Footprints Sticking Out of the Sand (Part I):

Children's Perception of Naturalistic and Embossed Symbol Stimuli

Target journal: Perception

File: chilldConvexity_June2010_v14.tex

JV Stone[1] and O Pascalis[2]

[1]Department of Psychology, University of Sheffield, England, S10 2TP.

[2]Laboratoire de Psychologie et NeuroCognition,

Université Pierre Mendes France, BP 47, 38040 Grenoble Cedex 9, France.

Corresponding author: j.v.stone@shef.ac.uk

Key words: Perception, lighting direction.

Short title: Footprints Sticking Out of the Sand

October 28, 2010

Abstract

The shading information in images that depict surfaces of 3D objects cannot be perceived correctly unless the direction of the illuminating light source is known, and, in the absence of this knowledge, adults interpret such images by assuming that light comes from above. In order to investigate if children make use of a similar assumption, we analysed data from 171 children between the ages of 4.6 and 10.8 years using 10 images that could be perceived as either convex or concave. Each of five images depicted a naturalistic picture (eg a footprint), each of the other five depicted an embossed symbol (eg a square). On each of 20 trials, a child was presented with either an upright or upside-down image, and indicated whether the depicted shape appeared convex or concave. Our main findings are that, 1) naturalistic stimuli are significantly more likely to be perceived as if light comes from above than symbol stimuli, and, 2) children's propensity to interpret stimuli as if light comes from above increases significantly with age, and at a similar rate for naturalistic and symbol stimuli. These results suggest that, irrespective of any innate competence, children's ability to interpret shading information is gradually refined throughout childhood.

1 Introduction

Perception involves recovering the three dimensional structure of a scene from a two dimensional retinal image. Unfortunately, the process of projecting a scene onto the retina discards information about the three dimensional structure of that scene. This makes it impossible, in principle, to recover the scene structure from a retinal image alone, making perception a classic example of an ill-posed problem (Poggio et al. (1985)). It is therefore necessary for the visual system to rely on extra information, in the form of constraints, or assumptions.

One assumption which adults adopt is that light comes from above (Rittenhouse (1786); Brewster (1826); Sun and Perona (1998); Mamassian and Landy (2001); Stone et al. (2009)). For example, the images in Figure 1 can be interpreted either as convex or as concave, depending on the direction from which light is assumed to originate. However, the finding that perception of similarly ambiguous shaded figures can be modified by experience in adults (Adams et al. (2004)), suggests that adults may have learned to interpret such figures during development (in contrast, chickens are immune to the effects of experience (Hershberger (1970))). Indeed, there is evidence that 7 month old infrants (but not 5 month olds) perceive a picture of a

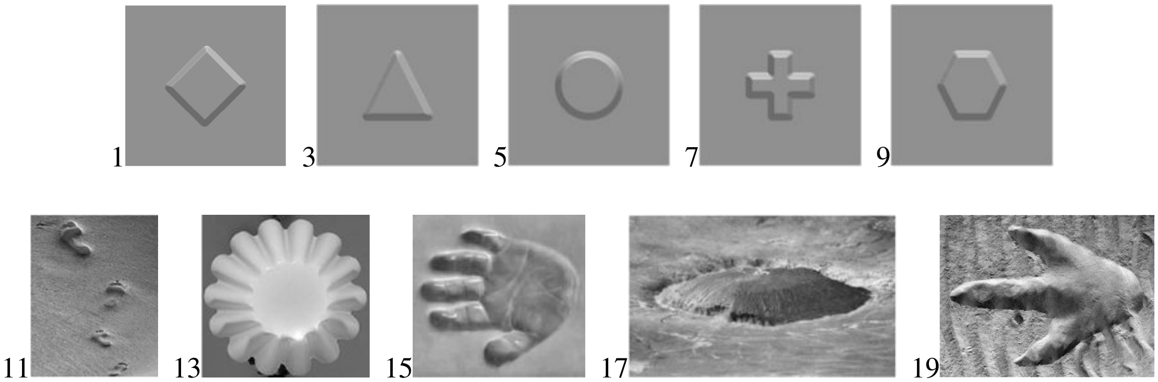


Figure 1: **Symbol stimuli (labelled 1-9), picture stimuli (11-19)**. Each stimulus was presented as here (odd-numbered stimuli), and upside-down (even-numbered stimuli, not shown), and the observer indicated whether the shape appeared to be convex ('out') or concave ('in'). All the stimuli here are perceived as convex if the observer assumes light comes from above (ie from the top of the page). Conversely, turning the page upside-down forces the observer to perceive these stimuli as concave if light is assumed to come from above. (Figures reproduced with permission from 11: Footprints by Jan Sevcik, 13: Hill and Johnston (2007), 17: Courtesy of the U.S. Geological Survey, 19: Courtesy of Weston Park Museum, Sheffield).

dome-like shaded stimulus as if light comes from above (Granrud et al. (1985)). Additionally, 3-8 year olds have an increasing tendency to interpret this stimulus as if light comes from above (Yonas et al. (1979)), and this also applies to 'polo mint' stimuli in 4-12 year olds (Thomas et al. (2010 (in press)). However, it is possible that the developmental trajectories observed in these studies might have been specific to children's reaction to the abstract artificial stimuli used. Here, we investigate if these developmental changes apply to naturalistic pictures and abstract symbols for children aged 4-11 years.

Methods

Participants: The participants were 172 children between 4.6 and 10.8 years of age (one child was excluded, see below).

Materials: The stimuli were 5 naturalistic pictures and 5 geometric embossed symbols, as shown in Figure 1. Each stimulus was presented twice, the right way up, and upside-down, making a total of 20 stimuli, which were presented in one of four fixed random orders to each child. The response to each stimulus implicitly defined the direction of the light source perceived by the observer. For example, if the stimuli in Figure 1 are seen as convex then this implies that the observer perceives the light as coming from above (ie from the top of the page), but if they are seen as concave then this implies the observer perceives the light as coming from below (and *vice versa* during trials for which these stimuli were presented in an upside-down orientation).

By definition, the lighting direction of the picture stimuli could not be controlled, and is roughly vertically aligned. The lighting direction of the symbol stimuli (produced using MatLab) is 10° from vertical because a vertical lighting direction gave a very impoverished appearance. In both cases, the lighting direction clearly appears to be roughly vertically aligned.

Procedure: Testing took place in a quiet room in each child's school, with conventional overhead lighting. Initially, each child was asked to identify hollow three-dimensional plastic letters as either concave or convex, by responding verbally that they could see its 'inside' or 'outside', respectively, until each child correctly responded to three stimuli in succession. Then, each child was presented with 20 ambiguous stimuli (see Figure 1), on a 15" laptop screen for 2 seconds, followed by a blank screen, and the child's verbal response to each stimulus was written down. After each response, the child was shown the next stimulus. If a child perceived a stimulus as if the light originated from above (within the picture plane) then this was deemed to be a 'correct' response.

Data Analysis: The data was collated into $n = 7$ year-long bins, according to age. For example, the data from all children between 60 months (5 years) and 72 months (6 years) were placed in the same bin. The mean age of children with data in the same bin was then calculated, and these are the values used in all subsequent analyses, and graphs. The mean ages of children in each bin were [4.8, 5.5, 6.5, 7.4, 8.4, 9.8, 10.4] years, and the corresponding numbers of children that contributed to data in each bin were [16, 32, 39, 29, 21, 12, 22].

The responses were checked to see if any child indicated that all stimuli were either convex or all concave. One such set of such responses was found, and removed, making a total of n=171 participants.

The responses of all 171 children to each stimulus were checked to see if any stimulus evoked unusual responses. The proportion (out of 171) of correct responses for each stimulus is shown in Figure 2, which does not indicate that any stimulus stands out as being unusual.

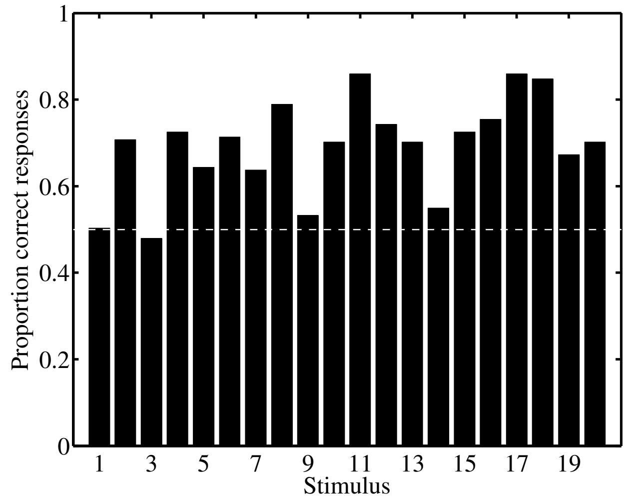


Figure 2: **Proportion of ‘correct’ responses to each stimulus**.
Each bar represents the proportion of children (out 171 children) who made a ‘correct’ response to each stimulus, where the identity of the stimulus corresponds to those indicated in Figure 1. Even-numbered stimuli are inverted versions of the odd-numbered stimuli in Figure 1. The white dashed line represents chance performance.

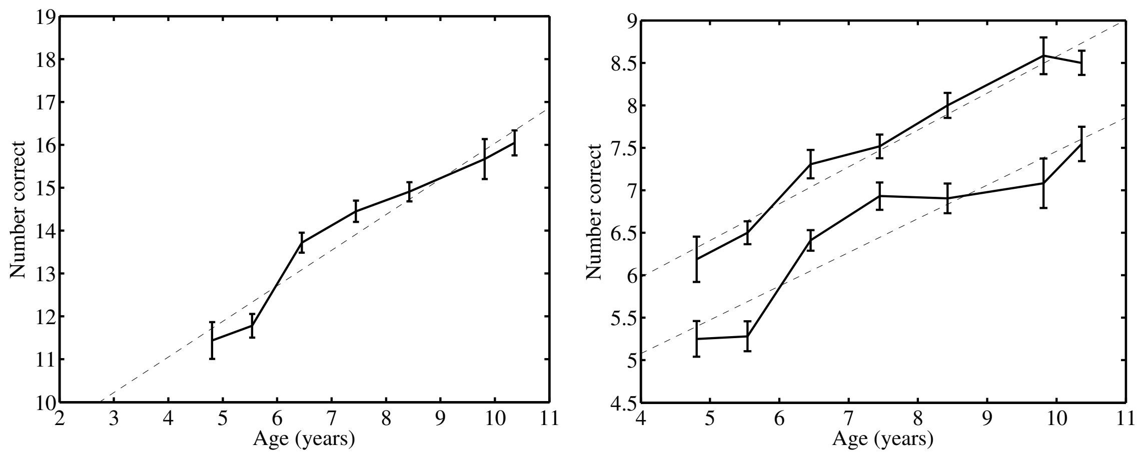
2 Results

We present two main results. First, naturalistic picture stimuli are significantly more likely to be perceived as if light comes from above than symbol stimuli. Second, children’s propensity to interpret stimuli as if light comes from above increases significantly with age for both naturalistic picture and symbol stimuli, and at a rate that is not significantly different for picture and symbol stimuli (Figure 3b).

Analysis of Combined Picture and Symbol Stimuli: A linear regression (see Figure 3a)[1] of ‘correct’ responses against age yielded a slope of 0.84 (out of 20) additional ‘correct’ responses per year. This slope is non-zero ($p < 0.001$), and predicts chance performance at age 2.8 years, as indicated by the intersection of the regression line with the abscissa for 10/20 ‘correct’ responses. Indeed, the number of ‘correct’ responses was significantly greater (ie $p < 0.05$) than chance for all age-groups except for those in the 4-5 age range when tested with the picture, symbol and combined picture/symbol stimulus sets, and except for children in the 5-6 age range when tested with the symbol stimuli (see Figure 3a,b).

Analysis of Separate Picture and Symbol Stimuli: These data were further analysed by considering per-

[1]For each linear regression reported here, a weighted linear regression was also run (using the known variance of each data point), but results showed only negligible differences.

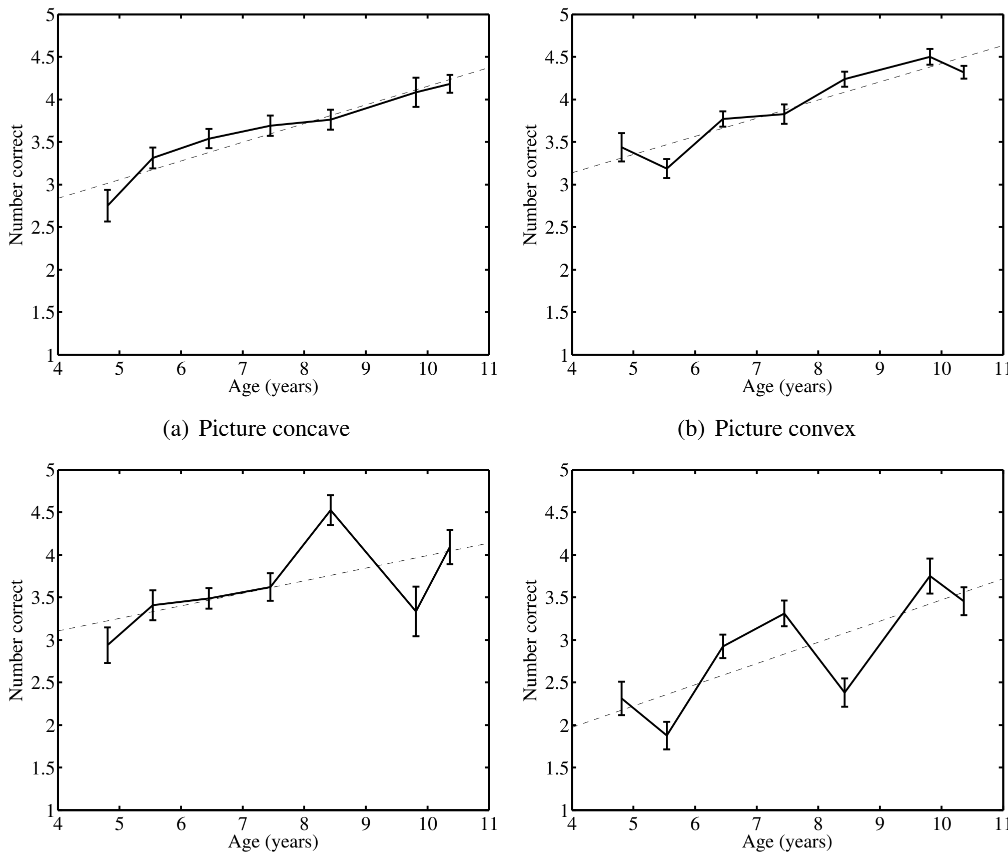


(a) Picture and symbol (b) Picture (upper), symbol (lower)

Figure 3: **Changes in perception with age**.
(**a**) The overall number of ‘correct’ (ie responses consistent with a light source above the stimulus) measures the extent to which each child perceives light as coming from above, where chance performance is 10. The mean number of correct responses is 16.0 (sem=0.632). A regression of ‘correct’ responses y against age yielded $y = 0.84 \times \text{age} + 7.65$ ($R^2 = 0.937, F = 74.5, p < 0.001$).
(**b**) Correct responses to picture (upper curve) and symbol (lower curve) stimuli, where chance performance is at 5. A regression of ‘correct’ picture responses y against age yielded $y = 0.433 \times \text{age} + 4.24$ ($R^2 = 0.964, F = 133.1, p < 0.001$). A regression of ‘correct’ symbol responses y against age yielded $y = 0.397 \times \text{age} + 3.49$ ($R^2 = 0.865, F = 32.13, p = 0.002$). Each dashed line is a fitted regression line (see text), and bars denote standard errors.

formance on the 10 picture and 10 symbol stimuli separately, as shown in Figure 3b. Regression analyses yielded significant fits for both the picture stimuli and symbol stimuli (see legend of Figure 3b). These analyses revealed that the rate at which the number of ‘correct’ responses increased with age was 0.433 (sem=0.078) picture stimuli per year (out of 10) compared to 0.397 (sem=0.145) symbol stimuli per year (out of 10). The sems associated with these slopes suggest they do not differ significantly ($z = 0.268, p > 0.05$). The mean number of ‘correct’ picture responses was 7.7/10 (sem=0.33) compared to the mean number of ‘correct’ symbol responses of 6.8/10 (sem=0.32), and a paired t-test revealed that this difference of 0.9 stimuli was significant ($t = 9.32, p < 0.001$). Thus, even though the mean number of ‘correct’ responses differed between picture and symbol stimuli, the rate at which the number of ‘correct’ responses increased with age did not.

Analysis of Separate Picture/Symbol and Convex/Concave Stimuli: Regression analysis of number of ‘correct’ response against age on each of the four stimulus subsets (ie picture/convex, picture/concave, sym-



(a) Picture concave

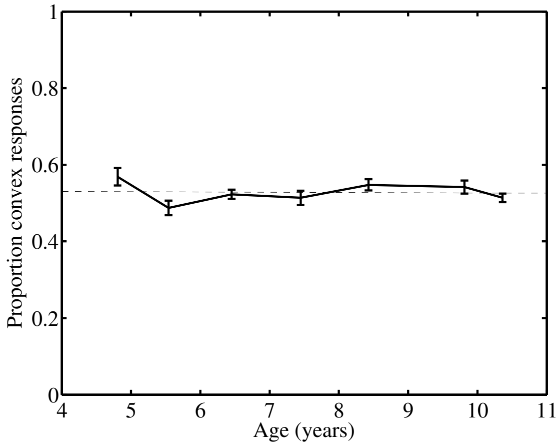
(b) Picture convex

(c) Symbol concave

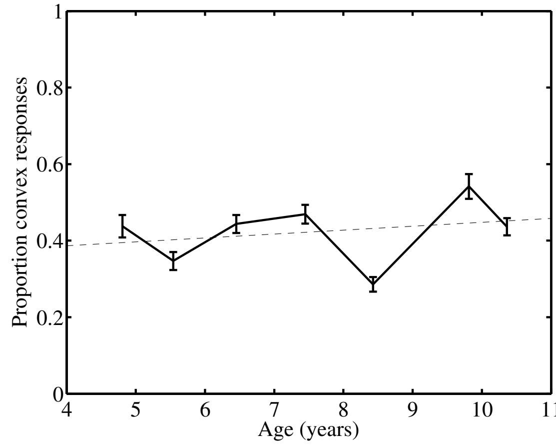
(d) Symbol convex

Figure 4: **The number of 'correct' responses for different stimuli (see Figure 2)**.
Note that the label *convex* or *concave* is associated with an assumption that lighting direction is above, and that chance performance is at 2.5 for these graphs.
(**a**) The number of 'correct' responses (see Figure 2) for concave picture stimuli, where chance performance is 2.5. A regression of 'correct' symbol responses y against age yielded $y = 0.220 \times \text{age} + 1.96$ ($R^2 = 0.908, F = 49.29, p < 0.001$).
(**b**) The number of 'correct' responses for convex picture stimuli. A regression of 'correct' symbol responses y against age yielded $y = 0.214 \times \text{age} + 2.28$ ($R^2 = 0.872, F = 34.03, p = 0.002$).
(**c**) The number of 'correct' responses for concave symbol stimuli. A regression of 'correct' symbol responses y against age yielded $y = 0.147 \times \text{age} + 2.51$ ($R^2 = 0.350, F = 2.69, p = 0.162$).
(**d**) The number of 'correct' responses for convex symbol stimuli. A regression of 'correct' symbol responses y against age yielded $y = 0.249 \times \text{age} + 0.975$ ($R^2 = 0.580, F = 6.91, p = 0.047$).
Each dashed line is a fitted regression line (see text), and bars denote standard errors.

bol/convex, symbol/concave) yielded a positive slope in all four cases, and all except the symbol/concave subset (ie symbol stimuli that are perceived as concave if light is assumed to come from above) yielded a significant fit ($p < 0.05$), see Figure 4.



(a) Picture convex responses



(b) Symbol convex responses

Figure 5: **Proportion of *convex* responses**.
(**a**) Proportion of *convex* responses for picture stimuli, mean = 0.528 (sem=0.009). A regression of convex responses y against age yielded $y = -0.001 \times \text{age} + 0.533$ ($R^2 = 0.002, F = 0.011, p = 0.921$).
(**b**) Proportion of *convex* responses for symbol stimuli, with mean = 0.422 (sem = 0.029). A regression of convex responses y against age yielded $y = 0.010 \times \text{age} + 0.346$ ($R^2 = 0.066, F = 0.356, p = 0.577$). Each dashed line is a fitted regression line (see text), and bars denote standard errors.

Analysis of Concave/Convex Responses: The proportion of convex responses for picture stimuli is shown in Figure 5a, and for symbol stimuli in Figure 5b, and a paired t-test revealed a significant difference between them ($t = 0.330, p = 0.017$). Moreover, both means (see Figure 5 legend for means and sems) are significantly different from chance performance of 0.5, suggesting that picture stimuli tend to be perceived as convex, whereas symbol stimuli tend to be perceived as concave.

3 Discussion

Our results, and those reported in (Yonas et al. (1979); Thomas et al. (2010 (in press)) suggest that, irrespective of any nascent innate ability, children's interpretation of shading information in terms of 3D shape depends on the assumption that light comes from above, and that this dependence increases with age.

The two types of stimuli (picture and symbol) yield changes in the number of 'correct' responses with age (regression slopes) that are not significantly different from each other, even though performance with picture stimuli is significantly better than with symbol stimuli. Together, these results suggest a generic improvement in performance of about 4% per year (ie 0.84 extra 'correct' response out of 20 per year), which is overlaid on a basic difference in ability to interpret different types of stimuli. The finding that children perform better on picture stimuli than on symbol stimuli may be because, even though the picture stimuli are more complex, this complexity entails a richer array of shading cues than those associated with the symbol stimuli.

Indeed, Figure 5b suggests that symbol stimuli tend to evoke a disproportionate proportion of $concave$ responses, whereas Figure 5a suggests that picture stimuli tend to evoke disproportionate proportion of $convex$ responses. Moreover, examination of Figure 4d suggests that this difference is mainly caused by children perceiving symbol stimuli as concave (when they should be perceived as convex if light is assumed to come from above), an effect which appears to be more prevalent in younger children.

Our results may also depend on changes in children's accuracy in detecting the possible lighting directions implicit in each stimulus, but this hypothesis cannot be tested with the type of data presented here.

Relation to previous work: From our data, the regression line that predicts the youngest chance performance is from picture stimuli (Figure 3b), which predicts performance should be at chance levels (ie 10) at 21 months (1.7 years) of age for these stimuli (and for symbol stimuli at 46 months or 3.8 years). A previous study (Yonas et al. (1979)) on 3-8 year old children yielded data which, when re-analysed here, yields a regression line which predicts chance performance at 9 months (0.75 years).

Stimuli similar to those used in Yonas' study were later used to show that seven month old children (but not 5-month olds) can interpret ambiguous shaded stimuli as if light comes from above (Granrud et al. (1985)). Using an approximation to a 2-alternative forced choice procedure (in which infants could also reach for both stimuli), their conclusions are based on a 63% preference (as indicated by a reaching response) for stimuli which appear convex if lighting is assumed to come from above. This result is based on a sample of 24 infants, after 14 infants had been excluded for non-compliance, and after ambiguous responses in which infants reached for both stimuli were excluded. If the excluded infants could not perceive shape from shading then these results suggest that a subset of 7-month olds can perceive shape-from-shading. Even within this subset, the existence of ambiguous responses may indicate both stimuli were sometimes perceived to have the same shape, and excluding such responses from the analysis suggests that 63% is an over-estimate of infants' true ability. A more conservative estimate would be obtained by replacing each ambiguous response with a randomly chosen definite response, and including these in the analysis. Taking such considerations into account, this 63% preference may be compatible with the proportion of 'correct' responses (about 60%) found here in our youngest (4 year old) children.

4 Conclusion

The results reported here suggest that children interpret ambiguous shading information from symbol and naturalistic picture stimuli in an increasingly adult-like manner as they grow older. Our results do not rule out the possibility that children have an innate, but weak, predisposition for interpreting stimuli as if light comes from above, and that their ability to make use of this information increases throughout childhood. However, the precise nature of the mechanism that underpins this change with age is not known. It is possible that children require time to learn the statistics of the natural world, or that this information is not integrated optimally in their estimates of 3D shape (or both). Of course, it is also possible that the changes with age reported here are purely innate, but we consider this to be unlikely.

In conclusion, despite the fact that light has rarely come from below during the 540 million years since eyes first evolved, the fact that light usually comes from above does not seem to have been hard-wired into the human brain in the form of a strong innate light-from-above assumption.

Consent: Informed consent was obtained in all cases.

Acknowledgments: Thanks to two anonymous referees for their detailed and cogent criticisms, and to A Mercier and R Wilson for administering the tests.

A partial account of results reported here was reported in (Stone and Pascalis (2009)).

References

Adams, W., Graf, E. and Ernst, M. (2004), 'Experience can change the 'light-from-above' prior', *Nature Neuroscience* **7**(10), 1057–1058.

Brewster, D. (1826), 'On the optical illusion of the conversion of cameos into intaglios, and of intaglios into cameos, with an account of other analogous phenomena.', *Edinburgh Journal of Science* **4**, 99–108.

Granrud, C., Yonas, A. and Opland, E. (1985), ‘Infants sensitivity to the depth cue of shading’, *Perception and Psychophysics* **37**, 415–419.

Hershberger, W. (1970), ‘Attached-shadow orientation perceived as depth by chickens reared in an environment illuminated from below’, *J Comp Physiol Psychol* **73**, 407–411.

Hill, H. and Johnston, A. (2007), ‘The hollow-face illusion: Object-specific knowledge, general assumptions or properties of the stimulus?’, *Perception* **36**, 199–223.

Mamassian, P. and Landy, M. (2001), ‘Interaction of visual prior constraints’, *Vision Research* **41**, 2653–2668.

Poggio, T., Torre, V. and Koch, C. (1985), ‘Computational vision and regularization theory’, *Nature* **317**, 314–319.

Rittenhouse, D. (1786), ‘Explanation of an optical deception’, *Transactions of the American Philosophical Society* **2**, 37–42.

Stone, J.V., Kerrigan, I. and Porrill, J. (2009), ‘Where is the light? Bayesian perceptual priors for lighting direction’, *Proceedings Royal Society London (B)* **276**, 1797–1804.

Stone, J. and Pascalis, O. (2009), Where is the light? developmental priors for lighting direction, *in* ‘Society for Research in Child Development Conference’.

Sun, J. and Perona, J. (1998), ‘Where is the sun?’, *Nature Neuroscience* **1**(3), 183–184.

Thomas, R., Nardini, M. and Mareschal, D. (2010 (in press)), ‘Interactions between light-from-above and convexity priors in visual development’, *Journal of Vision* .

Yonas, A., Kuskowski, M. and Sternfels, S. (1979), ‘The role of frames of reference in the development of responsiveness to shading information’, *Child Development* **50**, 495–500.