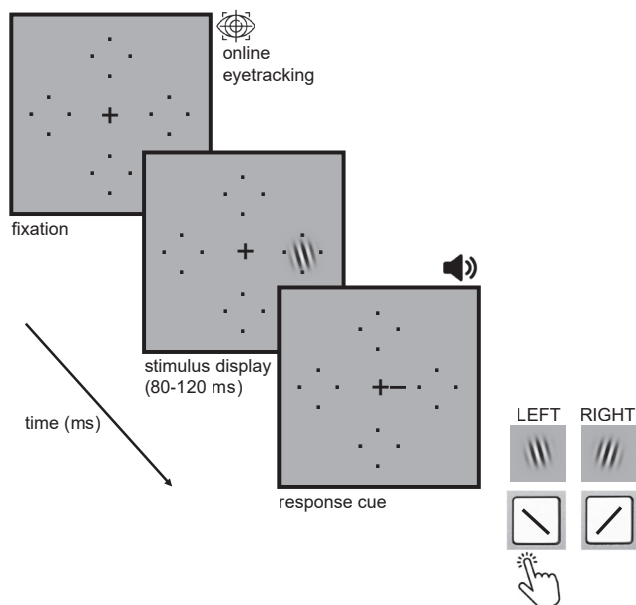
Figure 1. Experimental trial: orientation discrimination task
Observers fixated on the plus sign in the display center. Stimuli were briefly presented at four isoeccentric locations. A response cue indicated the target location, and observers reported its orientation (left vs. right) with a key press. Observers' eyes were tracked to ensure stable fixation. A feedback tone indicated a correct or incorrect response.

children's cortical surface area is larger for the horizontal than the vertical meridian but similar for the upper and lower vertical meridians.[35] It remains to be determined whether these late-stage polar-angle changes in the human visual system arise from environmental influences during development, from the way in which the visual system is hard-wired to develop, or from a combination of both.[35,36]

In addition to these ontogenetic differences, phylogenetic differences exist. Whereas human adults show the typical VMA in a motion-discrimination task, non-human adult primates show an inverted VMA: discrimination is better for stimuli at the upper than the lower vertical meridian. These findings suggest that evolutionary differences in locomotion, navigation, and tool use between humans and non-human primates may give rise to distinct visuomotor interactions at specific visual field locations.[37] Thus, both biological maturation and environmental input likely contribute to shaping visual-field organization, although the mechanisms by which they do so remain unknown.

Here, we investigated whether the extent of the HVA varies and whether the VMA emerges and fully develops during adolescence, or whether the VMA emerges only in adulthood. Adolescents aged 13–17 years ($n = 155$) and adults ($n = 112$) performed an orientation-discrimination task. The adult data were previously reported.[36] Gabor patch stimuli were presented briefly (~100 ms) at four isoeccentric locations along the cardinal meridians. All participants indicated whether the target was tilted right or left from vertical (Figure 1). Performance (d') was calculated at each location using to signal detection theory. Moreover, because height can affect the visual-field location of relevant perceptual input, we

examined whether the extent of these polar-angle asymmetries correlates with height across children, adolescents, and adults.

RESULTS

The horizontal vertical anisotropy and vertical meridian asymmetry continue to develop throughout adolescence

Adolescents' discriminability (d') revealed both an HVA –overall discriminability was higher for the horizontal than the vertical meridian– and a VMA –overall discriminability was higher at the lower than the upper vertical meridian– as did adults' discriminability (Figures 2A–2C). The d' HVA was more pronounced for adults than adolescents. A 2×2 (age X location) analysis of variance (ANOVA) revealed an interaction ($F(1,265) = 28.26$, $p < 0.0001$). The superior performance on the horizontal than vertical meridian was more pronounced for adults ($F(1,111) = 142.89$, $p < 0.0001$) than adolescents ($F(1,154) = 48.48$, $p < 0.0001$).

The d' VMA also differed between age groups (Figures 2A–2C): a 2×2 (age x location) ANOVA revealed an interaction ($F(1,265) = 6.99$, $p < 0.01$). The superior performance on the lower than upper vertical meridian was more pronounced for adults ($F(1,111) = 62.9$, $p < 0.0001$) than adolescents ($F(1,154) = 29.16$, $p < 0.0001$).

The HVA and VMA were paralleled in response times (Figure 2B). Both groups had both asymmetries: HVA in adults ($F(1,111) = 51.983$, $p < 0.0001$) and adolescents ($F(1,154) = 48.847$, $p < 0.0001$); VMA in adults ($F(1,111) = 17.79$, $p < 0.0001$) and adolescents ($F(1,154) = 11.499$, $p < 0.001$). There was no age $\times$ location interaction for either the HVA ($F(1,265) = 1.61$, $p > 0.1$) or the VMA ($F(1,265) = 0.55$, $p > 0.1$). Thus, there were no speed-accuracy trade-offs in either adolescents or adults, and no difference in RT between groups.

The horizontal vertical anisotropy emerges before the vertical meridian asymmetry

To assess the developmental trajectory of the HVA and emergence of the VMA, we divided the adolescent participants into 5 groups according to their age and analyzed whether the extent of these asymmetries differed for these subgroups (Figure 3A): An HVA was present for all ages after 14 years and became more pronounced with age. A 5×2 (age X location) analysis of variance (ANOVA) revealed an effect of location ($F(1,150) = 41.62$, $p < 0.0001$) and an interaction with age ($F(4,150) = 3.409$, $p < 0.05$). The VMA also marginally interacted with age ($F(4,150) = 2.383$, $p = 0.054$).

The magnitude of the HVA [(Horizontal–Vertical)/(Horizontal+ Vertical); Figure 3B] differed for adolescents and adults ($F(1,265) = 29.02$, $p < 0.0001$); the asymmetry was less pronounced for adolescents ($t(154) = 7.05$, $p < 0.0001$) than adults ($t(111) = 12.586$, $p < 0.0001$). Moreover, HVA ratios differed among adolescent age groups ($F(4,150) = 4.72$, $p = 0.001$), becoming significant by age 15 ($t(26) = 4.648$, p bonf <0.001), and increasing with age. Likewise, the magnitude of the VMA [(Lower Vertical–Upper Vertical)/(Lower Vertical+Upper Vertical); Figure 3C] differed for adolescents and adults ($F(1,265) = 9.51$, $p < 0.01$); the asymmetry was less pronounced for adolescents ($t(154) = 5.519$, $p < 0.0001$) than adults ($t(111) = 8.66$, $p < 0.0001$). Moreover, the VMA differed among adolescent
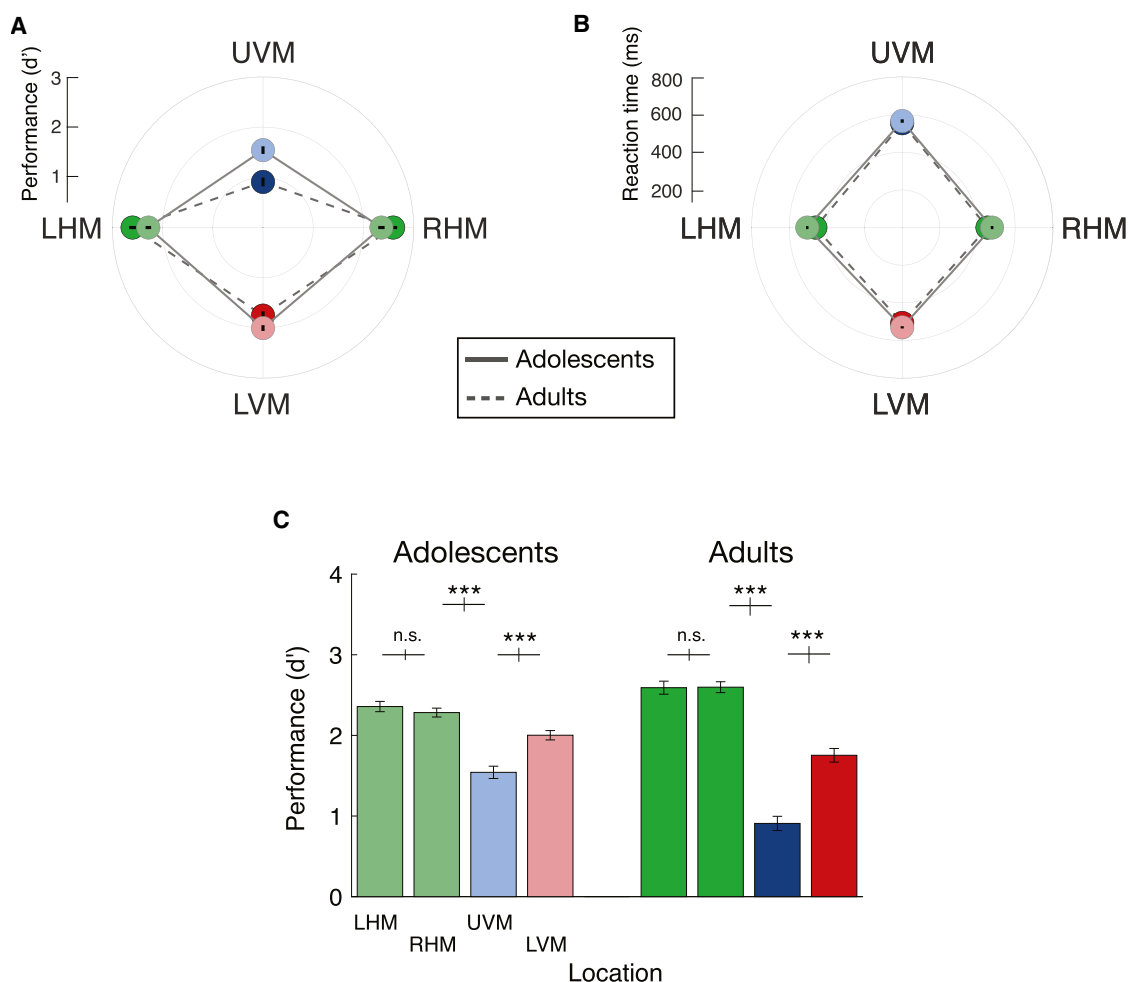
Figure 2. Polar angle asymmetries differ between adolescents and adults

(A) Adolescents' (n = 155) and adults' (n = 112) polar angle asymmetries in visual performance (d'). The target was presented at one of the four isoeccentric cardinal locations on each trial. The center point represents chance performance and each of the four points represents discriminability (d') at those locations, with the black line inside representing ±1 SEM. For adults (dashed lines), performance shows the typical asymmetries: (1) horizontal–vertical anisotropy (HVA): better performance along the horizontal than vertical meridian; and (2) vertical–meridian asymmetry (VMA): better performance at the location directly below (LVM) than above (UVM) fixation. For adolescents (solid line), both asymmetries are present, but less pronounced.

(B) Adolescents' and adults' polar angle asymmetries in response time (ms). HVA and VMA are present in both groups. Neither asymmetry interacted with age.

(C) Orientation discriminability (d') at each location: left-horizontal meridian (LHM), right-horizontal meridian (RHM), upper vertical meridian (UVM) and lower vertical meridian LVM) for adolescents and adults. In A and B, error bars = ±1 within-subject SEM. In C, error bars between locations = standard error of the difference * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

age groups (F(4,150) = 2.57, $p = 0.041$), becoming significant by age 16 (t(47) = 2.64, p bonf <0.05), and increasing with age.

We also plotted individual values for each subject in each group level for the HVA and VMA. The HVA becomes significant at age 15 and is more consistent by age 17 (Figure 4A). The VMA becomes significant at age 16 and is more pronounced and consistent by age 17 and into adulthood (Figure 4B).

The vertical meridian asymmetry, but not the horizontal vertical anisotropy, correlates with height

To evaluate whether height contributes uniquely to the magnitude of the HVA and VMA independently from age, we regressed out age from these measures and then correlated the residuals

with height (e.g.,[20,33]). These analyses included the 347 observers (91% of the total number of adolescents, children, and adults) for whom height was available. We found no significant correlation for HVA (Spearman's r = 0.039, $p > 0.1$; Figure 5A). In contrast, height correlated with VMA residuals (Spearman's r = 0.188, $p < 0.001$; Figure 5B), demonstrating a significant association between observers' height and VMA magnitude when age-related variance is removed.

DISCUSSION

In this study we found that both the HVA and the VMA continue to develop throughout adolescence. The HVA, already present for
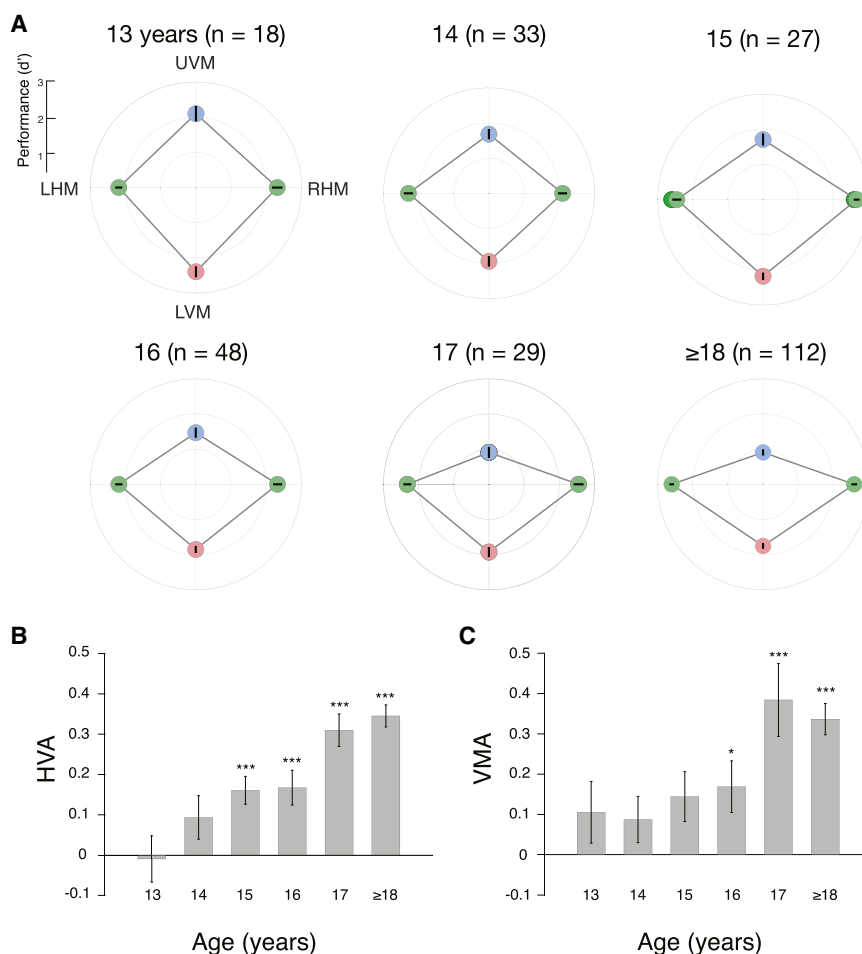
Figure 3. Polar angle asymmetries per adolescents' age groups

(A) Polar angle asymmetries per age group (same format as in 2A). Data for adults (dashed lines) have been published in Carrasco et al.[36]

(B and C) Magnitudes of the (B) HVA ratios [(Horizontal–Vertical)/(Horizontal+Vertical)] and (C) VMA ratios [(Lower Vertical–Upper Vertical)/(Lower Vertical+Upper Vertical)] for each group of adolescents and adults (asterisks reflect within-adolescent Bonferroni-corrected significance). Data for adults (≥18) have been published in Carrasco et al.[36] Error bars = ±1 within-subject SEM. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

be reached by age 12,[39] our results show that the enhancement is not uniform across the visual field. If it were, the HVA and VMA would not exhibit distinct developmental trajectories.

Consistent with this idea, a recent study reported a protracted increase in the horizontal bias of eye movements.[40] Those authors noted that the prolonged development of saccadic anisotropies aligns with our findings on visual field geometry in children[36] and adolescents (this study), which reveal a less pronounced horizontal-vertical asymmetry than in adults. We concur with their suggestion that future work should investigate the relation between the development of eye movement patterns and polar-angle asymmetries in visual performance.

children both behaviorally[36] and in visual cortex,[35] becomes stronger with age and appears to be well established by age 15. Using the same vertical stimuli across all age groups, we observed significant differences in the HVA from adolescence to adulthood, despite the stronger HVA reported for horizontal relative to vertical stimuli.[20] The VMA, by contrast, is absent in children both behaviorally[36] and in visual cortex[35]; it only emerges during adolescence and appears to be well established by age 17.

These findings suggest that the HVA and VMA develop gradually and independently. Both progress throughout adolescence, though the HVA emerges at an earlier developmental stage than the VMA.[35,36] To assess the continuity of this development more precisely, longitudinal studies following the same participants every few months would be ideal.

The systematic differences in performance around the visual field during adolescence, and between adolescents and adults, provide further evidence that some basic aspects of visual perception and brain function continue to develop until the onset of adulthood.[38–41] For instance, from ages 4 to 18, the contrast sensitivity function (CSF) improves by ∼0.3 log_{10} units—approximately a doubling of contrast sensitivity—at an exponentially decaying rate. Although ∼90% of this improvement appears to

Even within the high-acuity foveola, adult humans are more sensitive to stimuli presented along the horizontal than the vertical meridian.[42] Interestingly, the VMA in the foveola is reversed: objects are more easily discriminated when presented slightly above, rather than slightly below, the center of gaze.[42] Future studies should assess whether the HVA and inverted VMA within the foveola are also present in children and track their developmental trajectories across adolescence.

The effects of covert attention and adaptation on polar-angle asymmetries have been investigated in adults. Both exogenous (i.e., involuntary[2,3,36,43–45]) and endogenous (i.e., voluntary[12,37]) covert spatial attention, as well as temporal attention[46] enhance sensitivity similarly around the visual field, indicating that covert attention does not modulate the extent of the HVA or VMA. In contrast, adaptation exerts a stronger effect along the horizontal than vertical meridian, reducing the HVA in contrast sensitivity and promoting perceptual uniformity around the visual field.[20] We are currently investigating whether and how covert attention affects sensitivity in children and adolescents.

A comprehensive account of visual development must consider interactions between biological maturation and environmental input.[36,40,47] Upper–lower hemifield asymmetries may relate to functional specialization, as they contain

A HVA

B VMA
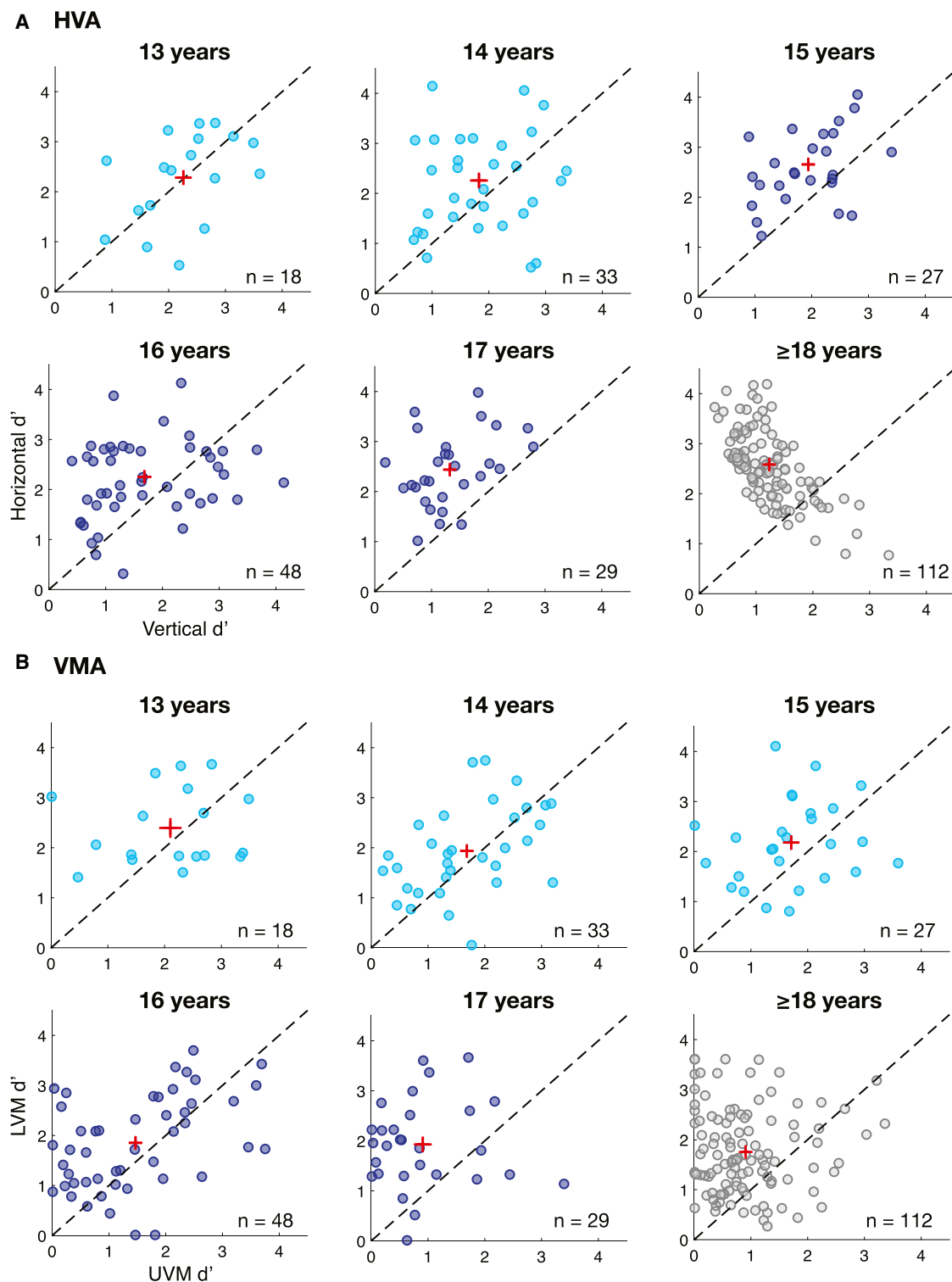
Figure 4. Individual asymmetry ratios for each age group

(A) The HVA for each adolescent subgroup and for adults. For each age group, data above the diagonal indicate better performance at the horizontal than vertical meridian and vice versa.

(B) The VMA for each adolescent subgroup and for adults. For each group, data above the diagonal indicate better performance at the lower than upper vertical meridian and vice versa. Lighter blue panels indicate age groups that did not show significant asymmetries; darker blue panels indicate age-groups that showed significant asymmetries. The center of the red cross indicates the mean value for each group and their line lengths represent ±1 SEM.
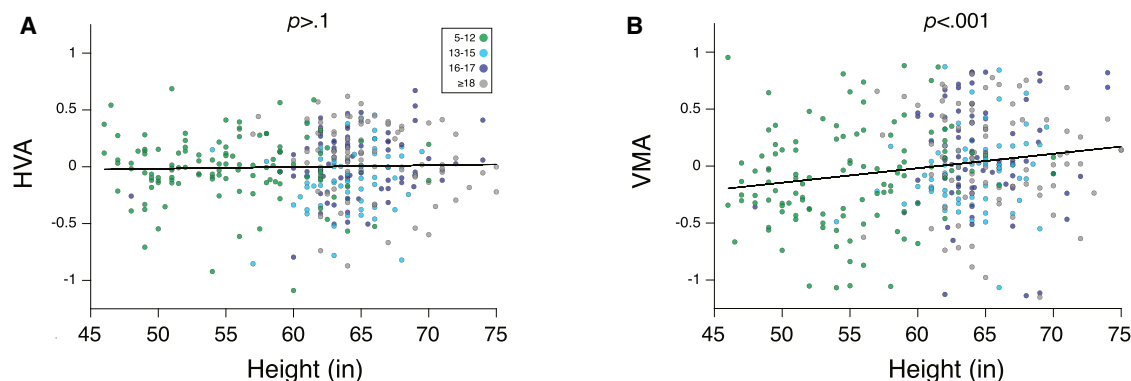
Figure 5. Correlations between individuals' asymmetry ratios and height
(A) Correlation between (age-residualized) HVA ratios and height for 347 observers, Spearman's r = 0.039, *p* > 0.1.
(B) Correlation between (age-residualized) VMA ratios and height for 347 observers, Spearman's r = 0.189, *p* < 0.001. HVA and VMA values for observers aged 5–12 and ≥18 ys old have been reported in Carrasco et al.[36]

information about extra- and peri-personal space, respectively; the upper visual field processes distant objects, supporting the rapid detection of prey and predators, whereas the lower visual field processes nearby objects, supporting reaching and manipulation close to the body.[48] For adults, many tasks requiring manual action involve stimuli in the lower visual field. For children, however, relevant visual input often occurs above eye level, and this changes with growth.

Nonetheless, these asymmetries are primarily driven by the cardinal meridians, rather than the entire hemifields. The VMA decreases with polar angle distance from the vertical meridian and is no longer present at intercardinal locations for contrast sensitivity[19] and acuity[9] (reviewed in[35]). Therefore, whereas functional specialization for distant versus near objects may contribute to meridional asymmetries, it cannot fully account for the polar-angle-specific effects observed.

In the present study with adolescents, as in our previous study with children,[36] we focused on the cardinal meridians—two horizontal and two vertical locations—because adults show the strongest behavioral HVA and VMA at these locations.[2,9,15,16,19] An open question is whether adolescents who already exhibit a significant VMA also show no performance differences between the upper and lower visual fields at intercardinal locations.

Interestingly, we found that height—after controlling for age—correlates with the VMA, but not with the HVA. These distinct results support the idea that the HVA and VMA are independent and may reflect the spatial statistics of environmental input.[20,35–37] A possible explanation for the height–VMA link is that as individuals grow taller, relevant visual input is more likely to appear below rather than above fixation. We speculate that environmental spatial statistics may help shape visual-field organization. Although perceptual asymmetries for properties such as color[49] and orientation[50,51] have been related to environmental statistics, there is no evidence that natural scene statistics account for the HVA or VMA. Future studies should explore whether scene statistics contribute to these location-specific asymmetries.

Another possibility is that visual-field asymmetries reflect adaptations to locomotion. For bipedal humans, information

directly below gaze—i.e., at the lower vertical meridian—may be critical for monitoring the environment during locomotion.[37] Walking relies on perceptual adaptation to optic flow[52] and may be particularly sensitive to calibration in the lower visual field[53] given the downward directional bias of stabilizing eye movements, especially when the gaze is directed forward.[54] It also remains unknown whether some biological factors may correlate with, cause, or reflect visual-field asymmetries related to height.

We recently discovered that the VMA is inverted in adult non-human primates: macaques perform better at the upper than the lower vertical meridian. This phylogenetic difference suggests that evolutionary pressures related to locomotion, navigation, and tool use may give rise to distinct visuomotor interactions at specific visual field locations.[37]

Characterizing performance around the visual field across development is essential for understanding the functional plasticity of the human brain and how visual systems adapt environmental demands. Consistent with evidence that contrast sensitivity[39] and gaze behavior[40] continue to mature throughout adolescence, our findings reveal that visual-field asymmetries in contrast sensitivity also develop, reaching adult-like levels only in the final years of adolescence.

Future research comparing natural scene statistics across age groups—and between humans and non-human primates—could clarify how biological maturation and environmental factors interact to shape visual-field organization. Overall, our findings underscore the importance of conducting behavioral and neurophysiological studies that consider polar angle as a key factor in linking cortical anatomy and function with perceptual performance across development. They also highlight the need to account for both age-related and species-specific variation when developing models of vision and brain function.

Limitations of the study

For the present study, we could recruit many more females than males; thus, we lack appropriate statistical power to assess possible biological sex differences. It is an open question if

the age effects we report here for the HVA and VMA equally represent both males and females. We did not record participants' ancestry, race, ethnicity, or socioeconomic status and therefore could not perform analyses according to these demographic characteristics. To minimize the influence of other individual differences, we aimed to obtain large and roughly equal sample sizes for each adolescent age group. Moreover, our participants vary across age and thus some differences contributing to the effect of age could still be related to other individual factors. A longitudinal study assessing both the HVA and VMA would be ideal but would take many years to complete.

RESOURCE AVAILABILITY

Lead contact
Further information and requests should be directed to and will be fulfilled by the lead contact, Marisa Carrasco (marisa.carrasco@nyu.edu).

Materials availability
This study did not generate new unique reagents.

Data and code availability
Data: All data reported in this article are available from the lead contact upon request.

Code: All original experimental code is freely available via an open-access repository (Database: https://github.com/CarrascoLab/PF_adolescents).

Additional information: Any additional information required to reanalyze the data reported in this article is available from the lead contact upon request.

ACKNOWLEDGMENTS

AUTHOR CONTRIBUTIONS

MC conceptualized the study, acquired the funding, and supervised and administered the study. CM and MR collected the data. CM analyzed the data and created the figures. MC wrote the original draft. All authors reviewed, edited, and approved the final article and figures.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

None.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
- METHOD DETAILS
  - Stimuli
  - Procedure
- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

REFERENCES

1. Himmelberg, M.M., Winawer, J., and Carrasco, M. (2023). Polar angle asymmetries in visual perception and neural architecture. Trends Neurosci. 46, 445–458. https://doi.org/10.1016/j.tins.2023.03.006.

2. Carrasco, M., Talgar, C.P., and Cameron, E.L. (2001). Characterizing visual performance fields: effects of transient covert attention, spatial frequency, eccentricity, task and set size. Spat. Vis. 15, 61–75. https://doi.org/10.1163/15685680152692015.

3. Cameron, E.L., Tai, J.C., and Carrasco, M. (2002). Covert attention affects the psychometric function of contrast sensitivity. Vision Res. 42, 949–967. https://doi.org/10.1016/S0042-6989(02)00039-1.

4. Himmelberg, M.M., Winawer, J., and Carrasco, M. (2020). Stimulus-dependent contrast sensitivity asymmetries around the visual field. J. Vis. 20, 18–19. https://doi.org/10.1167/jov.20.9.18.

5. Jigo, M., and Carrasco, M. (2020). Differential impact of exogenous and endogenous attention on the contrast sensitivity function across eccentricity. J. Vis. 20, 1–25. https://doi.org/10.1167/jov.20.6.11.

6. Pointer, J.S., and Hess, R.F. (1989). The contrast sensitivity gradient across the human visual field: With emphasis on the low spatial frequency range. Vision Res. 29, 1133–1151. https://doi.org/10.1016/0042-6989(89)90061-8.

7. Rijsdijk, J.P., Kroon, J.N., and van der Wildt, G.J. (1980). Contrast sensitivity as a function of position on the retina. Vision Res. 20, 235–241. https://doi.org/10.1016/0042-6989(80)90108-X.

8. Rovamo, J., and Virsu, V. (1979). An estimation and application of the human cortical magnification factor. Exp. Brain Res. 37, 495–510. https://doi.org/10.1007/BF00236819.

9. Barbot, A., Xue, S., and Carrasco, M. (2021). Asymmetries in visual acuity around the visual field. J. Vis. 21, 2. https://doi.org/10.1167/jov.21.1.2.

10. Montaser-Kouhsari, L., and Carrasco, M. (2009). Perceptual asymmetries are preserved in short-term memory tasks. Atten. Percept. Psychophys. 71, 1782–1792. https://doi.org/10.3758/APP.71.8.1782.

11. Kwak, Y., Hanning, N.M., and Carrasco, M. (2023). Presaccadic attention sharpens visual acuity. Sci. Rep. 13, 2981. https://doi.org/10.1038/s41598-023-29990-2.

12. Purokayastha, S., Roberts, M., and Carrasco, M. (2021). Voluntary attention improves performance similarly around the visual field. Atten. Percept. Psychophys. 83, 2784–2794. https://doi.org/10.3758/s13414-021-02316-y.

13. Kwak, Y., Zhao, Y., Lu, Z.L., Hanning, N.M., and Carrasco, M. (2024). Presaccadic attention enhances and reshapes the Contrast Sensitivity Function differentially around the visual field. eNeuro 11, 1–15. https://doi.org/10.1523/ENEURO.0243-24.2024.

14. Carrasco, M., Williams, P.E., and Yeshurun, Y. (2002). Covert attention increases spatial resolution with or without masks: support for signal enhancement. J. Vis. 2, 467–479. https://doi.org/10.1167/2.6.4.

15. Baldwin, A.S., Meese, T.S., and Baker, D.H. (2012). The attenuation surface for contrast sensitivity has the form of a witch's hat within the central visual field. J. Vis. 12, 23. https://doi.org/10.1167/12.11.23.

16. Corbett, J.E., and Carrasco, M. (2011). Visual performance fields: Frames of reference. PLoS One 6, e24470. https://doi.org/10.1371/journal.pone.0024470.

17. Fuller, S., Rodriguez, R.Z., and Carrasco, M. (2008). Apparent contrast differs across the vertical meridian: Visual and attentional factors. J. Vis. 8, 1–16. https://doi.org/10.1167/8.1.16.

18. Jigo, M., Tavdy, D., Himmelberg, M.M., and Carrasco, M. (2023). Cortical magnification eliminates differences in contrast sensitivity across but not around the visual field. eLife 12, e84205. https://doi.org/10.7554/eLife.84205.

19. Abrams, J., Nizam, A., and Carrasco, M. (2012). Isoeccentric locations are not equivalent: The extent of the vertical meridian asymmetry. Vision Res. 52, 70–78. https://doi.org/10.1016/j.visres.2011.10.016.

20. Lee, H.-H., and Carrasco, M. (2025). Visual adaptation stronger at horizontal than vertical meridian: Linking performance with V1 cortical surface area. Proc. Natl. Acad. Sci. USA 122, e2507810122. https://doi.org/10.1073/pnas.2507810122.

21. Sasaki, Y., Rajimehr, R., Kim, B.W., Ekstrom, L.B., Vanduffel, W., and Tootell, R.B.H. (2006). The radial bias: A different slant on visual orientation sensitivity in human and nonhuman primates. Neuron 51, 661–670. https://doi.org/10.1016/j.neuron.2006.07.021.

22. Ezzo, R., Winawer, J., Carrasco, M., and Rokers, B. (2023). Asymmetries in the discrimination of motion direction around the visual field. J. Vis. 23, 19–20. https://doi.org/10.1167/jov.23.3.19.

23. Ryu, J., and Lee, S.H. (2024). Bounded contribution of human early visual cortex to the topographic anisotropy in spatial extent perception. Commun. Biol. 7, 1–15. https://doi.org/10.1038/s42003-024-05846-x.

24. Rubin, N., Nakayama, K., and Shapley, R. (1996). Enhanced perception of illusory contours in the lower versus upper visual hemifields. Science 271, 651–653. https://doi.org/10.1126/science.271.5249.651.

25. Mackeben, M. (1999). Sustained focal attention and peripheral letter recognition. Spat. Vis. 12, 51–72. https://doi.org/10.1163/156856899x00030.

26. Schwarzkopf, D.S. (2019). Size perception biases are temporally stable and vary consistently between visual field meridians. i-Perception 10, 2041669519878722. https://doi.org/10.1177/2041669519878722.

27. Roux-Sibilon, A., Peyrin, C., Greenwood, J.A., and Goffaux, V. (2023). Radial bias in face identification. Proc. Biol. Sci. 290, 20231118. https://doi.org/10.1098/rspb.2023.1118.

28. Chakravarthi, R., Papadaki, D., and Krajnik, J. (2022). Visual field asymmetries in numerosity processing. Atten. Percept. Psychophys. 84, 2607–2622. https://doi.org/10.3758/s13414-022-02585-1.

29. Kupers, E.R., Carrasco, M., and Winawer, J. (2019). Modeling visual performance differences "around" the visual field: A computational observer approach. PLoS Comput. Biol. 15, e1007063. https://doi.org/10.1371/journal.pcbi.1007063.

30. Kupers, E.R., Benson, N.C., Carrasco, M., and Winawer, J. (2022). Asymmetries around the visual field: From retina to cortex to behavior. PLoS Comput. Biol. 18, e1009771. https://doi.org/10.1371/journal.pcbi.1009771.

31. Silva, M.F., Brascamp, J.W., Ferreira, S., Castelo-Branco, M., Dumoulin, S.O., and Harvey, B.M. (2018). Radial asymmetries in population receptive field size and cortical magnification factor in early visual cortex. Neuroimage 167, 41–52. https://doi.org/10.1016/j.neuroimage.2017.11.021.

32. Benson, N.C., Kupers, E.R., Barbot, A., Carrasco, M., and Winawer, J. (2021). Cortical magnification in human visual cortex parallels task performance around the visual field. eLife 10, e67685. https://doi.org/10.7554/eLife.67685.

33. Himmelberg, M.M., Winawer, J., and Carrasco, M. (2022). Linking individual differences in human primary visual cortex to contrast sensitivity around the visual field. Nat. Commun. 13, 3309. https://doi.org/10.1038/s41467-022-31041-9.

34. Himmelberg, M.M., Kurzawski, J.W., Benson, N.C., Pelli, D.G., Carrasco, M., and Winawer, J. (2021). Cross-dataset reproducibility of human retinotopic maps. Neuroimage 244, 118609. https://doi.org/10.1016/j.neuroimage.2021.118609.

35. Himmelberg, M.M., Tünçok, E., Gomez, J., Grill-Spector, K., Carrasco, M., and Winawer, J. (2023). Comparing retinotopic maps of children and adults reveals a late-stage change in how V1 samples the visual field. Nat. Commun. 14, 1561. https://doi.org/10.1038/s41467-023-37280-8.

36. Carrasco, M., Roberts, M., Myers, C., and Shukla, L. (2022). Visual field asymmetries vary between children and adults. Curr. Biol. 32, R509–R510. https://doi.org/10.1016/j.cub.2022.04.052.

37. Tünçok, E., Kiorpes, L., and Carrasco, M. (2025). Opposite asymmetry in visual perception of humans and macaques. Curr. Biol. 35, 681–687.e4. https://doi.org/10.1016/j.cub.2024.12.024.

38. Benedek, K., Janáky, M., Braunitzer, G., Rokszin, A., Kéri, S., and Benedek, G. (2010). Parallel development of contour integration and visual contrast sensitivity at low spatial frequencies. Neurosci. Lett. 472, 175–178. https://doi.org/10.1016/j.neulet.2010.02.001.

39. Dekker, T.M., Farahbakhsh, M., Atkinson, J., Braddick, O.J., and Jones, P.R. (2020). Development of the spatial contrast sensitivity function (CSF) during childhood: Analysis of previous findings and new psychophysical data. J. Vis. 20, 4–16. https://doi.org/10.1167/jov.20.13.4.

40. Linka, M., Karimpur, H., and de Haas, B. (2025). Protracted development of gaze behaviour. Nat. Hum. Behav. 9, 1887–1897. https://doi.org/10.1038/s41562-025-02191-9.

41. Toga, A.W., Thompson, P.M., and Sowel, E.R. (2006). Mapping brain maturation. TINS (Trends Neurosci.) 29, 148–159. https://doi.org/10.1016/j.tins.2006.01.007.

42. Jenks, S.K., Carrasco, M., and Poletti, M. (2025). Asymmetries in foveal vision. J. Neurosci. 45, e0055252025. https://doi.org/10.1523/JNEUROSCI.0055-25.2025.

43. Roberts, M., Cymerman, R., Smith, R.T., Kiorpes, L., and Carrasco, M. (2016). Covert spatial attention is functionally intact in amblyopic human adults. J. Vis. 16, 30. https://doi.org/10.1167/16.15.30.

44. Roberts, M., Ashinoff, B.K., Castellanos, F.X., and Carrasco, M. (2018). When attention is intact in adults with ADHD. Psychon. Bull. Rev. 25, 1423–1434. https://doi.org/10.3758/s13423-017-1407-4.

45. Talgar, C.P., and Carrasco, M. (2002). Vertical meridian asymmetry in spatial resolution: Visual and attentional factors. Psychon. Bull. Rev. 9, 714–722. https://doi.org/10.3758/bf03196326.

46. Fernández, A., Denison, R.N., and Carrasco, M. (2019). Temporal attention improves perception similarly at foveal and parafoveal locations. J. Vis. 19, 1–10. https://doi.org/10.1167/19.1.12.

47. Braddick, O., and Atkinson, J. (2011). Development of human visual function. Vis. Res. 51, 1588. https://doi.org/10.1016/j.visres.2011.02.018.

48. Previc, F.H. (1990). Functional specialization in the lower and upper visual fields in humans: Its ecological origins and neurophysiological implications. Behav. Brain Sci. 13, 519–542. https://doi.org/10.1017/S0140525X00080018.

49. Webster, M.A., Mizokami, Y., and Webster, S.M. (2007). Seasonal variations in the colors statistics of natural images. Network 18, 213–233. https://doi.org/10.1080/09548980701654405.

50. Girshick, A.R., Landy, M.S., and Simoncelli, E.P. (2011). Cardinal rules: visual orientation perception reflects knowledge of environmental statistics. Nat. Neurosci. 14, 926–932. https://doi.org/10.1038/nn.2831.

51. Hussain Ismail, A.M., Solomon, J.A., Hansard, M., and Mareschal, I. (2016). A tilt after-effect for images of buildings: evidence for selectivity for the orientation of everyday scenes. R. Soc. Open Sci. 3, 160551. https://doi.org/10.1098/rsos.160551.

52. Bruggeman, H., and Warren, W.H. (2010). The direction of walking—but not throwing or kicking—is adapted by optic flow. Psychol. Sci. 21, 1006–1013. https://doi.org/10.1177/0956797610372635.

53. Fujimoto, K., and Ashida, H. (2019). Larger head displacement to optic flow presented in the lower visual field. i-Perception 10, 2041669519886903. https://doi.org/10.1177/2041669519886903.

54. Muller, K.S., Matthis, J., Bonnen, K., Cormack, L.K., Huk, A.C., and Hayhoe, M. (2023). Retinal motion statistics during natural locomotion. eLife 12, e82410. https://doi.org/10.7554/eLife.82410.

55. Gardner, J.L., Merriam, E.P., Schluppeck, D., and Larsson, J. (2018). MGL: Visual psychophysics stimuli and experimental design package (2.0). Zenodo. https://doi.org/10.5821/zenodo.1299497.

56. Levitt, H. (1971). Transformed up-down methods in psychoacoustics. J. Acoust. Soc. Am. *49*, 467–477. https://doi.org/10.1121/1.1912375.

57. Ramirez, L.D., Foster, J.J., and Ling, S. (2021). Temporal attention selectively enhances target features. J. Vis. *21*, 6. https://doi.org/10.1167/jov.21.6.6.

58. Szinte, M., Jonikaitis, D., Rangelov, D., and Deubel, H. (2018). Pre-saccadic remapping relies on dynamics of spatial attention. eLife *7*, e37598. https://doi.org/10.7554/eLife.37598.

59. Tomassini, A., Spinelli, D., Jacono, M., Sandini, G., and Morrone, M.C. (2015). Rhythmic oscillations of visual contrast sensitivity synchronized with action. J. Neurosci. *35*, 7019–7029. https://doi.org/10.1523/JNEUROSCI.4568-14.2015.

60. White, A.L., Boynton, G.M., and Yeatman, J.D. (2019). The link between reading ability and visual spatial attention across development. Cortex *121*, 44–59. https://doi.org/10.1016/j.cortex.2019.08.011.

61. Hanning, N.M., Deubel, H., and Szinte, M. (2019). Sensitivity measures of visuospatial attention. J. Vis. *19*, 17. https://doi.org/10.1167/19.12.17.

62. Brown, G.S., and White, K.G. (2005). The optimal correction for estimating extreme discriminability. Beh. Res. Methods *37*, 436–449. https://doi.org/10.3758/bf03192712.

63. Hautus, M.J. (1995). Corrections for extreme proportions and their biasing effects on estimated values of d′. Beh. Res. Meth. Instr. Comp. *27*, 46–51. https://doi.org/10.3758/BF03203619.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Psychophysical data	This paper	Open Science Framework: https://osf.io/XJH36/
Software and algorithms		
Experimental code	This paper	[Database]: [https://github.com/CarrascoLab/PF_adolescents]
MATLAB R2020b	Mathworks, Natick, MA, USA	http://www.mathworks.com/products/matlab/; RRID:SCR_001622
MGL Toolbox	Gardner et al.[55]	http://justingardner.net/mgl

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Two groups of observers participated in this study: 155 adolescents, 13-17 year-olds (median age = 15.98, mean = 15.64, sd = 1.22; 120 females, 35 males) and 112 adults (median age = 23.79, mean = 28.16, sd = 11.43; 76 females, 32 males, 4 unreported). We did not record participants' ancestry, race, ethnicity, or socioeconomic status. The data for the adults have been previously reported in Carrasco et al.[36] All participants provided written informed consent. The adults were undergraduate or graduate students at New York University and other New York City residents. This study was approved under IRB-FY2016-466 by the Institutional Review Board of New York University.

METHOD DETAILS

Stimuli

Observers viewed a computer display from 57 cm on a 21-in. IBM P260 CRT monitor (1,280 x 960 pixel resolution, 90-Hz refresh rate) calibrated and linearized using a Photo Research (Chatworth, CA, USA) PR-650 SpectraScan Colorimeter. Viewing distance was maintained with a chin-and-forehead rest. On each trial, following a 500 ms fixation period, a target stimulus appeared in one 4 iso-eccentric locations centered at 6.2° eccentricity for 80-120 ms (Figure 1).

The stimulus was a 4 (84%) or 6 (16%) cycles/degree Gabor patch (a sinusoidal grating embedded in a Gaussian envelope), appearing by itself (35%) or amidst 3 distractors (65%), subtending 2° (19%), 3.2° (65.5%) or 4° (15.5%) of visual angle, oriented 20° (34%) or 30° (66%) from vertical. Previous studies with adults have revealed polar angle asymmetries with all these stimulus parameters (e.g.,[2–4,12–14,19,36]). The stimulus contrast was ∼25% for adults and ∼24.5% for adolescents, adjusted individually before and throughout the experiment through an up-down staircase,[56] to yield ∼80% performance accuracy across all locations.

Procedure

The experiment took place in a darkened and sound attenuated room to provide optimal viewing of the displayed stimuli. Observers viewed the display binocularly. We used a 2- alternative forced-choice orientation discrimination task; performance in this task is contingent upon the observers' contrast sensitivity and has been used to characterize performance at different locations (e.g.,[4,19,20,57–60]).

The experimenter instructed observers to fixate on a central point or cross throughout each trial and to indicate whether the stimulus was tilted right (clockwise) or left (counterclockwise) from vertical with a keypress. A feedback tone indicated whether the response had been correct or incorrect after each trial. Instructions stressed accuracy, and there was no time pressure. Each observer performed 1-2 practice block(s) of 40 trials each, and on average, adults performed 77 trials, and adolescents 47 trials, per location.

Observers' eyes were tracked to ensure that they maintained fixation throughout the trial using an EyeLink 1000 Desktop Mount eye tracker (SR Research, Ontario, Canada). If observers broke fixation, the trial would be discontinued and replaced at the end of the block, to ensure that stimulus locations and retinal locations were equated.

QUANTIFICATION AND STATISTICAL ANALYSIS

Discriminability, d' = z(hit rate) minus z(false-alarm rate), was computed for each observer. A hit was (arbitrarily) defined as a left response to a left orientation and a false alarm as a left response to a right orientation.[5,58,61] The log-linear rule correction was applied while estimating d'.[62,63]

Response time (ms) was recorded from stimulus onset until participant's key press. This secondary dependent variable enabled us to assess any potential speed-accuracy tradeoffs. We calculated the geometric mean for each participant.

In all analyses reported, we collapsed across stimulus parameters, as there was no significant difference in the magnitude of the HVA and VMA for the different stimulus parameters between adults or adolescents. There were no significant interactions for the HVA. When there were interactions for the VMA, it was due to being more pronounced for smaller stimuli ($F(2,261) = 8.6974$, $p < 0.001$) and higher spatial frequencies ($F(1,263) = 14.141$, $p < .001$).

To evaluate whether height contributes uniquely to the magnitude of the HVA and VMA independently from age, we regressed out age from these measures and then correlated the residuals with height (e.g.,[20,33]). We computed semi-partial Spearman correlations by first regressing the HVA and VMA magnitudes on age, extracting the raw residuals, and then correlating those residuals with height.