The Stereoscopic Anisotropy Develops During Childhood

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PURPOSE. Human vision has a puzzling stereoscopic anisotropy: horizontal depth corrugations are easier to detect than vertical depth corrugations. To date, little is known about the function or the underlying mechanism responsible for this anisotropy. Here, we aim to find out whether this anisotropy is independent of age. To answer this, we compare detection thresholds for horizontal and vertical depth corrugations as a function of age.

METHODS. The depth corrugations were defined solely by the horizontal disparity of random dot patterns. The disparities depicted a horizontal or vertical sinusoidal depth corrugation of spatial frequency 0.1 cyc/deg. Detection thresholds were obtained using Bayesian adaptive band-pass noise rather than random dots, also concluded that vertical and horizontal stereo corrugations are detected by multiple disparity channels.15 Thus, the single versus multiple disparity channel hypothesis for explaining the stereoscopic anisotropy cannot be sustained.

Another possible explanation of stereoscopic anisotropy relates to the anisotropy of summation fields. Tyler and Kontsevich14 found that summation fields extended only in the horizontal orientation and increased in size as the spatial frequency of the Gabor depth ripples was reduced (aspect ratio 4:1 cycles). They argue that the presence of high contrast vertical contours support stereopsis in vertical objects like branches, whereas for horizontal contours, only the surface texture supports stereoscopic depth. Thus, they suggest that horizontally elongated summation fields are needed to compensate the differences in disparity and luminance information present in natural images. According to this compensation mechanism, if we measure disparity thresholds for vertical and horizontal sinusoidal corrugations of low spatial frequency and low frequencies.5 However, direct tests of this speculation using masking experiments4 have found multiple disparity channels for both orientations. Witz and Hess,12 using spatially

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only one cycle visible then, given that the size of the stimulus is smaller than the predicted summation field for that spatial frequency, we should expect to find higher disparity thresholds for horizontal than for vertical corrugations. Previous results have found exactly the opposite. Using a very low spatial frequency (0.05 cyc/deg) and only one cycle visible, the disparity thresholds for vertical corrugations were higher than for horizontal corrugations. Thus, this anisotropy of summation fields cannot explain the stereoscopic anisotropy.

Recently, van der Willigen et al. suggested that the origin of the stereoscopic anisotropy could be explained by a theoretical analysis of natural images. Having found the opposite orientation stereo anisotropy in barn owls, they explained this result suggesting that the brain could promote the use of disparity gradients, present in natural images, that are behaviorally most relevant. However, this explanation does not state whether the difference in sensitivity to horizontal/vertical disparity corrugations reflects a learnt response to the visual environment or whether it is present from birth.

One way to test this is to measure the stereoscopic anisotropy as a function of age. If this anisotropy changes with age then this would suggest that the anisotropy is not genetically “hardwired,” but develops as a result of exposure to the visual environment. In this research, we measured the stereoscopic anisotropy of 159 participants spanning a large age range (between 3 and 73 years). We compared disparity thresholds for horizontal and vertical corrugations using sinusoidal wave corrugations of low spatial frequency (see Fig. 1). Results revealed that the stereoscopic anisotropy, although present in both children and adults, is stronger for adults than for children. This is the first developmental study of the stereoscopic anisotropy, and represents strong evidence that visual experience plays a critical role in developing and strengthening the orientation stereo anisotropy.

Materials and Methods

We performed two psychophysical experiments, described in detail below. Experiment 1 measured the stereoacuity of the participants and Experiment 2 measured disparity thresholds for detecting vertical and horizontal sinusoidal corrugations.

Subjects

A total of 161 participants (98 female) took part in the experiments. Seventy participants (35 female) were children aged from 3 to 13 years (see Table 1 for details); and 91 participants (63 female) were adults aged from 18 to 73 years. Adults were recruited through Newcastle University’s (Framlington Place, Newcastle upon Tyne, United Kingdom) student population and a participant pool, while children were recruited at the Centre for Life science center (http://www.life.org.uk). All participants (or their parents) reported having normal or corrected to normal visual acuity. All participants completed at least one of the two experiments in this study, but two participants failed to complete Experiment 1 and a different two failed to complete Experiment 2. Thus, we have data from 159 participants in each experiment.

Adult participants were given an instruction sheet to read before completing the two experiments, while children were given oral explanations with the help of cardboard models depicting the depth structure of the stimuli (see Fig. 1). Adult participants, and parents or other accompanying adults of child participants, provided informed written consent. The study protocol was compliant with the Declaration of Helsinki and was approved by the Ethics Committee of the Newcastle University Faculty of Medical Sciences (approval number 00625).

Apparatus

Adult participants were tested in a dark room at Newcastle University and children performed the experiment on the same equipment in a dimmed area at the Newcastle Centre for Life, a public science center. The stimuli were presented on a 47-inch LG 3D monitor (47LD920; LG, Yeouido-dong, Seoul, South Korea) with a screen size of 104 cm × 58.5 cm. This is a patterned-retarder passive 3D monitor, where circular polarization is used to separate the left and right images. The spatial resolution of the monitor was 1920 × 1080 pixels and the refresh rate was 60 Hz. Observers sat at a viewing distance of 200 cm so a pixel subtended 54.65 seconds of arc (arcsec) on average. Adult participants used a forehead and chin rest. Children did not use a headrest, but head position was closely monitored by the experimenter. Observers wore appropriate passive 3D glasses (Sky 3D glasses, Middlesex, UK). Participants recorded their responses by pressing the left or right button of a standard computer mouse. The experiments were conducted using a DELL workstation (DELL, Round Rock, TX, USA), with a NVIDIA Quadro K600 graphics card (NVIDIA, Santa Clara, CA, USA), running Matlab (R2012b; MathWorks, Natick, MA, USA). The experiments were programmed using Psychophysics Toolbox extensions15–17 (in the public domain, www.psychtoolbox.org).

Stimuli

The 3D was rendered with the monitor in standard 2D mode, using the line-interleaved stereo mode of Psychtoolbox’s Psychimaging function. That is, our software generated left...
and right stimuli each 1920 pixels wide by 540 high, and interleaved them row by row to produce a single 1920 × 1080 image to send to the monitor.

The stimuli were dynamic random-dot stereograms consisting of bright dots on a black background. In order to make the stimulus more visually appealing for children, each dot was given a color generated by choosing the Red, Green, and Blue values independently from a uniform distribution between minimum and maximum luminance. Dots could overlap and occlude one another when they did so. The dots were drawn using Psychtoolbox’s “Screen (‘DrawDots’)” function, specifying circles 10 pixels in diameter with high-quality antialiasing. Because of the line interleaving, the dots appeared as ellipses on-screen, with a width of 10 pixels and a height of 20 physical pixels (9 × 18 arcmin). The dot density was such that if none of the dots had occluded each other, they would have occupied 16% of the stimulus; a stimulus filling the screen contained 2074 dots (density of 4.27 dots/deg²).

**Figure 2.** Anaglyph versions of the stimuli used in the experiments (for correct viewing, place the red filter in front of the left eye). In the real stimuli, dots were presented on a black background and there were no axis labels or numbers. (A) Stereoacuity experiment. The left panel contains the signal (disparate patch). The sketches above represent the expected 3D percept. (B) Horizontal/vertical corrugations. The left anaglyph corresponds to a vertical corrugation. The right anaglyph corresponds to a horizontal corrugation. The spatial frequency is 0.1 c/deg. The panels with the lines represent the disparities shown in the anaglyphs. The corresponding 3D percepts are shown in the top right part of the figure.
The disparity structure of the stimuli is described for each experiment below. On each trial, the disparity structure of the stimulus remained constant, but the dot pattern was updated (new random positions and colors) every frame (i.e., at 60 Hz). The stimulus was displayed until the subject made a response. No feedback was provided about correctness.

Threshold Estimation

As in many aspects of perception, disparity thresholds are distributed roughly normally in log-space rather than linear. We accordingly work in log-disparity throughout; for example we report the geometric rather than the arithmetic mean of stereo thresholds in arcsec, which corresponds to the arithmetic mean of log thresholds.

To obtain participants’ 75% threshold, we used a Bayesian staircase procedure, with some modifications designed to help child participants. For the likelihood function we used the logistic function of log-disparity (see details in the Supplementary information). The prior on the first trial was a uniform distribution between $x_{\text{min}} = \log_{10}(0.5 \text{ arcsec})$ and $x_{\text{max}} = \log_{10}(3600 \text{ arcsec})$. The posterior distribution on the threshold was updated after each trial by multiplying the prior by the likelihood function: $L = \Psi(x; \theta)$ for correct responses and $L = (1-\Psi(x; \theta))$ for incorrect responses, where $x$ is the log-disparity just presented. The posterior after $n$ trials was taken to be the prior after $n-1$ trials.

The stimulus disparity was set to be the mean of the currently-estimated posterior distribution, in the usual way. The staircase disparity proceeds, this becomes closer and closer to the true threshold, meaning that on most trials the target is not clearly visible to the participant, even if they are performing well above chance. We have found that naive participants, especially children, can become demotivated as a result, and that it is helpful to include “easy trials” with a clearly visible stimulus. Accordingly, on each trial in this study, there was a 0.25 probability that the stimulus disparity would be chosen independently of the staircase and set to a value designed to be clearly visible. The results of these easy trials was still used to update the staircase. In most cases, the participant answered correctly and our estimate of the threshold barely changed. However, a wrong answer on an “easy trial” would cause our threshold estimate to increase, affecting the value chosen for the subsequent trial. The threshold estimate was taken to be the mean of the posterior distribution after 40 trials. The 68% confidence limits on this estimate were taken to be the 16% and 84% percentiles of this distribution and are used to draw error bars in the results figures.

Experiment 1: Stereoacuity

Each participant first completed a measure of stereoacuity on a two-alternative forced choice (2AFC) disparity-detection task. Here, the random dot pattern covered the whole of the screen. The target was presented on one side of the screen (left or right). The target consisted of a square patch of dots $480 \times 480$ pixels ($7.3^\circ \times 7.3^\circ$), that had a crossed disparity relative to the background dots (see Fig. 2A). The stimulus disparity was defined as the relative disparity between the square target and background. The target and background had equal and opposite disparity relative to the screen. This avoided monocular cues to target location if the viewer removed their glasses (if the background is in the screen plane and the target in front, the target appears blurred when viewed without glasses). Participants were asked to indicate which side (left or right) of the screen contained the target square.

To familiarize participants with the task, the first five trials had a large disparity (1800 arcsec) and a nonstereo color/luminance cue. These trials were not, of course, used to update the estimate of disparity threshold. On the first trial, the target dots were colored red, and the saturation of the red tinge was reduced over the next four trials. On the sixth trial, there was no color cue and the disparity was reduced to 42 arcsec, the mean of the initial prior distribution. Thereafter, the staircase proceeded as described above. If, however, the mean of the posterior distribution for threshold exceeded 400 arcsec, we began to mix in easy trials with a nonstereo cue (target dots colored red) to check the participant’s understanding of the task. The probability that the next trial would contain a nonstereo cue was 50% when the mean of the posterior exceeded 1000 arcsec, 0% for less than 400 arcsec, and rose linearly from 0% to 50% as a function of mean-posterior from 400 to 1000 arcsec. We consider that threshold estimates

| Age Group | Age, y | Participants | Stereo Threshold Available | H and V Thresholds Available |
|-----------|-------|--------------|---------------------------|-----------------------------|
| Children  | 3     | 2            | 2                         | 1                           |
|           | 4     | 3            | 3                         | 3                           |
|           | 5     | 9            | 7                         | 9                           |
|           | 6     | 9            | 9                         | 8                           |
|           | 7     | 6            | 6                         | 6                           |
|           | 8     | 8            | 8                         | 8                           |
|           | 9     | 14           | 14                        | 14                          |
|           | 10    | 8            | 8                         | 8                           |
|           | 11    | 5            | 5                         | 5                           |
|           | 12    | 5            | 5                         | 5                           |
|           | 13    | 1            | 1                         | 1                           |
|           | 14    | 1            | 1                         | 1                           |
|           | 15    | 1            | 1                         | 1                           |
|           | 16    | 1            | 1                         | 1                           |
|           | 17    | 1            | 1                         | 1                           |
|           | 18    | 13           | 13                        | 13                          |
|           | 19    | 19           | 19                        | 19                          |
|           | 20    | 13           | 13                        | 13                          |
|           | 21    | 4            | 4                         | 4                           |
|           | 22    | 4            | 4                         | 4                           |
|           | 23    | 2            | 2                         | 2                           |
|           | 24    | 2            | 2                         | 2                           |
|           | 25    | 1            | 1                         | 1                           |
|           | 26    | 1            | 1                         | 1                           |
|           | 27    | 2            | 2                         | 2                           |
|           | 28    | 3            | 3                         | 3                           |
|           | 29    | 2            | 2                         | 2                           |
|           | 30    | 1            | 1                         | 1                           |
|           | 31    | 1            | 1                         | 1                           |
|           | 32    | 1            | 1                         | 1                           |
|           | 33    | 1            | 1                         | 1                           |
|           | 34    | 1            | 1                         | 1                           |
|           | 35    | 1            | 1                         | 1                           |
|           | 36    | 1            | 1                         | 1                           |
|           | 37    | 1            | 1                         | 1                           |
|           | 38    | 1            | 1                         | 1                           |
|           | 39    | 1            | 1                         | 1                           |
|           | 40    | 1            | 1                         | 1                           |
|           | 41    | 1            | 1                         | 1                           |
|           | 42    | 1            | 1                         | 1                           |
|           | 43    | 1            | 1                         | 1                           |
|           | 44    | 1            | 1                         | 1                           |
|           | 45    | 1            | 1                         | 1                           |
|           | 46    | 1            | 1                         | 1                           |
|           | 47    | 1            | 1                         | 1                           |
|           | 48    | 1            | 1                         | 1                           |
|           | 49    | 1            | 1                         | 1                           |
|           | 50    | 1            | 1                         | 1                           |
|           | 51    | 1            | 1                         | 1                           |
|           | 52    | 1            | 1                         | 1                           |
|           | 53    | 1            | 1                         | 1                           |
|           | 54    | 1            | 1                         | 1                           |
|           | 55    | 1            | 1                         | 1                           |
|           | 56    | 1            | 1                         | 1                           |
|           | 57    | 1            | 1                         | 1                           |
|           | 58    | 1            | 1                         | 1                           |
|           | 59    | 1            | 1                         | 1                           |
|           | 60    | 1            | 1                         | 1                           |
|           | 61    | 2            | 2                         | 2                           |
|           | 62    | 2            | 2                         | 2                           |
|           | 63    | 1            | 1                         | 1                           |
|           | 64    | 1            | 1                         | 1                           |
|           | 65    | 1            | 1                         | 1                           |
|           | 66    | 1            | 1                         | 1                           |
|           | 67    | 2            | 2                         | 2                           |
|           | 68    | 3            | 3                         | 3                           |
|           | 69    | 1            | 1                         | 1                           |
|           | 70    | 1            | 1                         | 1                           |
|           | 71    | 1            | 1                         | 1                           |

For each year of age, columns give the number of participants who completed any experiment, the number who completed the stereoacuity experiment (Experiment 1), and the number who completed the correlation experiment (Experiment 2).

TABLE 1. Age Distribution of Participants
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We measured the disparity amplitude, defined as half the relative disparity between peaks and troughs, required for performance at 75% correct. Since participants were by now familiar with the depth percept from the 3D monitor, we did not include any nonstereo cues in this experiment, although we continued to mix in 25% of “easy trials” as described above. Each threshold was estimated from 40 trials. Trials with horizontal and vertical corrugations were interleaved at random, so each participant completed 80 trials in this experiment (except for 3 participants who stopped early, after 60, 60, and 71 trials).

For each participant we computed an anisotropy index, defined as the log_{10} ratio of the detection thresholds for vertical versus horizontal corrugations.

RESULTS

Stereocuity: Distribution and Age-Dependence

Figure 3 shows the results of Experiment 1. Figure 3 plots the stereocuity thresholds as a function of age. Three of 159 subjects (2%) who performed the experiment had a threshold over 1000 arcsec (white dots), which is too poor to be measured accurately and should be considered “nil stereo,” so we did not consider these thresholds in the statistical analysis. The literature contains widely varying estimates of the prevalence of stereoblindness, but 2% is typical.23,24 Thresholds in the remaining 156 subjects ranged from 1.4 arcsec to 565 arcsec. Table 2 shows the means and the SDs for three different age groups: children (3–13 years), young adults (aged 18–32 years), and older adults (39–73 years).

We see an improvement in measured stereocuity between 3 years and 13 years (Pearson correlation coefficient on log_{10}[thresholds] versus log_{10}[age]: r = -0.348, P = 0.003, N = 68), then no change between 18 years and 32 years (r = -0.05, P = 0.67, N = 66), and a decline between 39 years and 73 years (r = 0.314, P = 0.15, N = 22). We performed a one-way ANOVA in order to compare the means (obtained from log_{10}[thresholds]) of the three age-groups. We found a significant effect of group age on stereocuity, (F_{2,155} = 10.49, P < 0.001). Post hoc analysis for multiple comparisons using the Bonferroni critical value showed a significant difference between children and young adults, and between young and older adults.

Disparity Thresholds for Horizontal and Vertical Corrugations

Figures 4A and 4B plot the disparity amplitude threshold needed to detect a disparity corrugation (horizontal or vertical) against the stereocuity threshold needed to detect a disparity-defined square. The gray-dashed lines mark 1000 arcsec. Points

![Diagram](https://via.placeholder.com/150)

**Figure 3.** Results from Experiment 1. Stereocuity thresholds (arcsec) as a function of age (years) for 159 subjects. Error bars represent the 68% confidence interval. The upper dashed line marks 1000 arcsec; thresholds above this are shown with white symbols. The limits of the vertical axis are the bounds of the posterior used in our staircase procedure (i.e., 0.5–3600 arcsec).

We assume the distribution of stereocuity is roughly Gaussian when expressed as log_{10}(threshold in arcsec). We therefore cite the mean and SD of our data expressed in log_{10} (threshold in arcsec). In the penultimate column, we convert this mean back to a threshold in arcsec. In the final column, we convert the SD in log space to a range of threshold values. We quote 10^{2*SD}, which is the factor spanned by the central 68% of the distribution. That is, someone at the 84% percentile will have a threshold 10^{2*SD} as large as someone at the 16% percentile.

### Table 2. Means and SDs of the Stereocuity Thresholds in Our Data Set, Divided by Age-Group, Excluding 3 Stereoblind Individuals (Thresholds > 1000 arcsec)

| Age Group | Number of Subjects | log_{10} (Stereocuity in arcsec) Mean | SD | Geometric Mean | Factor Spanned by Central 68% |
|-----------|--------------------|-------------------------------------|----|---------------|-----------------------------|
| Children: 3–13 y | 68 | 1.141 | 0.355 | 25.79 | 5.09 |
| Young adults: 18–32 y | 66 | 1.208 | 0.312 | 16.15 | 4.21 |
| Older adults: 39–73 y | 22 | 1.556 | 0.415 | 35.99 | 6.76 |

The distribution of stereocuity is roughly Gaussian when expressed as log_{10}(threshold in arcsec). We therefore cite the mean and SD of our data expressed in log_{10} (threshold in arcsec). In the penultimate column, we convert this mean back to a threshold in arcsec. In the final column, we convert the SD in log space to a range of threshold values. We quote 10^{2*SD}, which is the factor spanned by the central 68% of the distribution. That is, someone at the 84% percentile will have a threshold 10^{2*SD} as large as someone at the 16% percentile.
in the square region within these lines represent participants for whom we measured a threshold less than 1000 arcsec on both tests. Participants beyond these lines could not perform one or both tests reliably, and are therefore excluded from the following analysis. The $N$ at the top left of each panel in Figure 4 gives the total number of participants for whom data were collected; the $N$ at the bottom right gives the number after exclusion.

Figure 4A shows the results for horizontal corrugations. Horizontal corrugation thresholds and stereoacuity thresholds are moderately correlated (Pearson correlation coefficient on the log-thresholds: $r = 0.43$, $P < 0.001$, $N = 150$) as one would expect because both assess the quality of stereo vision. In fact, the two thresholds are not significantly different ($t[149] = 0.59$, $P = 0.55$, paired-sample $t$-test on log-thresholds). This is despite the fact that the stereoacuity threshold is defined as the relative disparity between the target and background, whereas the disparity amplitude threshold is half the relative disparity between the peaks and troughs of the waves, so one might have expected the disparity amplitude threshold to be half the stereoacuity threshold. Yet a $t$-test firmly rejects this hypothesis ($t[149] = -9.57$, $P < 0.001$, paired-sample $t$-test on log-threshold of horizontal corrugation amplitude threshold and log-half-threshold of stereoacuity).

Figure 4B shows the results for vertical corrugations. As expected given the stereo anisotropy, thresholds on the vertical corrugation detection task are much larger. The geometric mean threshold is 61.83 arcsec for vertical corrugations, compared with 20.58 arcsec for horizontal and 22.17 arcsec for stereoacuity. This difference is highly significant (paired-sample $t$-test comparing log-thresholds for vertical corrugations versus horizontal corrugations, $t[150] = 11.77$, $P < 0.001$, or versus stereoacuity, $t[148] = 10.87$, $P < 0.001$, including only thresholds <1000 arcsec).

Despite the higher thresholds on the vertical corrugation task, performance is slightly correlated both with thresholds on the horizontal corrugation task (Fig. 4C: $r = 0.20$, $P = 0.01$, $N = 151$) and with stereoacuity (Fig. 4B: $r = 0.17$, $P = 0.04$, $N = 149$).

Stereo Anisotropy: Age-Dependence

Figures 5A and 5B show the results for horizontal and vertical corrugations, respectively, as a function of age. Figure 5A shows that, remarkably, horizontal corrugation thresholds are not correlated with age (Pearson correlation coefficient on the log-thresholds: $r = -0.004$, $P = 0.96$, for thresholds < 1000 arcsec). We performed a one-way ANOVA to compare the
horizontal thresholds ($\log_{10} [\text{thresholds}]$; thresholds $< 1000$ arcsec) for the three age groups specified in Table 2. We did not find significant differences ($F_{2,149} = 0.74$, $P = 0.479$; mean$_{\text{Children}} = 1.324$ [21.1 arcsec], SD$_{\text{Children}} = 0.29$, $N_{\text{Children}} = 68$; mean$_{\text{Adults}} = 1.28$ [19.1 arcsec], SD$_{\text{Adults}} = 0.35$, $N_{\text{Adults}} = 64$; mean$_{\text{OAdults}} = 1.379$ [23.9 arcsec], SD$_{\text{OAdults}} = 0.37$, $N_{\text{OAdults}} = 20$). We also compared horizontal thresholds ($\log_{10} [\text{thresholds}]$; thresholds $< 1000$ arcsec) across participants in two groups, children ($\leq 13$ years) and adults ($\geq 18$ years). Again, we did not find significant differences ($t_{150} = 0.36$, $P = 0.713$, two-sample $t$-test; mean$_{\text{Children}} = 1.324$ [21.1 arcsec], SD$_{\text{Children}} = 0.29$, $N_{\text{Children}} = 68$; mean$_{\text{Adults}} = 1.30$ [19.95 arcsec], SD$_{\text{Adults}} = 0.36$, $N_{\text{Adults}} = 84$). Thus, interestingly, although children performed significantly worse than adults in the stereoacuity task (see Fig. 3), no difference was found for horizontal thresholds.

Figure 5B shows a mild but significant correlation between disparity thresholds for vertical corrugations and age (Pearson correlation coefficient on the log-thresholds: $r = 0.243$, $P = 0.002$, for thresholds $< 1000$ arcsec). We used ANOVA to compare vertical corrugation thresholds ($\log_{10} [\text{thresholds}]$; thresholds $< 1000$ arcsec) for the three age groups (3–13 years, 18–32 years, and 39–73 years). We found significant differences ($F_{2,148} = 5.829$, $P = 0.0036$; mean$_{\text{Children}} = 1.66$ [45.80 arcsec], SD$_{\text{Children}} = 0.37$, $N_{\text{Children}} = 67$; mean$_{\text{Adults}} = 1.87$ [74.41 arcsec], SD$_{\text{Adults}} = 0.51$, $N_{\text{Adults}} = 64$; mean$_{\text{OAdults}} = 1.97$ [95.47 arcsec], SD$_{\text{OAdults}} = 0.32$, $N_{\text{OAdults}} = 20$). Post hoc comparisons using the Bonferroni critical value showed significant differences between children (3–13 years) and young adults group (18–32 years) and between children (3–13 years) and older adults (39–73 years). We also compared vertical thresholds ($\log_{10} [\text{thresholds}]$; thresholds $< 1000$ arcsec) across participants in two groups, children ($\leq 13$ years) and adults ($\geq 18$ years). We found significant differences ($t_{149} = -3.29$, $P = 0.001$, two-sample $t$-test; mean$_{\text{Children}} = 1.66$ [45.8 arcsec], SD$_{\text{Children}} = 0.37$, $N_{\text{Children}} = 67$; mean$_{\text{Adults}} = 1.89$ [78.55 arcsec], SD$_{\text{Adults}} = 0.476$, $N_{\text{Adults}} = 84$). Thus, for vertical corrugations, children performed better than adults. This is remarkable given that in the stereoacuity task children performed worse than adults.

To quantify the stereoscopic anisotropy, we define the anisotropy index to be the $\log_{10}$ ratio of the detection thresholds for vertical versus horizontal corrugations (see Figs. 5A, 5B). This is only meaningful for subjects who could perform both tasks, so the analysis reported in this section excludes 8 of 159 participants whose threshold on either corrugation task (see Fig. 4C), exceeded 1000 arcsec. The mean anisotropy index is 0.48 (SD = 0.5, $N = 151$). This means that on average, the detection threshold for vertical corrugations of 0.1 cyc/deg is a factor of 3 higher than for horizontal corrugations. This anisotropy index is highly significantly different from zero ($t_{150} = 11.76$, $P < 0.001$, $t$-test). It is not significantly correlated with stereoacuity ($r = -0.154$, $P = 0.06$, Pearson’s correlation coefficient, $N = 149$ nonstereoblind

![Figure 5](image-url)


Discussion

Previous studies on the development of stereopsis have measured vergence, sensitivity to binocular correlation and, overwhelmingly, stereoacuity. Here, we assess the stereoscopic anisotropy (i.e., the greater sensitivity for horizontal depth corrugations [or to slant about a horizontal axis] than for vertical corrugations). To our knowledge, this is the first study to examine, across the lifespan, any property of stereopsis other than stereoacuity. We find that the orientation stereo anisotropy is present in childhood at the earliest ages we were able to examine (i.e., 3–5 years). However, it is more pronounced in adults (≥18 years) than in children (≤13 years). This difference implies that the stereo anisotropy increases during development.

Our confidence in this result is increased by the fact that the study reported here is our third study to find this result. Two pilot studies, using slightly different stimuli and methodology, each found the same basic result: a positive correlation between stereoscopic anisotropy and age, and a highly significant difference between the stereo anisotropy indices of children versus adults. Together, these studies contain data on 302 participants. Details of these studies are provided in the Supplementary Material.

Detecting Corrugations

For horizontal corrugations, stereoacuity thresholds (i.e., the relative disparity between target and background) agreed with the disparity amplitude threshold (i.e., the relative disparity between peaks/troughs and zero disparity). Stereoacuity did not agree with the relative disparity between peaks and troughs of the corrugation. This suggests that, at least for the low frequency used here, corrugations are detected by comparing peaks and troughs to a zero-disparity reference (e.g., the other patch [Fig. 2B] or the sides of the monitor). However, this alone would not explain why the thresholds for vertical corrugations were so much higher, as described below, because the same strategy would have been available (using the top and bottom of the monitor as a reference, rather than its sides).

Individual Differences in Stereo Anisotropy

Like other aspects of stereovision, stereo anisotropy is highly variable between individuals (Figs. 5, 6). This may explain why we could not detect a gradual increase in anisotropy throughout childhood or indeed adulthood. An additional problem is that we lack data between the ages of 13 and 18 years, reflecting the visitor demographics of the science center where the experiment was performed. The correlation between anisotropy index and age is thus driven mainly by the difference between preteen children and adults. Part of the reason for the wide variability in our study will certainly be the small number of trials on which each threshold was based: just 35. This was necessary in order to ensure that we could measure anisotropy in very young children, who are rarely willing to complete the hundreds of trials necessary for a really rigorous measure. However, other studies have also reported that the stereoscopic anisotropy shows wide variability between adult observers.11 Hibbard et al.13 computed thresholds as the mean estimates from three independent 3-up, 1-down staircases, compared with our single 35-trial staircase. By taking the logarithm of data in their Figure 3C, we deduce that the SD of the anisotropy index was 0.38 in their study, as compared with 0.55 in our 84 adults. At the extremes, 14% (6/42) of their young adult observers showed an anisotropy in the opposite direction (better for a vertical than a horizontal axis).
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(Hibbard et al. say in their text that “5 out of the 42 observers showed a small anisotropy in the opposite direction,” but they must mean “a significant anisotropy,” since it is clear from their data figures that in fact 6 observers have a measured ratio < 1.) This agrees well with our results using a different stimulus and task (11% [9/84] of our adults and 16% [11/67] of our children showed opposite anisotropy). This confirms that the variability in our data is not simply due to measurement error. Rather, although the stereoscopic anisotropy is a robust phenomenon at the population level, individuals show considerable variation, implying that the developmental forces favoring anisotropy must be fairly weak. Intriguingly, individuals who are more sensitive to orientation differences than to spatial frequency differences in luminance are also more likely to show a strong stereoscopic anisotropy,11 presumably reflecting the fact that slant of a physical surface about a vertical axis introduces spatial frequency differences between the two eyes, whereas inclination about a horizontal axis introduces orientation differences.

It appears in Figures 4A and 4B that the interindividual variability in detection threshold may be larger for vertical corrugations than horizontal. This agrees with a previous study of slant thresholds11, observers showed greater variability in their ability to discriminate disparity-defined rotation of an originally frontoparallel plane about a vertical axis than about a horizontal axis.31 However, in our data the larger SD reflects the larger mean. If we consider coefficient of variation on log threshold (CV = SD[log-thresholds]/mean[log-thresholds]), there is little difference between the three tasks (CV = 0.25 for both vertical and horizontal corrugation detection, 0.27 for stereoeacuity, considering only thresholds < 1000 arcsec. Including thresholds > 1000 arcsec increases the CV to about 0.36 for horizontal, 0.3 for vertical, and 0.35 for stereoeacuity, but again reveals little difference between tasks.)

Effect of Visual Acuity

Poor visual acuity, interocular acuity differences, and latent or manifest binocular misalignment can all affect stereopsis. Because we were already requiring young children to complete approximately 100 psychophysical trials, it was not feasible to include measurements of these quantities. We did measure stereoeacuity, and excluded from analysis participants whose stereo threshold exceeded 1000 arcsec. We know that visual acuity improves up to the age of approximately 10, so if we had measured it, doubtless we would have found that our child participants had worse visual acuity than our young adults, as well as worse stereoeacuity. Given the known links between visual acuity and stereoeacuity,25 the age-related improvement in stereoeacuity probably at least partly reflects the age-related improvement in visual acuity. However, in our data the larger SD reflects the larger mean. If we consider coefficient of variation on log threshold (CV = SD[log-thresholds]/mean[log-thresholds]), there is little difference between the three tasks (CV = 0.25 for both vertical and horizontal corrugation detection, 0.27 for stereoeacuity, considering only thresholds < 1000 arcsec. Including thresholds > 1000 arcsec increases the CV to about 0.36 for horizontal, 0.3 for vertical, and 0.35 for stereoeacuity, but again reveals little difference between tasks.)

The Reasons for the Stereoscopic Anisotropy

The reason for the stereoscopic anisotropy is still unclear. Other visual anisotropies have been related to the statistical distribution of the natural environment. For example, with luminance gratings, humans are more sensitive to orientations close to vertical or horizontal than to oblique orientations (the oblique effect). This effect could be related to the predominance of horizontal and vertical luminance edges in natural scenes. However, using broad-band oriented stimuli, the sensitivity was higher for oblique orientations and worst for horizontal orientations (the horizontal effect). Thus, in this case, it is not clear whether the visual system develops to match the most prevalent orientations in the visual world or whether the visual system perceptually discounts the most prevalent orientation in order to accommodate to the natural anisotropy. Regarding stereopsis, Sprague et al. recently showed that the horizontal and vertical disparities to which the visual system is most sensitive are those most commonly encountered in natural active viewing. To achieve this tuning, many aspects of the visual system are not genetically hard-wired, but depend critically on visual experience. The fact that the stereo anisotropy strengthens during development could also imply that it develops as an individual samples the natural environment. Our results show that although the sensitivity to horizontal corrugations does not change, or indeed slightly improves, with age, the sensitivity to vertical corrugations declines with age across the lifespan. Given that the stereoscopic anisotropy has been found mainly with low spatial frequency gratings (or slanted surfaces), an image-statistical account of the stereo anisotropy would require that in natural scenes, low-frequency disparity components are more common at horizontal orientations than at vertical (whereas high-frequency components are equally common at horizontal and vertical orientations). No one has yet produced evidence of such a difference.

It is also possible that the stereoscopic anisotropy may reflect differences in the functional significance, rather than frequency, of disparity gradients. For example, apparent rotation of a frontoparallel surface about a horizontal axis might occur because the viewer has swayed slightly forward or backward on their feet or because their head has tilted up or down on their neck (pitch). Detecting such a change could be important in maintaining postural stability. On the other hand, rotation about a vertical axis would occur if the person’s head rotated on their neck (yaw). If unintended changes in pitch are more challenging to avoid than yaw, it might make sense to design the system to be more sensitive to visual cues indicating pitch than yaw.

Stereoeacuity Across the Lifespan

Although our sample is concentrated mainly on children and younger adults, our results are similar to previous reports about the development and decline of stereoeacuity using standard clinical tests. We compared three different age-groups: “children” (3–13 years), “young adults” (18–32 years), and “older adults” (39–75 years). We found significant differences between young adults and children or older adults. Our results are consistent with previous studies, which reported an improvement in measured stereoeacuity until
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Stereopsis emerges in the first 11 and 18 weeks of life. Stereovisuality improves rapidly and reaches near adult levels at approximately 2 years of age, although improvement continues until around the age of 10, when visual maturation is generally considered to be complete (though recently, Giachetti et al. found that stereo thresholds in adults were significantly better than even 12- to 14-year-olds). At least part of the apparent improvement in stereovisuality from early childhood to approximately age 10 years is due to the age-dependent changes in the visual system. The stereo anisotropy emerges in early childhood but grows stronger with age. Although stereovisuality improves throughout early childhood and remains constant from visual maturation until old age, children are significantly better than adults at detecting vertical depth corrugations. Sensitivity to disparity gradients emerges in parallel, initially with roughly isotropic sensitivity to disparity gradients along all axes. However, long after stereovisuality has stabilized, neural resources continue to be reallocated from detecting disparity gradients along horizontal axes to detecting disparity gradients along vertical axes.

CONCLUSIONS

The stereo anisotropy emerges in early childhood but grows stronger with age. Although stereovisuality improves throughout early childhood and remains constant from visual maturation until old age, children are significantly better than adults at detecting vertical depth corrugations. Sensitivity to disparity gradients emerges in parallel, initially with roughly isotropic sensitivity to disparity gradients along all axes. However, long after stereovisuality has stabilized, neural resources continue to be reallocated from detecting disparity gradients along horizontal axes to detecting disparity gradients along vertical axes.

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