Interactions between "light-from-above" and convexity priors in visual development

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Having a prior assumption about where light originates can disambiguate perceptual scenarios. Previous studies have reported that adult observers use a "light-from-above" prior as well as a convexity prior to constrain perception of shape from shading. Such priors may reflect information acquired about the visual world, where objects tend to be convex and light tends to come from above. In the current study, 4- to 12-year-olds and adults made convex/concave judgements for a shaded "polo mint" stimulus. Their judgments indicated an interaction between a "light-from-above" prior and a convexity prior that changed over the course of development. Overall, observers preferred to interpret the stimulus as lit from above and as mostly convex. However, when these assumptions conflicted, younger children assumed convexity, whereas older groups assumed a light from above. These results show that both priors develop early but are reweighted during childhood. A convexity prior dominates initially, while a "light-from-above" prior dominates later and in adulthood. This may be because convexity can be judged relative to the body, whereas judging the direction of light in the world requires the use of an external frame of reference.

Keywords: 3D surface and shape perception, shading, visual development

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Introduction

The idea that object perception might be influenced by the assumption that light comes from above was reported as early as 1826; Brewster (1826) described an illusion in which a physically convex surface appears concave (or vice versa) when lit from below. He also proposed a developmental trajectory for this phenomenon, suggesting that his younger participants were less susceptible to the illusion. More recently, experiments have confirmed that human adults use a "light-from-above" heuristic (e.g., Champion & Adams, 2007; Kleffner & Ramachandran, 1992; Ramachandran, 1988a, 1988b), but the developmental trajectory for its acquisition is still unclear. Perceptual heuristics may reflect either innately specified mechanisms or learning about the statistics of the visual world (Kersten, Mammassian, & Yuille, 2004). In Bayesian inference, a "prior probability distribution" represents *a priori* knowledge about the distribution of possible stimuli. Within this framework, the assumption that light tends to come from above can be termed a "light-from-above" prior. Recent findings that adults' perceptual priors can be altered through training (Adams, Graf, & Ernst, 2004; Champion & Adams, 2007) support the thesis that they depend on statistical learning. To study the time course of such learning, we tracked development of the "light-from-above" heuristic in 4- to 12-year-olds as compared with adults.

The classic stimulus used to test lighting assumptions when judging shape from shading (Ramachandran, 1988a, 1988b) is shown in Figure 1. Figure 1a could be perceived either as a bump lit from above, or a dent lit from below. However, having a "light-from-above" prior predicts a bias toward perceiving this shape as a bump (convex). In contrast, Figure 1b could either be perceived as a bump lit from below, or a dent lit from above; hence, a "light-from-above" prior predicts a bias toward perceiving this shape as a dent (concave). In research with these stimuli, human adults have responded consistently with a "light-from-

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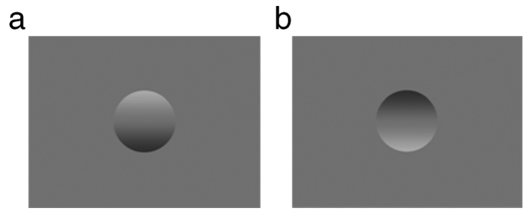


Figure 1. Examples of the classic bump/dent stimuli used to test lighting assumptions when judging shape from shading, with shading orientations (a) 0° and (b) 180° from the vertical.

above" prior (Champion & Adams, 2007; Kleffner & Ramachandran, 1992; Ramachandran, 1988a, 1988b). In addition, human adults respond more quickly to convex than to concave scenes, suggesting that they also have a weaker convexity prior biasing them to perceive shapes as convex rather than concave (Kleffner & Ramachandran, 1992).

Research is emerging which suggests that there might actually be a "light-from-above-left" heuristic (e.g., Mamassian & Goutcher, 2001; McManus, Buckman, & Woolley, 2004; Sun & Perona, 1998). Gerardin, de Montalembert, and Mamassian (2007) used a novel stimulus ("polo-mint," Figure 3) to investigate this possibility. Their "polo-mint" stimuli provide a compelling percept of 3D shape from shading and are not as easily reversible as the classic stimulus. When participants viewed these stimuli lit from 45 degrees to the left of vertical, they were more likely to respond as if the shape were lit from above than when they viewed the same stimuli lit from 45 degrees to the right. When stimuli were extremely blurred participants stopped responding differently to stimuli lit from left vs. right and instead showed a bias toward seeing most of the shape as convex.

Some studies have examined the development of priors constraining perception of shape from shading. Granrud, Yonas, and Opland (1985) found that 7-month-olds reached preferentially both for an actual convexity (where shape was indicated by both shading and binocular disparity) and for an image shaded to appear convex viewed monocularly (no binocular disparity). No reaching preference was shown when a flat image shaded to appear convex was viewed binocularly; this suggests that the shape information obtained from binocular disparity overrode the shape information available from shading. Five-month-olds only showed a preference when shading and binocular disparities both depicted a convexity. This suggests that from 7 months of age infants can perceive shape from shading. However, this experiment does not provide us with conclusive evidence that children have a "light-from-above" prior as the experiment was lit from above; hence, children could have used this explicit cue to lighting rather than relying on their own prior knowledge. Yonas, Kuskowski, and Sternfels (1979) found that children from 4 years of age tend to act as if objects are lit from above with respect to the orientation of their own bodies. Yonas et al. found that while explicit lighting cues and the gravitational frame of reference played a role in the way shading was interpreted, these cues were dominated by an egocentric frame of reference until around the age of seven. Finally, Stone and Pascalis (2009) presented children aged 7 to 11 with shaded images of geometric or natural shapes that could be perceived as either convex or concave, depending on assumed light direction. The youngest children tested (7-year-olds) assumed a light from above significantly more often than chance, and linear regression showed that the rate of responses assuming light from above increased with age.

Thus, although substantial work has been conducted into the "light-from-above" and convexity priors, no detailed comparison of their developmental trajectories has been established. The current study therefore investigated development of both "light-from-above" and convexity priors at ages 4 to 12 years, comparing performance with adults on the same task. Participants' lighting and convexity priors were examined using Gerardin et al.'s (2007) "polo-mint" stimuli.

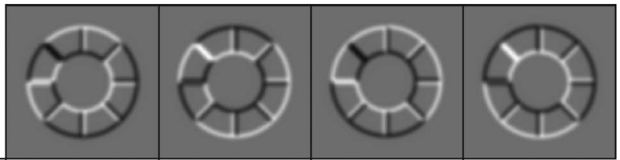
Method

Participants

Participants ranged in age from 4 to 22 years. For some aspects of analysis, participants were divided into the following age groups; 4- to 5-year-olds (n = 7, mean = 4.9, SD = 0.5 years), 6- to 8-year-olds (n = 17, mean = 7.4, SD = 0.8 years), 9- to 12-year-olds (n = 16, mean = 10.2, SD = 1.0 years), and adults (n = 11, mean = 21.1, SD = 1.8 years). Adult participants were recruited through word of mouth. Children were recruited from a database of volunteers. One participant (male, aged 7 years) was excluded from analysis as he gave the same response on every trial. All participants completed a control condition (see Footnote 1) before participating in the task.

Materials

The experiment was conducted in a room dimly lit using two 5-LED lights attached to the walls in front and behind the participant, in line with their mid-line, at a height of 1.34 m. These ensured that lighting in the room was not in any of the directions simulated within the study. Experimental stimuli were presented in E-Prime, on a Hewlett Packard G6000 notebook with a TFT screen with resolution 800 × 600 and 32-bit-color, refreshed at 60 Hz. The luminance of the three levels of gray used in the stimuli (see Figure 2) were 4, 23, and 43 cd/m^2. Participants viewed stimuli from a comfortable distance of approximately 40 cm. The images presented (see Figure 2)



'Light-from-above' and 'convexity' assumptions	Consistent	Conflicting	Consistent	Conflicting
Side of light if above:	Left	Left	Right	Right

Figure 2. Examples of the "Polo-mint" stimuli used. If an "above" light source is assumed then the stimuli show, from left to right, a mainly convex stimulus (i.e., with many raised pieces) lit from above-left, a mainly concave stimulus (i.e., with only one raised piece) lit from above-left, a mainly convex stimulus lit from above-right, and a mainly concave stimulus lit from above-right. Alternatively, if a "below" light source is assumed, then "mainly convex" items lit from above-left become "mainly concave" items lit from below-right and so on. Participants' judgements of whether few or many segments are raised therefore show their assumptions about light direction and convexity. Stimuli 1 and 3 could be both convex and lit from above, and therefore these assumptions are consistent with each other. In stimuli 2 and 4, "convexity" and "above" assumptions conflict in that both cannot be true at the same time. Images taken from Gerardin et al. (2007).

were those devised by Gerardin et al. (2007) and details of their composition can be found in that paper. Each image represents a complex shaded figure with eight segments, one of which appears either convex or concave relative to the rest. Each image is ambiguous in having two interpretations in terms of light direction and convexity. For example, the first stimulus in Figure 2 can be interpreted either as a mostly convex figure lit from above-left, or a mostly concave figure lit from below-right. Gerardin et al. investigated the effects of different levels of blur on shape judgments with these stimuli. To shorten the procedure, we used a single, intermediate level of blur throughout, a Gaussian filter with standard deviation 4 pixels.

The stimuli were 7.8 cm wide, taking up 11.1 degrees of viewing angle at distance 40 cm. The visual aid used was a three-dimensional model made from Styrofoam with a depth of 0.5 cm and a diameter of 10 cm. This model closely resembled the computer generated polo mint stimuli (Figure 2). The model had eight removable segments and was used to illustrate the idea that either one segment would be present or all but one segment would be present. This model was manipulated and seen from multiple angles so that its shape was apparent from many cues not present in the experimental stimulus (e.g., stereo disparity, motion, perspective, touch). This model did not mimic the shading found in the test stimuli as the odd segment was removed or was the only segment present rather than being at a different height to the other segments.

Procedure

For the main task, grayscale "polo-mint" stimuli (Figure 2) were presented and participants judged whether they perceived one or many raised segments. There were up to 96 trials: 8 segments × 2 consistency conditions × 2 lighting directions (total 32 trials) × up to 3 repetitions (see Figure 2), with a break after every repetition. Participants reported whether there appeared to be few raised pieces (i.e., the figure is mostly concave) or many raised pieces (i.e., the figure is mostly convex). These responses were scored in terms of whether the assumed light direction was from above or from below. In a 2 × 2 design, the four stimuli we used (Figure 2) varied (1) whether "light-from-above" and "convexity" assumptions are consistent with each other (i.e., whether both could be true at the same time) or not and (2) if the light is assumed to come from above, it comes from above-left or above-right. When "light-from-above" and "convexity" assumptions are consistent, having either or both assumptions predicts responding as if the light is coming from above. When these assumptions are inconsistent, observers must choose between them: either the stimulus is lit from above, but not convex, or the stimulus is convex, but not lit from above. By analyzing performance with respect to these factors, we assessed how convexity and light-from-above priors interact in development, and whether there is any difference in stimuli lit from the left vs. right.

Participants were encouraged to complete as many repetitions as possible—all but three (two in the 4- to 5-year group, one in the 6- to 8-year group) completed all three. Participants also completed a control condition, which confirmed that all age groups correctly interpreted the instruction to judge whether one or many pieces of a circle are presented.[1]

Children were told that they would earn a sticker if they concentrated on the task. Children aged below 6 years responded verbally and the experimenter entered their responses. Older children and adults responded using the left and right mouse keys to enter their response (left response indicated one piece raised, i.e., mostly concave). Images were presented until a response was made, with no limit to the response time available. We used an unlimited duration of presentation as during piloting with short display durations younger children reported not seeing any three-dimensional shape on a large proportion of trials.

This is likely to reflect slower processing of shape from shading in young children which would make it difficult to equate viewing times across participants of differing ages. An unlimited viewing duration avoided this difficulty. The experimenter sat behind the screen and was not aware of the stimulus being presented.

Results

To test for changes with age in any overall "light-from-above" bias, we examined the percentage of responses made as though stimuli were lit from above across all conditions of the "polo-mint" stimulus. Figure 3 plots individual percentages by age for children and adults. The majority of participants responded as though most stimuli were lit from above. The rate of responses consistent with light from above increased with age in the child group: a linear regression showed a significant increase with age (Figure 3); $r^2 = 0.262$, $F(1, 39) = 13.47$, $p = 0.001$. Points lying outside the two horizontal lines in Figure 4 correspond to participants whose responses differed significantly from chance (50%) on binomial test. The majority showed a statistically significant bias for perceiving the stimuli as lit from above, in proportions increasing with age. Although some participants, particularly younger ones, showed no statistically significant bias for perceiving the items as lit from above, only one participant performed outside of the chance levels as though they perceived the stimuli as consistently lit from below.

To examine interactions between light direction and convexity, participants were divided into age groups as described above and performance was compared across the four trial types (see Figure 2). Figure 4 shows the mean percentage of responses made as though the stimuli were lit from above for each trial type plotted by age group. When "light-from-above" and "convexity" assumptions were consistent, all age groups responded as though the stimuli were lit from above. When "light-from-above" and "convexity" assumptions conflicted, the percentage of responses given as though stimuli were lit from above increased with age, particularly for stimuli lit from "above-left." All but the youngest group responded consistently with a "light-from-above" assumption more often given stimuli lit from "above-left" than from "above-right." The youngest group responded consistently as if conflicting stimuli were lit from below, i.e., they interpreted them as convex, even though this entailed assuming that the light was from below.

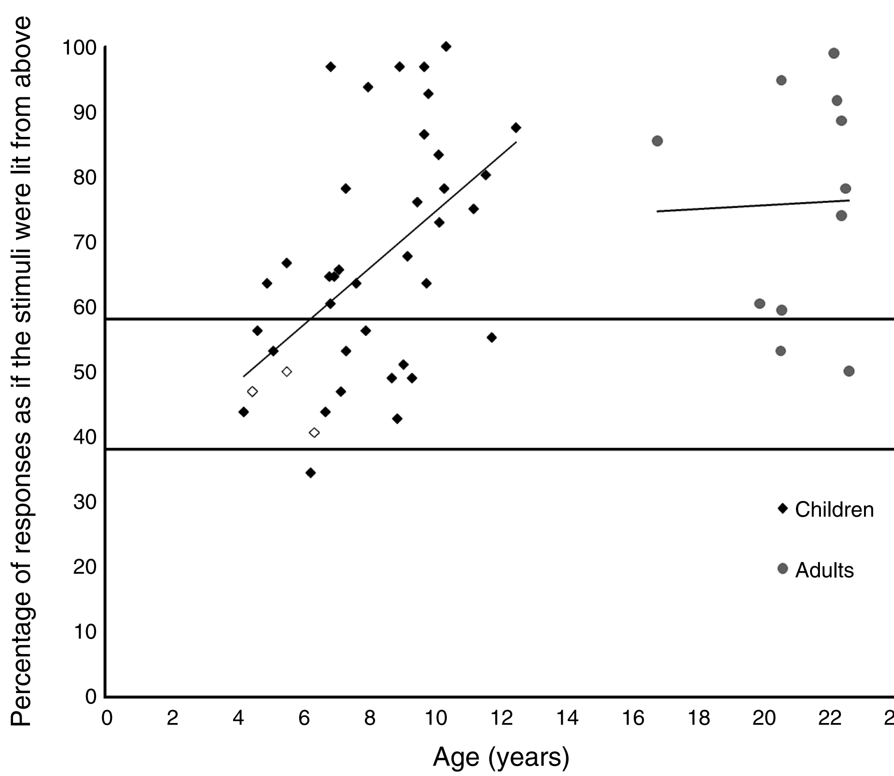


Figure 3. Scatter plot showing total percentage of responses made as though stimuli were lit from above by age. Lines of best fit have been plotted separately for children and adults. For participants who completed all trials (filled symbols), values falling outside the interval indicated by the two horizontal lines differ significantly from chance at the 5% level on binomial test. For participants who did not complete all trials (n = 3, open symbols), lines corresponding to significant difference from chance (not shown) are wider than those shown. Therefore, none of these participants scored outside the chance range.

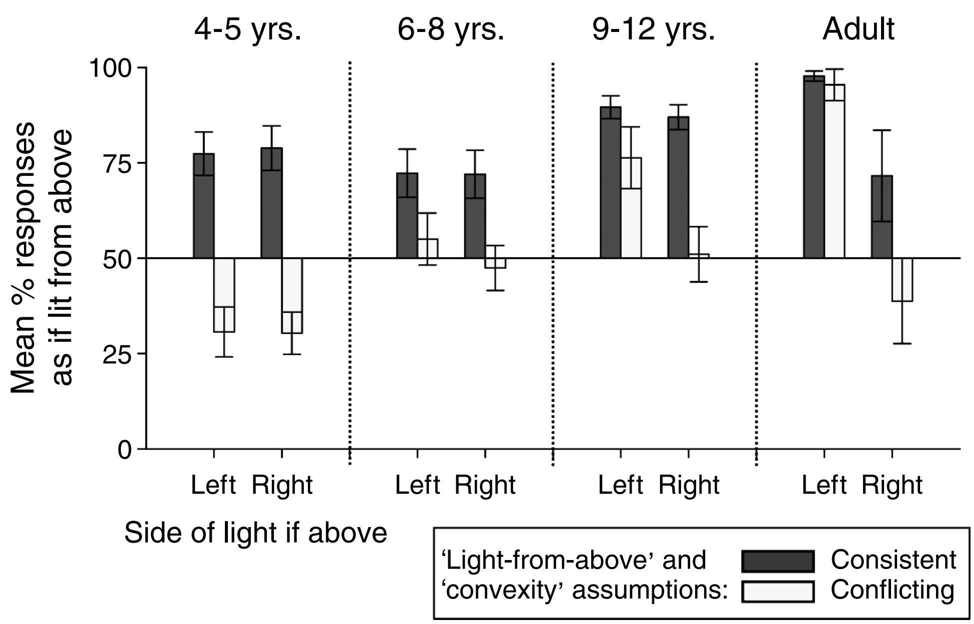


Figure 4. Mean ± *SEM* percentages of trials on which participants responded as though the stimulus was lit from above by age group, consistency between assumptions, and light direction.

An ANOVA was performed on the data in Figure 4 (n = 51) with *Assumption consistency* (consistent vs. conflicting) and *Light direction* (left if above vs. right if above) as within-subjects factors and *Age* as a between-subjects factor. There was a main effect of *Light direction* on the number of responses made as though the stimuli were lit from above; overall, participants were more likely to respond as though stimuli were lit from above when the "above" interpretation entailed above-left light than when it entailed above-right light, $F(1, 47) = 23.66$, $p < 0.001$. There was also a main effect of *Assumption consistency* on the number of responses made as though the stimuli were lit from above; overall, participants were more likely to respond as though the stimuli were lit from above when this was also consistent with interpreting the majority of the polo-mint as convex, $F(1, 47) = 46.68$, $p < 0.001$. There was a main effect of *Age*, with the number of trials on which participants responded as though the stimulus was lit from above increasing with age, $F(3, 47) = 4.29$, $p = 0.009$. There was a significant interaction between *Light direction* and *Age*, $F(3, 47) = 8.91$ $p < 0.001$; the increase in responses consistent with a "light-from-above" assumption was greater for trials on which the "above" interpretation entailed light from "above-left" than "above-right" (Figure 4). There was also a significant interaction between *Assumption consistency* and *Light direction*, $F(1, 47) = 18.64$, $p < 0.001$; overall, participants responded most consistently with a "light-from-above" assumption in the condition in which stimuli could be interpreted as both lit from the above-left and mainly convex (i.e., the first condition plotted at each age in Figure 3). The interaction between *Assumption consistency* and *Age* was not significant, $F(3, 47) = 2.18$, $p = 0.103$. There was a significant three-way interaction, $F(3, 47) = 3.32$, $p = 0.028$. One way to describe this interaction is that while judgements for stimuli in which "light-from-above" and convexity assumptions were consistent changed relatively little over development (they tended to be perceived as lit from above, with some preference for above-left-lit stimuli emerging with age), judgements for stimuli in which these assumptions were inconsistent changed from an early assumption that they were lit from below and convex at 4 to 5 years to a later assumption that they were lit from above when the light could be interpreted as above-left, but not above-right.

In sum, these results showed that convexity and "light-from-above" assumptions interact and that this interaction changes in development. An early tendency to interpret stimuli as convex (even when this requires an assumption that the light is coming from below) was supplanted by a later tendency to prefer a concave interpretation when this meant assuming a light from above, as long as the light is "above-left." A preference for convexity remained in adults given instances of conflict where the observer had to choose between a convex interpretation with "below-left" lighting or a concave interpretation with "above-right" lighting.

Discussion

The majority of participants responded to the polo-mint stimuli as if they were lit from above. Most of those who did not show this pattern were within chance intervals. Only one participant showed a pattern of responses that differed significantly from chance and was consistent with the assumption that the stimuli were lit from below. This is in agreement with previous findings (e.g., Ramachandran, 1988a, 1988b).

Analysis of conditions by *Assumption consistency* and *Light direction* factors showed several overall biases and developmental changes. Both factors influenced judgements; overall, stimuli were most likely to be perceived as lit from above when this was consistent with them being convex, rather than inconsistent, and when the direction of light could be interpreted as above-left rather than above-right. However, these effects changed with age. Most significantly, the way in which conflicts between "light-from-above" and convexity assumptions were resolved changed. The youngest group resolved such conflicts by assuming convexity, and disregarding whether this would entail light from above or below. By adulthood, this was replaced by a response also taking left vs. right direction into account. When light from above and convexity assumptions conflicted, adults favored a light-from-above-left interpretation over convexity but favored convexity over light-from-above-right. Our adult data are consistent with the results reported by Gerardin et al. (2007), which indicates that despite unlimited viewing duration our participants still experienced the polo-mint stimuli in the same manner.

The youngest children's persistent assumption of convexity could be likened to the widely reported "hollow-mask" illusion (e.g., Gregory, 1997) in which a concave mask lit from above is perceived as a convex mask lit from below. In this illusion, prior knowledge of faces' convexity appears to dominate over any knowledge that light tends to come from above. It seems that the youngest children in the present study made a similar assumption of convexity even for simple non-face stimuli. Adults' convexity assumption for faces, evident in the "hollow mask" illusion, could result from gradual narrowing of an early developing broad assumption that all shapes tend to be convex.

In children, we found a significant overall increase with age in the proportion of trials interpreted as though the stimulus was lit from above. This suggests that the "light-from-above" prior is developing across this time period. We also found that, overall, participants were more likely to respond as though the "polo-mint" stimuli were lit from above when this entailed light from above-left than light from above-right, with this effect getting stronger with increasing age.

As yet there is no satisfactory explanation for why observers might have a leftward bias in their assumed lighting position or why stimuli such as the polo-mint stimuli might be perceived differently given light from above-left compared with above-right. In various studies factors such as handedness (Sun & Perona, 1998), head-tilt (McManus et al., 2004) and cerebral lateralization (Mamassian & Goutcher, 2001) have been found to relate to bias in lighting assumption. Other potential avenues for future developmental research include studying differences in visual scanning or cultural differences.

We found an interaction between convexity and light-from-above priors, which changed with age. While younger participants relied on a convexity prior (even when this conflicted with a light-from-above assumption), with increasing age participants began to overcome this bias in favor of a light-from-above assumption, but only in instances when the light can be interpreted as above-left, and not above-right. In older participants, an above-left bias strongly dominates over a convexity bias; however, there is no similarly strong above-right bias.

In summary, this research has brought us a step closer to discovering when and how convexity and "light-from-above" priors emerge. It seems that 4-years-olds are biased toward perceiving all stimuli as convex, but a stronger light from above (left) bias comes to dominate over the convexity bias, although it continues to have an effect and may remain strong for particular stimuli (e.g., the hollow mask). From a very young age, infants explore objects tactually (particularly with their mouths, e.g., Rochat, 1983) and hence have experience of convexity. Meanwhile, light may be a less salient cue while vision is developing, and in addition light does not come from a consistent direction relative to one's own body (which is the frame of reference used in judging shape from shading until around 7 years of age; Yonas et al., 1979) until children are able to walk. The need to calculate light direction using an external frame of reference could prevent children from acquiring a stable "light-from-above" assumption until later in development.

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Footnote

[1]Participants completed 16 trials in which they judged whether a circle divided into 8 segments (like the polo-mint) had many segments or only one segment colored yellow. Four- to five-year-olds answered correctly on 98% of trials; 6- to 8-year-olds answered correctly on 97% of trials; 9- to 12-year-olds answered correctly on 94% of

trials and adults answered correctly on 97% of trials. This confirmed that all ages understood the judgement required for the task of the study.

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