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Abstract

The light-from-above prior enables observers to infer an object's three-dimensional shape-from-shading information. Young, Western adults implicitly assume the light source is placed not only above, but also to the left of, the observer. Previous evidence reached conflicting conclusions regarding the development of the assumed light source direction. In the present study, we measured the light source prior cross-sectionally in children aged 5-11 years, using an explicit shape judgement task. The light-from-above prior, and the left bias, were present as soon as children became sensitive to shading information, regardless of their age. Global processing preference was not related to the ability to perform the task. Similarly, scanning habits, as measured by reading proficiency and starting position in a cancellation task, were not related to the magnitude of the left bias. Children's ability to report shape-from-shading judgements increased with age, but age did not affect the direction of light priors. Thus, we concluded that the development of the light-from-above prior and leftward bias do not require an extended maturation period, but rather the direction of the light-source priors may be developmentally stable once measurable.

Keywords: Shape-from-shading; perceptual development; light source prior; 3D perception

1. Introduction

Shading refers to the pattern of luminance changes across a visible surface, and is a cue informative of an object's three-dimensional shape. Shading depends upon the local surface shape and the direction of the light source illuminating the object; for example, convex surfaces lit from above are light at the top and dark at the bottom, whereas concave surfaces have an opposite shading pattern. Observers must, therefore, account for the direction of light when interpreting the shape of an object from its shading information. When the direction of the light source is unknown, adult observers implicitly assume it is located above the object (Ramachandran, 1988). This assumption is demonstrated by observers categorizing two-dimensional shaded stimuli as convex when they are brighter at the top and concave when brighter at the bottom, corresponding with the patterns of light and shadow cast upon on objects under natural lighting conditions.

1.1 Development of Shape-from-Shading

It remains unclear whether the light prior is innate or learned. Benson and Yonas (1973) and Yonas, Kuskowski, and Sterfels (1979) demonstrated that children as young as three years of age were able to perceive shape-from-shading in keeping with a light from above prior. Using a preferential reaching task to assess infants' ability to distinguish an object's 3D shape, Granrud, Yonas, and Opland (1985) found that five and seven-month-old infants preferentially reached for convex protrusions rather than concave indentations. However, only seven-month-olds reached more readily toward photographs of shaded convexities. This suggests that a convexity bias may be present early in development, and that human observers become able to interpret shading gradients to perceive 3D shape in pictorial stimuli, from around seven months of age (see also Imura et al., 2008 and Kavšek, Yonas, & Granrud, 2011 for a review on the development of pictorial depth cues, including shading).

Yet more recent studies, such as Thomas, Nardini, and Mareschal (2010), suggested the ability to make explicit judgments of shape-from-shading has a more protracted developmental trajectory. They found that children under seven years of age could not reliably report the apparent 3D shape of shaded pictorial stimuli, favoring convex interpretations. Children only began using shading cues, in keeping with an overhead light source assumption, after the age of seven. The authors concluded that, in young children, the convexity bias dominates when interpreting 3D shape. Stone (2011) also found that children show a protracted developmental trajectory and confirmed that seven-year-old children seem insensitive to shading cues. Taken together, these more recent findings support the idea that human observers may require extensive visual experience for the acquisition of a light-from-above prior.

1.2 Assumed Light Source is Shifted Leftward

Interestingly, previous studies revealed that observers assume the light source is not only placed above, but also leftward of the zenith (e.g., Sun & Perona, 1998). Leftward biases have been replicated across laboratories (Andrews et al., 2013; Gerardin, Kourtzi, & Mamassian, 2007; Mamassian & Goutcher, 2001), although its magnitude may vary in different tasks (Adams, 2007).

Whilst an overhead light source assumption is consistent with our experience of the world, it is not clear why the assumed light direction is shifted leftward. Two explanations have been the focus of recent literature. The first is that the left bias reflects attentional and perceptual processes lateralized to the right hemisphere; and the second, that both the light-from-above prior and the leftward bias reflect the observer’s experience. The evidence supports both of these accounts. Neuroimaging and electrophysiological data have shown that a right lateralized network is involved in the perception of shape-from-shading (Taira et al., 2001; Mamassian et al., 2003; Halligan et al., 2003). Moreover, right hemisphere stroke patients show a diminished left bias of the assumed light source direction (De Montalembert, Auclair, & Mamassian, 2010). Support for the second hypothesis comes from two sources of evidence; firstly, in adults, the assumed light direction was found to be modified by experience (Adams, Graf, & Ernst, 2004), and cultural factors (Andrews et al., 2013). Secondly, children increasingly assumed the light to be above and left when making shape judgements after age seven, reaching adult-like performance around age ten (Thomas et al., 2010), suggesting the acquisition of the light source prior requires extensive visual experience.

1.3 Global Processing and Reading

The gradual change in the light-from-above prior and the leftward bias in Thomas et al.'s study (2010) was based on cross-sectional comparisons and included many children who produced random shape judgements. Inconsistent performance was attributed to a weak light-from-above prior. Similarly, Stone (2011) concluded that young children have a weak prior, leading to inconsistent shape judgements of shaded surfaces. However, two issues emerge from this interpretation. Firstly, the group-level changes presented by Thomas et al. and Stone cannot disambiguate whether these changes represent a gradually increasing reliance on the light-from-above prior in individual children, or if instead the ability to use the prior is acquired rapidly at an age that varies between children, manifesting in age-related changes at the group level. Secondly, children may be unable to provide explicit shape judgments for reasons other than immature priors. For example, Thomas et al.'s study used a complex stimulus that required the observer to process the global configuration to report its 3D shape. However, the age at which processing preferences shift from global to local (Dukette & Stiles, 2001) coincides with the age at which Thomas et al. detected the increasing influence of the overhead lighting prior, and the emergence of the leftward light source bias. Interestingly, in a pilot study we observed that some of the children assigned different depth values to the same surface element according to the brightness of the specific edge they focused on, suggesting that they did not integrate depth along the local contours into an hierarchically global form. Therefore, the near-chance performance among the youngest children might not reflect the immaturity of the overhead lighting prior, but rather an inability to process the global aspect of the stimulus.

If the age-related increases in the leftward bias observed by Thomas et al. (2010) and Stone (2011) does indeed indicate a gradual development of the light source prior, it may be related to increasing reading experience, given that the change in the leftward bias observed by Thomas et al. coincided with the age at which children's reading proficiency increases (Seymour et al., 2003). Indeed, many lateralized biases have been shown to be influenced by an individual's habitual reading direction: left-to-right readers have a leftward bias in tasks such as line bisection (Rinaldi, et al., 2014), number line processing (Shaki, Fischer, & Petrusic, 2009), and the light source bias (Andrews et al., 2013). Moreover, habitual reading direction alters typically leftward spatial biases in a number of non-linguistic tasks, generating rightward biases in right-to-left readers (e.g., Chokron & De Agostini, 2000; Chokron & Imbert, 1993). However, if the development of the leftward bias does not depend upon visual experience such as scanning habits, changes in the assumed light source direction should not be related to reading experience. Andrews et al. (2013) found that Israeli participants, who read from right-to-left, exhibited a reduced leftward bias rather than a rightward bias when making shape-from-shading judgements; furthermore, Smith and Elias (2013) found non-significant right-lighting preferences in right-to-left readers, compared with significant left-lighting preferences in left-to-right readers. Therefore, the variability in visuospatial biases in right-to-left readers, contrasted with the consistent leftward bias in left-to-right readers (Andrews et al., 2013; Rinaldi et al., 2014; Shaki et al., 2009), suggests that the leftward bias is a developmental default that may be modulated by opposite scanning habits.

1.4 The Current Study

In this study, we aimed to determine the relations of age, global processing, convexity bias, and reading proficiency to the development of the light source bias in children aged from five to eleven years. Because the reason young children previously exhibited a weak light-from-above prior is unclear, we measured children's ability to complete the task using a "sensitivity" measure and tested to what extent the ability to judge shape-from-shading correlated with the preference to process visual stimuli globally. Secondly, we assessed the assumed light source direction in those children who were sensitive to our stimulus when making shape-from-shading judgements to determine whether the assumed light source direction changed with age or reading abilities. Should the leftward bias be developmentally stable once acquired in an individual, there should be no relationship with age or reading fluency.

2. Methods

2.1 Participants

To determine the sample size necessary to detect an effect of age on children's ability to make explicit shape-from-shading judgements, we assumed that, similar to young adults (e.g., Andrews et al., 2013), 90% of 11-year-olds would be significantly sensitive to the stimulus (see Data Analysis). No equivalent data exists for young children; however, Thomas et al. (2010) found that 5-year-olds had a weak light-from-above prior. We therefore assumed 15% of 5-year-olds would be sensitive, and the proportion of sensitive children would increase linearly with age (40% at age 7 and 65% at age 9). A chi-squared statistic was computed to determine the significance of the age effect. The outcome of one million experiments was simulated numerically. Each calculated chi-squared statistic was compared against a critical value ($\chi2 = 7.23$, $\alpha = 0.05$). We found the sample size required to yield a power of .88 was 18 participants per group.

Seventy-seven participants from the same school took part in the experiment. Participants' ages ranged from five to eleven years, and they were divided into four age groups: 5-year-olds ($n = 19$); 7-year-olds ($n = 18$); 9-year-olds ($n = 22$); and 11-year-olds ($n = 18$). At the end of the experiment, children received a certificate and a small token for their participation. The study was approved by the ethics committee in Bangor University's School of Psychology and was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013). Participants' parents gave written informed consent prior to any experimental procedure.

2.2 Apparatus

The experiment was conducted within the school. The artificial light was dimmed, but the room had North-facing windows with no curtains or shutters. Participants were positioned at a table facing a wall with the windows to their back. The window was aligned with the center of the wall, and the participant's table faced the center of the opposite wall, ensuring that the diffused light in the room was not brighter on either side of the participant. In any case, the small amount of light in the room is unlikely to have influenced shape judgements, as the direction of external lighting has been found to have little effect on the perception of shape-from-shading (Yonas et al., 1979). The position of the computer displaying the stimuli, and the participant's chair, were marked to maintain a constant distance of approximately 60cm between the screen and participant. Participants viewed the stimuli at eye level. The computer tasks were presented using E-prime 1.0 (Psychology Software Tools, Pittsburgh, PA).

2.3 Procedure and Stimuli

2.3.1 The Honeycomb Task

The experimental stimulus - the “honeycomb” (Andrews et al., 2013), was used to measure the assumed light source direction.

The honeycomb stimulus comprised a central hexagon surrounded by six identical hexagons, with double-contrast borders suggesting a ridge or a valley between the elements, arranged on a uniform grey background (Figure 1A). This stimulus was selected because, in contrast with other commonly used stimuli such as shaded spheres, figures made of multiple adjoining elements produce effective and reliable impressions of convexity and concavity (Gerardin, de Montalembert, & Mamassian, 2007). The honeycomb stimulus has been used in several published studies and in a range of different populations and is sensitive to detect differences, for instance, between young and old adults (Andrews et al., 2017) and between left-to-right and right-to-left readers (Andrews et al., 2013. This stimulus has also been used to demonstrate that light priors are intact in autistic children, compared with typically developing children (Croydon et al., 2014)

The stimuli were created using a single hexagon, which was replicated to form the other hexagons and were assigned bright and dark edges according to their placement around the original central hexagon. This process should result in identical hexagons; however, a subtle misplacement of the hexagons resulted in a small overlap of the light and dark lines on some edges. The luminance values of the internal double-contrast lines on the left were slightly higher than those on the right (129 and 126 respectively – a difference of 1%). These differences, however, were symmetrical in those edges that imply left lighting and right lighting; the upper left double-contrast edge implies a right lighting condition (as it is tilted to the right), whilst the lower left implies a left lighting condition (as it is tilted to the left). The opposite is true of the double-contrast borders on the right side of the stimulus, and thus will not prejudice an observer’s light biases.

The stimulus size, measured from the uppermost edge to the lowermost edge of the hexagon when oriented at 0° (see Figure 1A), covered a visual angle of 17.6°. The edge of each hexagon was either brighter or darker than the background, resulting in a perception of depth. The stimulus was rotated from 0° to 330° in 30° increments, over twelve levels. Zero degree orientation represents a stimulus where the bright edges of the central hexagon point directly up. A stimulus orientation of 0° and 180° are pictured in Figure 1A. When the stimulus orientation is 0°, the central hexagon should be perceived as convex if the observer implicitly assumes the light originates from above. When the stimulus is rotated 180°, the central hexagon should be perceived as concave (e.g., Andrews et al., 2013; Andrews et al., 2017; Croydon et al., 2017). Each participant completed two blocks of 60 trials, as well as 12 practice trials preceding the first block. Each stimulus orientation was presented, in a random order, five times in each of the two blocks.

Before starting the task, participants were shown two static images of the stimulus (oriented at 0° and 180°) on a computer screen, and the task was explained. Participants were asked to describe the image to the experimenter by specifying whether any parts of the stimulus appeared closer to them or farther away. Then a story was formulated: They were told that a bee was working hard to fill every cell in the honeycomb with honey and they had to help the bee decide whether the central cell was full (convex) or empty (concave). This is the same procedure used in a previous study (Croydon et al., 2017), which used the honeycomb stimulus to test group level differences between autistic and typically developing children, seven years of age and older. Once participants indicated they understood the task, the practice trials began.

Trials began with a fixation cross, presented for 1000ms, followed by the stimulus, which was presented until a response was made. If no response was made for 3000ms, the question “is it empty or full?” appeared on the screen. Participants responded verbally and the experimenter entered their response by pressing a key on the keyboard.

In addition to the honeycomb computer experiment, the following paper-based tasks were conducted: a global/local task, a cancellation task, and a reading proficiency test.

2.3.2 The Global/Local Task

The Global/Local Task used Navon-like images (Navon, 1977) to assess each participant’s processing preference (based on Kimchi & Palmer, 1982). A target image appeared between two probes that represented either the global or local level of the target stimulus (Figure 1B). The participant was asked to choose the picture (probe) that “looked most like the one in the middle (target)”. Three blocks of six trials were performed, comprising 18 trials in total, with no time limit. The experimenter recorded the response. Global responses scored 1 point and local responses scored zero. This test was chosen for its speed and simplicity, given the number of tasks children were asked to perform, and for having previously been used with children aged 3 years and older (Kimchi & Palmer, 1982).

2.3.4 *The Reading Task*

The Reading Task was used to assess the participants’ reading proficiency. Participants aged seven and above completed the standardized Hertfordshire Reading Test, which was read from left-to-right in English (Needham et al., 1983).

2.3.5 The Balloon Cancellation Task

The Balloon Cancellation Task was created for this experiment (based on Edgeworth et al., 1998) and was used to assess the direction of visual scanning. An A4 sized paper with a random array of 126 colored balloons was placed horizontally in front of the participants (Figure 1C). Participants were asked to circle all 24 green balloons. The starting position was recorded for analysis.

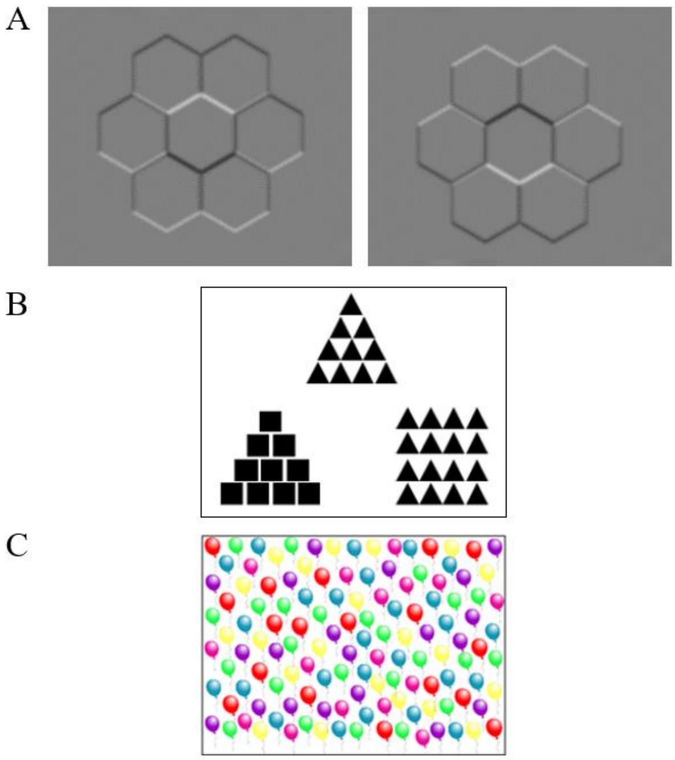


Figure 1: Illustrating the tasks and measures used in this experiment. *1A:* The Honeycomb stimulus, with the brightest edges at 0° orientation (left) and the 180°-rotated stimulus (right). *1B*: The Global/Local processing task, presenting the target above and the probes below. The lower left probe replicates the global form and the lower right the local form. *1C*: The balloon cancellation task.

2.3.6 *Procedure*

The four tasks were delivered in a fixed order, designed to prevent boredom and to offer an adequate number of breaks. Each participant completed the first set of the global/local task followed by the first block of the honeycomb task. Then the reading task was presented, followed by the second set of the global/local task. The second block of the honeycomb task was then performed and, finally, the third set of the global/local task, and the balloon cancellation task (Figure 2).

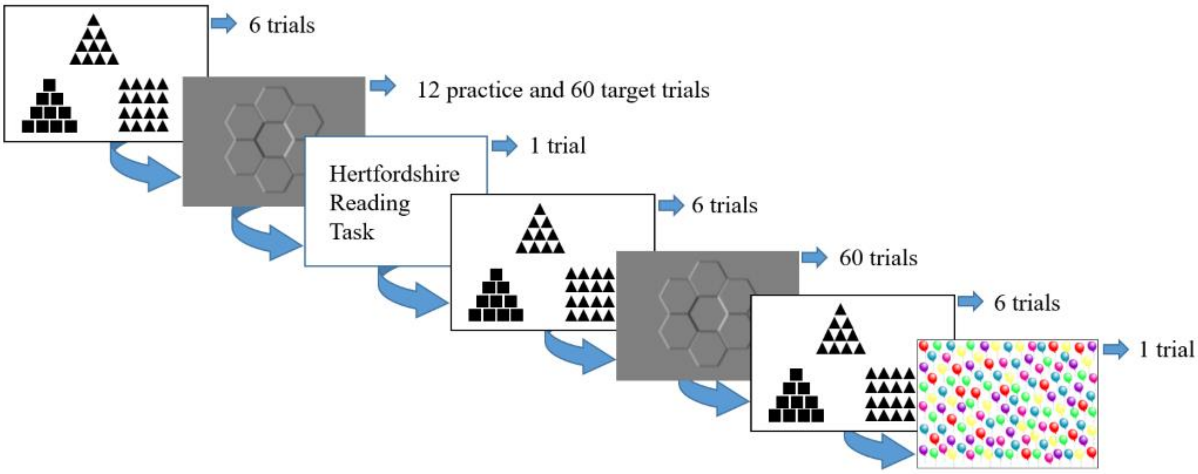


Figure 2. The order and number of trials for each task. The honeycomb task started with 12 practice trials, followed by two blocks of 60 trials each.

2.4 Data Analysis

A multivariate logistic regression was used to determine whether and how participants' responses were modulated by the orientation of the honeycomb stimulus. The logistic model predicted the odds of a child reporting a convex shape given the stimulus orientation. The model includes linear parameters of two predictors, namely the cosine and sine of the stimulus orientation. An individual participant's sensitivity to the orientation of the stimulus was generated from the ratio of the log likelihood of the shape judgements, given their observed values, over the log likelihood of the observed shape judgements, given the fitted model. This ratio is approximately distributed as a chi-square with two degrees of freedom and tests the hypothesis that there is no linear relation between the logarithm of the odds of making a convex judgement and the predictors. Data from participants whose logistic fits did not reach a significance level of 0.01 or less, thus demonstrating low sensitivity to stimulus orientation, were not included in the analysis of the assumed light source direction, in keeping with previously reported practice (Andrews et al., 2013; Andrews, d'Avossa, & Sapir, 2017).

3. Results

3.1 Age Effects

3.1.1 *Sensitivity to Stimulus Orientation*

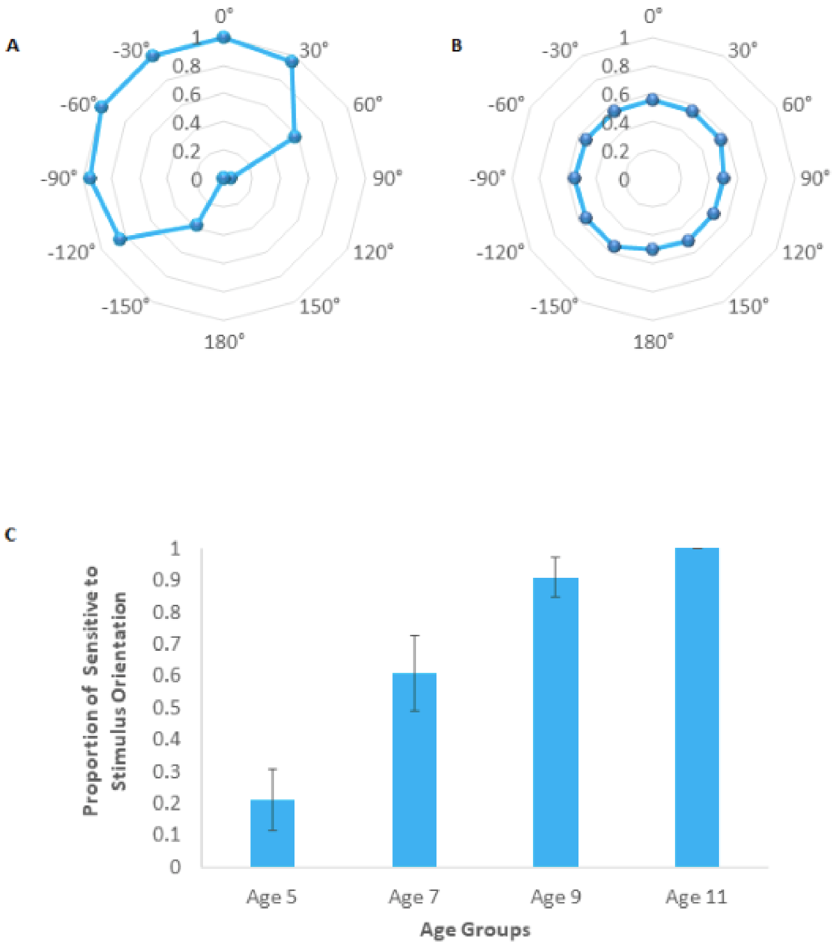
Figures 3A and 3B exemplify the pattern of data observed in two children with high and low sensitivity values on the honeycomb task and show the proportion of convex judgements for each of the 12 stimulus orientations. In Figure 3A, the participant showed high sensitivity to the orientation of the stimulus when making shape judgements (p < .001), and shows an above-left bias (-24.70˚). In Figure 3B, the participant demonstrated a low degree of sensitivity (p = .854), responding as though the stimulus was convex on around 50% of the trials, regardless of stimulus orientation, suggesting that the child responded at random.

The proportion of children whose shape judgments were significantly affected by the stimulus orientation increased across age groups (χ^2 (3) = 33.87, p < .001, ϕ = 0.66; Figure 3C). The mean and the standard deviation of the z-transformed sensitivity scores in children who were not sensitive to the orientation of the stimulus corresponded to the 55th and 81st percentiles of the null distribution respectively. This is within the 95% confidence interval of the null distributions, indicating that the sensitivity scores within this group of children were not significantly greater than predicted by guessing performance.

To further characterize the effect of age on sensitivity, logistic regression log-likelihoods were analyzed with a univariate ANOVA. Table 1 reports the group average values. The log-likelihoods showed a highly significant between-groups difference (F(3,73) = 147.64, p < .001, η_p^2 = .67), indicating that sensitivity was greatly affected by the children's age. Bonferroni-corrected post-hoc tests indicated a significant difference between age groups 5 and 9 (M_{diff} = -67.75, SE = 14.39, p < .001), and age groups 5 and 11 (M_{diff} = -67.75, SE = 14.39, p < .001).

Table 1. *Group Mean Values for the Log-Likelihood Measure of Sensitivity to the Orientation of the Honeycomb Stimulus When Making Shape Judgements.*

	Mean Log-Likelihood	SE
Age 5	20.28	11.06
Age 7	58.90	11.36
Age 9	88.04	10.28
Age 11	88.22	11.36



Figures 3A and 3B. Data from the honeycomb task, demonstrating the proportion of convex judgements for each stimulus orientation for two participants aged 7 years. Figure 3A displays the data for participant 74, whose logistic fit indicated they were highly sensitive to the orientation of the stimulus when judging its shape, whilst 3B shows participant 50, whose responses were close to chance at all orientations. *3C* displays the proportion of children in each age group who were able to consistently judge the 3-D shape of the honeycomb. Error bars represent the standard error of the mean.

3.1.2 Effect of Light Source

Next, we analyzed the effect of age on the assumed light source direction on children who were sensitive to the stimulus orientation. Because only four participants aged 5 years were sensitive, this group was excluded from further analyses. The following number of children were included in the analysis was: age 7, n = 10; age 9, n = 18; and age 11, n = 18.

The majority of participants showed a leftward bias for the assumed light source direction (M = -18.47°, n = 48, SD = 14.48). The assumed light source direction varied from 67.45° to the left to 14.14° to the right (see Figure 4). The average bias in the different age groups was as follows (negative values represent a leftward bias): age7 (M = -21.67°, SD = 16.58), age 9 (M = -18.89°, SD = 8.87), and age 11 (M = -19.23°, SD = 17.11). The difference between the three age groups was not significant ($F(2,42)$ = 0.13, p = .876).

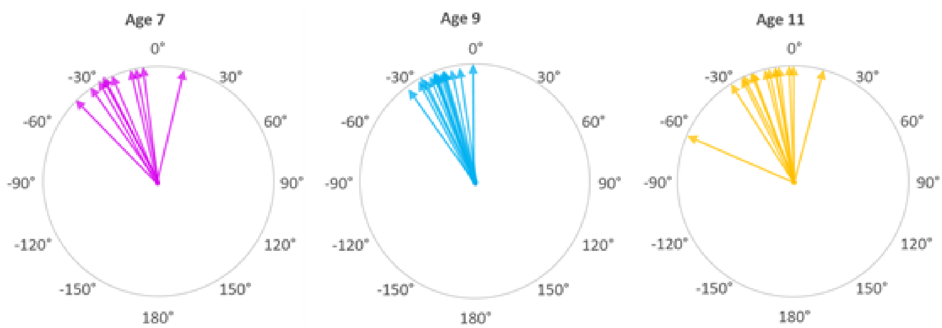


Figure 4. Polar plots displaying the bias, in degrees, for each participant, categorized according to their age group (7, 9, and 11).

3.1.3 Convexity

Convexity scores range from 0 (making no convex judgements) to 1 (exclusively making convex judgements). A factorial ANOVA was performed to determine whether age and sensitivity influenced participants' tendency to report convexity in the honeycomb task. There was no main effect of age (F(3,70) = 2.08, p = .111) or sensitivity (F(1,70) = 0.15, p =

.699) on participants' convexity judgements; however, there was an interaction between age and sensitivity that approached statistical significance ($F(2,70) = 2.97$, $p = .058$). In children who were sensitive to the orientation of the stimulus, the tendency to report a convex shape increased with age ($F(3, 49) = 4.09$, $p = .011$, $\eta_p^2 = .20$). No significant age effect was detected in children who were not sensitive to the stimulus orientation ($F(2, 21) = 0.95$, $p = .401$).

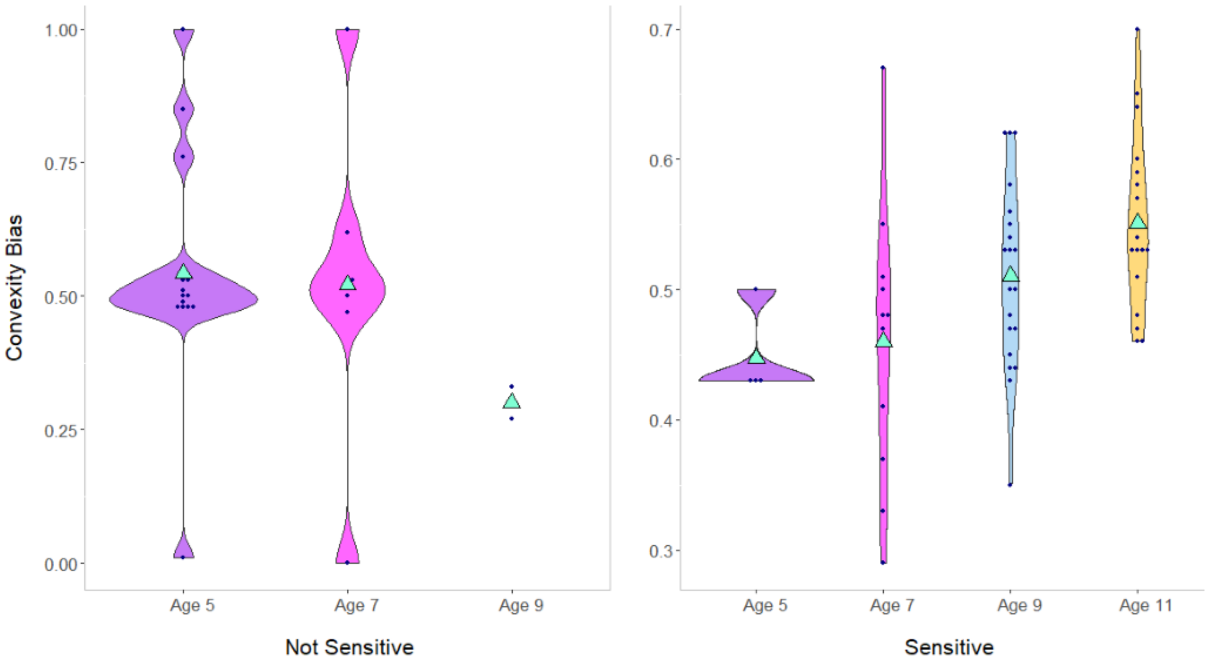


Figure 5. Violin plot to display the distribution of convexity scores according to sensitivity to the orientation of the stimulus and age. The two individual points in the 'Not Sensitive' plot represent the convexity bias of the only two 9-year-olds who were insensitive to the orientation of the stimulus when making shape judgements. The mean scores for individual age groups are represented by a triangle in each violin plot.

3.1.4 Reading Proficiency

Reading proficiency was only assessed in children aged seven years and above. Reading proficiency improved with age ($F(2, 55) = 32.48$, $p < .001$, $\eta_p^2 = .54$), with higher reading scores in older children (mean reading age for children aged 7 = 8.18, *SE* = .26; age

9: *M* = 9.99, *SE* = .23; and age 11: *M* = 11.07, *SE* = .26). All Bonferroni-corrected differences between age groups were significant (Ages 7 and 9: *M*diff = -1.81, *SE* = 0.35, $p < .001$; Ages 7 and 11: *M*diff = -2.89, *SE* = 0.36, $p < .001$; Ages 9 and 11: *M*diff = -1.08, *SE* = 0.35, $p < .008$).

3.1.5 Global Processing

The tendency to process stimuli globally increased with age ($F(3, 73) = 4.90$, $p = .004$, $\eta_p^2 = .17$). Out of 18 trials, younger children tended to categorize stimuli according to their local forms (Global score for age 5: *M* = 8.42, *SE* = 1.6; age 7: *M* = 8.22, *SE* = 1.6). A marked shift towards Global processing appeared at age 9 (*M* = 14.6, *SE* = 1.4) and 11 (*M* = 13.78, *SE* = 1.6). When corrected for multiple comparisons, the difference between the following age groups were significant: ages 5 and 9 (*M*diff = -6.17, *SE* = 2.12, $p = .029$), and ages 7 and 9 (*M*diff = -6.37, *SE* = 2.16, $p = .025$).

Children were then categorized according to their processing preference. Children who made six or fewer global judgements (of 18) were considered local processors, and those making 13 or more were categorized as global processors. Children who made between seven and twelve global judgements were categorized as ambivalent. A chi-squared analysis revealed a significant relationship between age and processing preference ($\chi^2(6) = 15.39$, $p = .017$, $\phi = 0.45$).

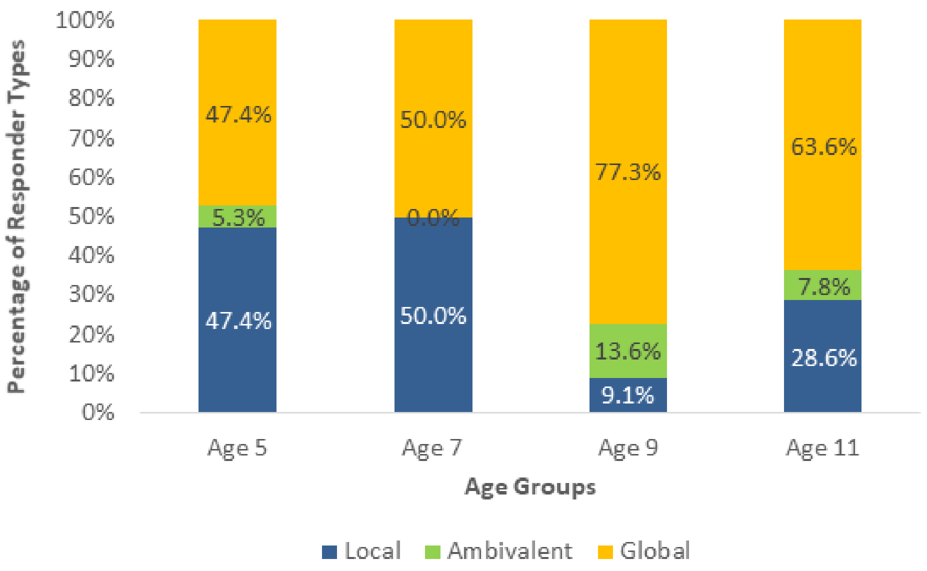


Figure 6. Percentage of children categorized as having a local, global, or ambivalent processing preference in each age group.

3.1.6 Balloon Cancellation

Scores varied from -2 for the left-most, to 2 for the right-most, starting position. The tendency to begin cancellation on the left increased with age ($F(3, 73) = 4.69$, $p = .005$, $\eta_p^2 = .16$). Children aged 5 started close to the center of the page ($M = -0.42$, $SE = 0.29$); the starting point for age 7 moved marginally leftward ($M = -0.78$, $SE = 0.30$); and ages 9 and 11 showed a strong tendency to start cancellation on the leftmost side of the page ($M = -1.82$, $SE = 0.27$, and -1.33, $SE = 0.30$, respectively). None of the children selected an incorrectly coloured balloon.

3.2 Correlations Between the Assumed Light Source Direction, Scanning Habits, and Sensitivity

Next, we calculated a number of correlations to assess the relationship between the assumed light source direction and reading proficiency, cancellation task starting position, and sensitivity. Because age affects performance on these tasks, all correlations were computed after controlling for age. These correlations were only computed on children who were sensitive to the stimulus orientation.

There was no significant correlation between reading proficiency and the assumed light source direction (*r*(42) = -.06; *p* = .713). Similarly, the assumed light source direction was not correlated with the tendency to initiate cancellation on the left (*r*(42) = .08; *p* = .585). Finally, the assumed light source direction did not correlate with the measure of the sensitivity to stimulus orientation (*r*(48) = .19; *p* = .297). No correlations were significant when age was controlled.

3.3 Correlations Between Sensitivity and Global Processing Preferences

To understand whether individuals' ability to judge shape-from-shading was related to their propensity to process the global aspect of stimuli, we correlated sensitivity scores (negative values represent greater sensitivity) with the percentage of global judgements made by children. A significant negative correlation was observed (*r*(77) = -.26; *p* = .021, R^2 = .07), indicating that greater sensitivity was associated with a greater global processing preference. However, when age was controlled via a partial correlation, the relationship was no longer statistically significant, (*r*(74) = -.10, *p* = .409).

4. Discussion

4.1 The Assumed Light Direction and Age

We measured the assumed light source direction in children aged between five and eleven years, to understand when the light source prior is established and which factors affect its development. Previously, Thomas et al. (2010) reported that the light source prior emerged at around seven years of age and the left bias increased steadily until age twelve. In contrast, we found that in children who were sensitive to the orientation of the stimulus when making shape judgements, the assumed light source direction was the same across age groups: the youngest children who were sensitive to stimulus orientation exhibited the same assumed light source direction as older children. Moreover, in these children the assumed light direction was broadly equivalent with estimates obtained in adult participants (e.g., Andrews et al., 2013), suggesting the direction of the prior does not change with age, showing a significant leftward bias from the moment a child becomes able to use shading as a cue to 3D shape in our task.

An obvious issue with our conclusion is that it disagrees with those reached by Thomas et al. (2010) and Stone (2011), who instead indicated that the development of the light source prior proceeds gradually. The latter proposals were based on the assumption that the prototypical developmental trajectory can be inferred from group averages obtained in cross-sectional samples. This assumption is only valid if the population is uniform in its ability to use shading cues. Our own data indicate instead that there are children as young as seven whose shape-from-shading performance does not differ appreciably from that of a 12-year-old, or an adult (Andrews et al., 2013), replicating recent findings in typically developing and autistic 7-14 year-olds (Croydon et al., 2017) and much younger children, 3-8 year-olds, using photographs of shaded images (Benson & Yonas, 1973; Yonas et al., 1979). Thus, it is conceivable that the ability to judge shape-from-shading, rather than maturing gradually, is gained rapidly in a given person, but at an age that differs broadly between individuals. We also found that the distribution of sensitivities in children who were not included in the analysis was consistent with guessing performance. This finding suggests that this group did not include individuals with intermediate levels of sensitivity as one would expect if shape-from-shading develops gradually. Although our data cannot conclusively determine whether the ability to judge shape-from-shading is gained abruptly or gradually, they nevertheless prompt a different interpretation of the evidence supplied by Thomas et al. (2010) and Stone (2011): rather than a following a gradual developmental trajectory between the ages of seven and twelve years, light heuristics are likely to be developmentally stable once measurable in an individual. Longitudinal studies would provide the best methodology to conclusively establish how shape-from-shading and directional biases mature in individuals.

Studies examining shape-from-shading development have consistently shown that young children have difficulty providing reliable reports of perceived 3D shape (Thomas et al., 2010; Stone, 2011). Even studies that found reliable shape-from-shading in young children had to exclude some of the participants (e.g., Yonas et al., 1979; and the current study). On the other hand, studies using implicit responses such as preferential looking and reaching (e.g., Granrud et al., 1985; Imura et al., 2008) have found that infants can interpret shaded stimuli consistently. The differences between the results obtained with different report methodologies may, therefore, reflect cognitive rather than perceptual limitations.

There are a number of possible reasons why the youngest children could not perform the task. One possibility is that young children cannot see 3D shape-from-shading. It is also possible they children did not fully understand the task instructions. Finally, the task may not have been engaging enough to sustain the limited attentional capacity of the youngest children (Atkinson & Braddick, 2012). Our data do not allow us to conclude which of these possibilities is most likely.

4.2 Sensitivity, the Assumed Light Direction, and Age

Our sensitivity measure critically contributes to the understanding of the development of light priors. It is not always possible to ascertain whether very young participants have successfully engaged with a task for its entire duration. Therefore, an objective method to validate the consistency of participants' shape judgements can increase confidence in experimental findings by excluding participants whose judgements were not significantly different from guessing performance, thus preventing the final group-level estimate of the assumed light direction from being unduly affected by random guesses.

There are at least two populations for whom the group-level assumed light direction does not match the typical leftward bias observed in left-to-right reading young adults; specifically, left-to-right reading older adults (Andrews et al., 2017) and right-to-left reading young adults (Andrews et al., 2013). Taken with the evidence from Thomas et al. (2010), which suggested that the leftward bias developed between the ages of seven and twelve years, the group-level assumed light directions might feasibly have fallen in any direction and gradually moved leftward with increasing age. However, we found that the average bias in seven-year-olds was the same as in twelve-year-olds, and closely resembled the leftward bias seen in left-to-right-reading young adults.

We did find age-related linear increases in sensitivity to the orientation of the stimulus when making shape judgements, and that sensitivity was unrelated to the assumed light direction. This suggests that either the ability to interpret the stimulus, or the ability to maintain attention, increased with age. The dissociation between sensitivity and the assumed light direction strongly implies that the direction of the bias is unrelated to the age-related ability to perceive and report shape-from-shading in this task.

4.3 Convexity, Sensitivity, and Age

Previous studies have suggested that younger children predominantly assume that objects are convex, and that this is a strong prior in the first years of life (Corrow et al., 2014), which diminishes with age in favor of the overhead lighting assumption (Thomas et al., 2010). A convexity bias that overrides the assumed light direction prior could explain why most of the younger children were not sensitive to the orientation of the honeycomb stimulus when making shape judgements. We therefore explored whether the convexity bias diminished children's ability to make shape-from-shading judgements. If this were so, we would have expected children who were less sensitive to the stimulus orientation to make a greater proportion of convex judgements than children who were more sensitive. However, the convexity scores did not differ between those who were sensitive and those who were not. This indicates that children do not default to the percept of convexity when unable to use shading cues.

Like Stone (2011), when we included all children in the analysis, we found that age had no overall effect on the convexity scores. However, we found that the convexity bias increased with age in children who were sensitive to stimulus orientation. This increase may signify that the convexity prior and shape-from-shading cues are integrated to a greater degree in the mature visual system. This idea is consistent with Dekker and colleagues (2015), who found that depth cues are integrated to generate adult-like precision in depth judgements at around 11 years of age.

4.4 Global Processing and Sensitivity

As the honeycomb stimulus requires the integration of contours to yield its global form, we expected global processing to be associated with children's sensitivity to shading. However, no relationship was observed between the two variables after age was controlled. This suggests that age, rather than the propensity to process global forms, was responsible for the observed age-related increases in sensitivity. It is possible that children's inability to perform the task reflects a perceptual limitation: namely, that they could not perceive depth in our images; however, the reason many of the youngest children were unable to perform this task remains unclear. Alternatively, the classification task we used to assess global figure processing may have been too simple to capture the extent to which children of different ages experience a global advantage or global-to-local interference; the Rey Complex Figure Organizational Strategy Score (RCF-OSS) might constitute a more robust measure of processing styles (see Milne & Szczerbinski, 2009, for a review of global/local processing tasks). The Rey-Osterrieth Complex Figure task has been performed with children aged five years and above (Martens et al., 2014). Children aged between five and seven years show significant developments in their copying strategies, consistent with a change from local to global processing preferences, every six months (Martens et al.). Nevertheless, given the absence of a relationship between sensitivity and global processing in our data, this suggests the ability to process global forms is unlikely to be the reason young children perform randomly on shape-from-shading tasks.

4.5 Scanning Habits

A range of lateralized biases, including the light source direction, are reliably affected by reading direction (Andrews et al., 2013; Chokron & Imbert, 1993; Friedrich & Elias, 2014; Rinaldi et al., 2014; Smith et al., 2015) suggesting that they are influenced by scanning habits. We measured the relationship between scanning habits (e.g., reading proficiency and the tendency to start cancellation on the left) and the assumed light source direction. A relationship between the assumed light source direction and reading proficiency or performance on the balloon cancellation task could indicate that the leftward bias develops in response to scanning habits emerging during literacy acquisition. As expected, we found that reading fluency increased with age, but did not correlate with the assumed light source direction. Similarly, the starting position in the balloon cancellation task shifted leftwards with increasing age (Woods et al., 2013), but was not related to the assumed light source direction. The dissociation between scanning habits and the assumed light source direction substantiates the claim that habitual scanning direction may modulate lateralized biases only when they are not consistent with the default (left) lateralization (Andrews et al., 2013).

4.6 Conclusion

We studied the development of the implicitly assumed light source direction in young children. We separated children who were sensitive to stimulus orientation from those who were not. An adult-like assumed light source direction was found in sensitive children as young as seven. Moreover, the assumed light source direction did not change with age and was not related to habitual reading direction. These findings suggest the leftward bias, and the light-from-above prior, are stable once measurable across age groups, and do not exhibit a gradual change in the orientation of the bias.

A longitudinal study is required to establish the developmental trajectory in individuals, given the presence of large individual differences in sensitivity. The development of more child-friendly tasks is essential to assess light source priors in very young children. Testing right-to-left reading populations, before and during reading acquisition, will elucidate how scanning habits affect the development of directional biases in light source priors.

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