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Developmentally distinct gaze processing systems: luminance versus geometric cues

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Abstract

Two experiments examined how the different cues to gaze direction contribute to children's abilities to follow and make explicit judgments about gaze. In each study participants were shown blurred images of faces containing only luminance cues to gaze direction, line-drawn images containing only fine-grained detail supporting a geometric analysis of gaze direction, and unmanipulated images. In Experiment 1a, 2- and 3- year olds showed gaze-cued orienting of attention in response to unmanipulated and blurred faces, but not line-drawn faces. Adult participants showed cueing effects to line drawn faces as well as the other two types of face cue in Experiment 1b. In Experiment 2, 2-year-olds were poor at judging toward which of four objects blurred and line-drawn faces were gazing, whereas 3- and 4-year-olds performed above chance with these faces. All age groups performed above chance with unmanipulated images. These findings are consistent with an early-developing luminance-based mechanism, which supports gaze following, but which cannot initially support explicit judgments, and a later-developing mechanism, additionally using geometric cues in the eye, which supports explicit judgments about gaze.

1. Introduction

Knowing what someone is attending to is one of the most fundamental 'theory of mind' abilities. Tracking attention is required to determine the content of more complex representational mental states such as knowledge or belief. Consequently, understanding of visual attention has been argued to be a precursor to understanding belief. As Gómez (1996) puts it, understanding eye direction is "an early and simple way to know what is in the other's mind, because the contents of the other's mind – the object looked at – is in front of the beholder's eyes" (p.334). Researchers on infant gaze-following typically conceptualise infants' understanding in terms of representational mental states. For example, Butler, Caron, and Brooks (2000) suggest that following an adult's gaze direction indicates that children understand "that there is a psychological and attentional relation between adult and target". This view is consistent with recent findings of early sensitivity to others' false beliefs from late infancy (Clements & Perner, 1994; Onishi & Baillargeon, 2005; Southgate, Senju, & Csibra, 2007).

Gaze-following[1] ability may be present in rudimentary form early in infancy. Hood, Willen, and Driver (1998) found that 4-month-olds' attention could be cued by an image of a face executing a gaze shift to one side, without a concomitant head turn. This only occurred when the face vanished before target onset, suggesting limitations on infants' ability to shift their attention. Naturalistic following of shifts in eye-direction alone can be reliably demonstrated by the age of 18 months (Moore & Corkum, 1998).

However, while they are able to *follow* gaze from infancy, children cannot make *explicit judgments* about the same stimuli until the age of about 3 years. For example, Doherty and Anderson (1999) found that only a minority of 3-year-olds and not all 4-year-olds were capable of judging which of four widely separated objects a schematic face was looking at, or which of two schematic faces was apparently looking at them. This difficulty is not limited to schematic faces, but also occurs with photographs (Anderson & Doherty, 1997; Doherty, Anderson, & Howieson, 2009) and in live interaction with a real person (Doherty & Anderson, 1999). The problem was not simply one of failing to understand the task, as the same children who were unable to judge gaze direction were well above chance in judging at which of the four objects a person was pointing (Doherty & Anderson, 1999; Doherty et al., 2009) or gazing, if the head also pointed in that direction (Doherty & Anderson, 1999). These findings seem to challenge the view, summarised above, that gaze following gauges a relatively sophisticated understanding of a psychological relationship between gazer and target.

How is it that children who can follow gaze, and who can make explicit judgments about pointing or head-and-eye direction cannot make such judgments solely on the basis of eye direction? Here we investigate the possibility that this is because infants' gaze following and older children's gaze judgments involve different aspects of visual information about gaze direction: luminance cues and the geometrical properties of the eye.

Ando (2002) has proposed that these two sources of information may each contribute to the perception of gaze direction. For example, the relative luminance of the iris and sclera can yield a measure which is proportional to the angle of rotation of the eye in the head (see also Langton, Watt, & Bruce, 2000), while a geometrical analysis involving, say, the spatial location of the iris within the eye region can also provide a measure of eye rotation. The luminance mechanism is likely to be fast but coarse, the geometrical mechanism slower but more precise, through operating at a higher spatial resolution.

Our suggestion is that the gaze following ability of children up to 2 to 3 years of age is likely to be based predominantly on luminance information. Certainly this seems likely for gaze following in early infancy: four-month-olds' visual acuity is poor – around 40 times lower than that of a normal adult (de Heering et al., 2008) – which limits their ability to resolve the edge between the iris and sclera necessary for geometrical analysis of gaze direction; however, they *are* able to perceive contrast at very low spatial frequencies (Banks & Salapatek, 1978), which should allow them to use the gross luminance configuration of the eye in order to compute gaze direction.

Furthermore, we suggest that children's gaze perception continues to be dominated by luminance information until around 3 years of age when they start to be able to make explicit judgments about the objects of other people's gazes (Doherty et al., 2009). This ability is initially fragile, however: 3-year-olds cannot yet distinguish between gaze to targets separated by 10 or 15 degrees of visual angle (Doherty et al., 2009). Development then proceeds gradually, not reaching adult levels of sensitivity until around 10 years of age (e.g., Vida & Maurer, 2012). This pattern of development, from very limited ability to make fine discriminations at 3 years and protracted gradual development thereafter, suggests children are acquiring a new skill. We suggest that this skill involves the use of precise geometric cues in the eye to compute gaze direction on the basis of which a verbal report can be given. If children were simply making the output of their existing luminance-based ability available to verbal report, we would expect a more rapid development of judgment precision.

In summary, the suggestion is that gaze-cued attention is initially based on gross luminance information about eye direction. On the other hand, explicit judgments, which children make from around 3 years of age, additionally rely on more precise information derived from assessing the spatial configuration of eye features.

These suggestions lead to two key predictions. First, the gaze-following abilities of 2- to 3-year-old children will be dominated by luminance cues in the eye. Gaze-following should therefore be impossible if the relevant luminance information is removed. Second, at around 3 years of age children will begin to use geometric cues in the eye in order to make explicit gaze judgments. We report three studies that test these predictions. In Experiment 1a we tested gaze-following in a sample of 2- and 3-year-old children, and adults in Experiment 1b. In Experiment 2 we examined explicit gaze judgment in samples of 2-, 3-, and 4-year-olds. In each study we presented three different types of face cue: normal greyscale photographs, which contain both gross luminance and geometrical cues; blurred versions of these faces which retain luminance cues to gaze direction but where the precise spatial locations of the relevant eye features are difficult to resolve; and line-drawn versions where the spatial locations of eye features are available (geometric cues), but gross luminance cues to gaze direction are removed.

2. Experiment 1a

In Experiments 1a and 1b we used a gaze-cued orienting procedure. Toddlers were asked to identify which of two children's TV characters appeared briefly on a computer. Prior to the character's appearance, a face appeared on the screen either gazing towards the location where the character was to appear (a cued trial) or gazing in the opposite direction (an uncued trial). Gaze-following was operationalized as increased accuracy identifying the character in cued versus uncued locations. The key manipulation concerned the availability of the two cues to gaze direction: face images contained only luminance cues (blurred faces), only geometric cues (line-drawn faces) or both cues (normal faces). We hypothesise that 2- to 3-year-olds only have the luminance mechanism available for analysing gaze direction. They should therefore show a normal gaze-following response to images containing luminance cues (the normal and blurred faces) but not to faces that only contain geometrical cues (line drawn images). Adults have been found to show a gaze-cued orienting response with luminance-free images (Langton, 2011); however, reaction time was used as the dependent variable in this study, and the images used were created using an edge detection algorithm applied to a greyscale image of a face. The images produced in this way, and through methods such as high-pass filtering are not particularly child friendly, so a different method was adopted to produce the corresponding images for Experiments 1a and 1b. Experiment 1b was conducted in order to establish whether these images are also capable of triggering a typical gaze following response in adult participants.

2.1. Method

2.1.1. Participants.

Participants were 45 children: 21 2-year-olds (10 girls, mean age = 2 years 8 months (2;8), *SD* = 3.4 months, range = 2;0 to 2;11) and 24 3-year-olds (11 girls, mean age = 3;6, SD = 3.9 months, range = 3;0 to 3;11).

2.1.2. Materials and apparatus

Cue images portrayed a Caucasian female with dark hair and dark eyes and were obtained under good quality fluorescent lighting. Three images were obtained, all with the head facing forward: one with the eyes directed towards the right, one with the eyes directed towards the left and one with the eyes directed straight ahead. The latter was used as a template onto which the left and right eye regions from the respective images were pasted using Adobe Photoshop Elements 5.0. The resulting leftwards and rightwards gazing images were therefore identical, save for the gaze direction. The images were then cropped to show the head and hair on a white background, scaled to 539 x 489 pixels and converted to greyscale. Blurred cue images were created by applying a Gaussian filter with a radius of 10 pixels to the original images. Line-drawn images were created in Adobe Photoshop by using the paintbrush tool to trace the outline of the model's head and facial features (see Fig. 1). The cue images subtended a horizontal viewing angle of approximately 9º at a distance of 70 cm. Target images of the TV animation characters Fireman Sam and Bob the Builder were cropped to show only the head including helmets and scaled to 113 x 123 pixels. They were shown in colour and were positioned approximately 9º to the left or right of the centre of the screen (see Fig. 2). Stimuli were presented using E-Prime 2.0 software on a desktop PC with a

17-inch LCD monitor at 1280 x 1024 resolution. Responses were recorded via a standard keyboard.

Fig. 1. Examples of the face stimuli used in the experiments. Left, a normal face image; centre, a blurred image; and right, a line drawn image.

2.1.3. Design

Cue type (normal vs. blurred vs. line-drawn image) and trial type (cued vs. uncued) were within-subjects variables and age group (2-year-olds vs. 3-year-olds) a between-subjects variable. The dependent variable was the proportion of trials in which the child correctly identified the target stimulus.

2.1.4. Procedure

Participants played with the experimenter prior to formal testing in a room adjoining the main nursery. The procedure commenced with a series of practice trials; on the first screen images of Bob the Builder and Fireman Sam were shown and the children were asked to name them; if they did not know either the experiment was halted. Children were instructed to look out for Bob and Sam and call out the name when one appeared. The first practice trial showed a single image of Fireman Sam's head. If the child did not respond they were asked who was in the picture. The second practice trial showed Bob the Builder. The experimental trials commenced if the child could recognise and identify both target images. Children were encouraged to watch carefully because Bob and Sam would be very fast.

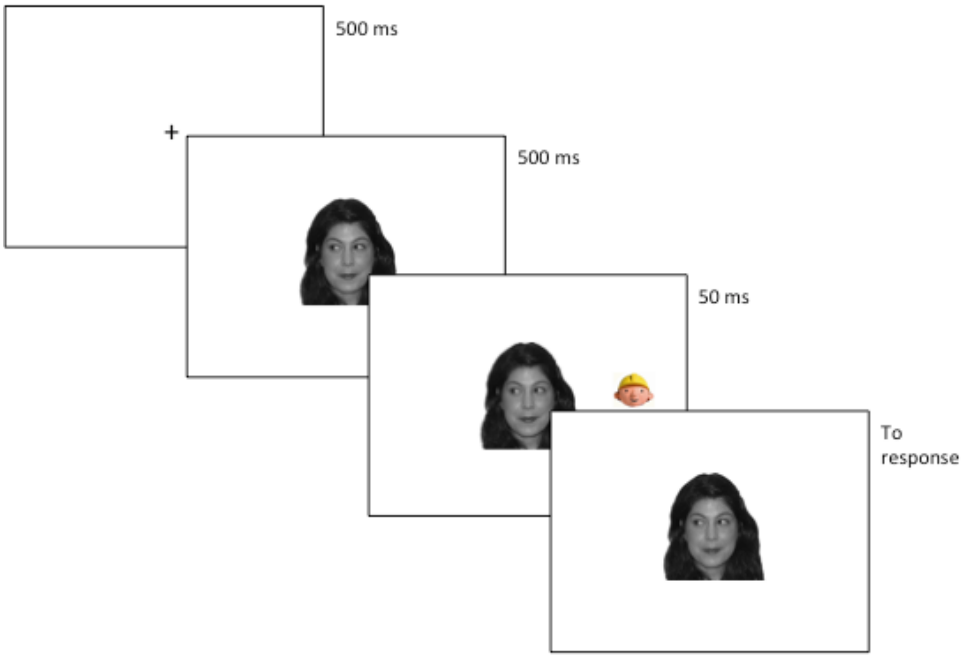

Fig. 2. An example of the sequence of events in a trial of Experiment 1.

Each experimental trial began with a fixation cross in the centre of the screen for 500 ms. The cue face was then shown in the centre of the screen. After 500 ms the target item was shown to the left or the right of the cue face for 50 ms. The cue face remained on screen until the child responded (see Fig. 2). Experimental trials were blocked by cue type, 8 for each type of image. The 8 trials within each block arose from combining each target identity (Bob and Sam) with both levels of trial type (cued and uncued) and each gaze direction (left and right). Trials were randomised within each block. The order of blocks was counterbalanced across participants.

2.2. Results

The proportions of correctly identified targets in cued and uncued trials for each face type were computed (see Fig. 3.). Target identification accuracy was greater for cued targets than for uncued targets for normal and blurred face trials. However, this cueing effect was not apparent with line drawn face cues; there was little difference in 3-year-olds' identification of uncued and cued targets and two-year-olds' accuracy was actually greater for uncued trials.

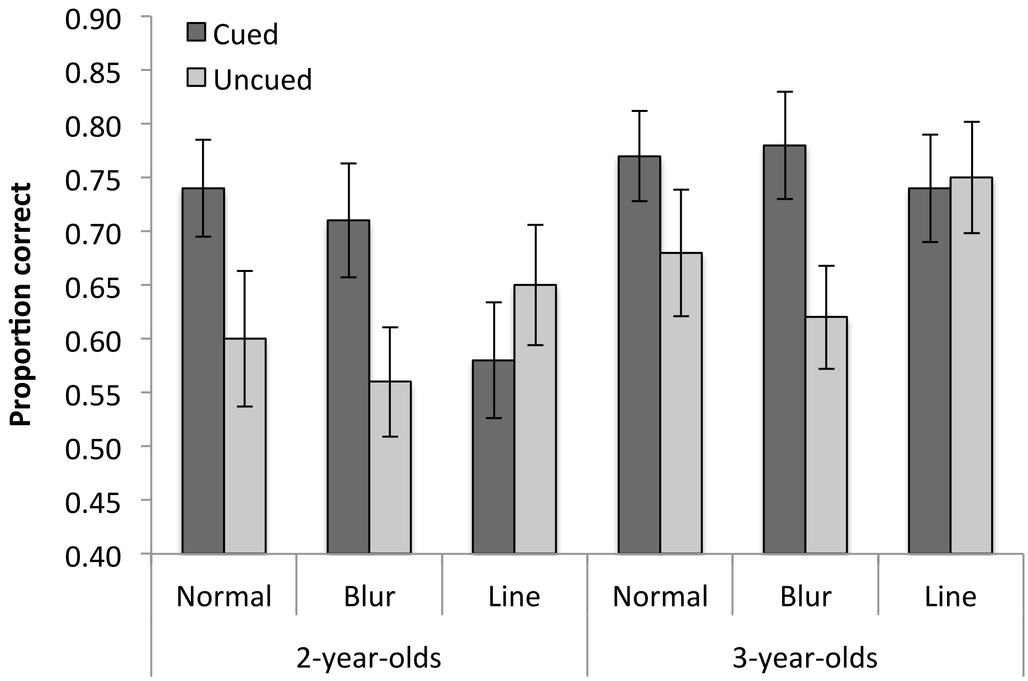

Fig. 3. Proportion of correct target identification responses in each condition of Experiment 1. Error bars represent the standard error of the mean

A repeated measures analysis of variance (ANOVA) was conducted with cue type (normal, blur, line) and trial type (cued, uncued) as within-subjects factors and age (2-year-olds, 3-year-olds) as a between-subjects factor. This analysis yielded significant main effects of age, $F(1, 43) = 4.08$, $p < .05$, $\eta_p^2 = .09$, and trial type, $F(1, 43) = 7.41$, $p < .01$, $\eta_p^2 = .15$, and a significant interaction between cue type and trial type, $F(2, 86) = 5.46$, $p < .01$, $\eta_p^2 = .11$. No other effects or interactions reached significance (*p*s > .54). The interaction between cue type and trial type was followed up using simple main effects analyses. These confirmed that for normal face images, targets were identified on a higher proportion of cued trials ($M = .75$) than uncued trials ($M = .64$), $F(1, 44) = 4.73$, $p < .05$. Similarly, for blurred images, accuracy was higher for cued targets (*M* = .75) than for uncued targets (*M* = .59), $F(1, 44) = 16.35$, $p < .001$. However, for line-drawn cues, the difference in accuracy between cued targets (*M* = .66) and uncued targets (*M* = .70) was not significant ($p = .40$).

2.3. Discussion

As predicted, 2- and 3-year-old children showed evidence of gaze cueing from luminance cues (blurred faces) and combined luminance and geometric cues to gaze direction (normal faces), although the latter effect just failed to reach statistical significance; however there was no evidence whatsoever of gaze cueing in response to faces where luminance information was removed (line-drawn faces). These data support the hypothesis that preschool children's gaze-following is based on a luminance mechanism for processing gaze direction. These children have either not yet learned to use geometric gaze cues to determine gaze direction, or this ability has not yet been coupled with the system that orients attention to gaze.

One problem with this conclusion is that it is not known whether these cues can ever be used to trigger the kind of automatic gaze following response studied in Experiment 1a. This issue was addressed in Experiment 1b, which employed a modified version of the procedure used in Experiment 1a with a sample of adult volunteers.

3. Experiment 1b

3.1. Method

3.1.1. Participants

These were 24 undergraduate students (15 female) from the University of Stirling with a mean age of 26.

3.1.2. Materials, Design and Procedure

These were identical to those used in Experiment 1a, with the following exceptions. To ensure that adults did not perform at ceiling in the task, the presentation time of the targets was reduced to 32 ms and they were immediately followed by a pattern mask, which remained on the screen until participants responded with a keypress. Pilot testing indicated that this exposure duration yielded correct identification on around 75% of trials. Participants performed 12 practice trials with a 200 ms exposure duration of the target stimuli and a representative set of all possible trial types. The experimental trials were divided into three blocks according to cue type, with block order counterbalanced across participants. Each block contained 32 trials, with 4 repetitions of each combination of target location (cued vs. uncued), target identity (Sam vs. Bob), and gaze direction (left vs. right). Trials were presented in a random order within each block. A set of 8 practice trials, this time with the 32 ms target exposure duration, preceded each block.

3.2. Results

The proportions of correctly identified targets in each condition were first computed. Data were removed from 5 participants who scored below 50% correct in one or more of the experimental conditions. Data from the remaining 19 participants are summarised in Figure 4.

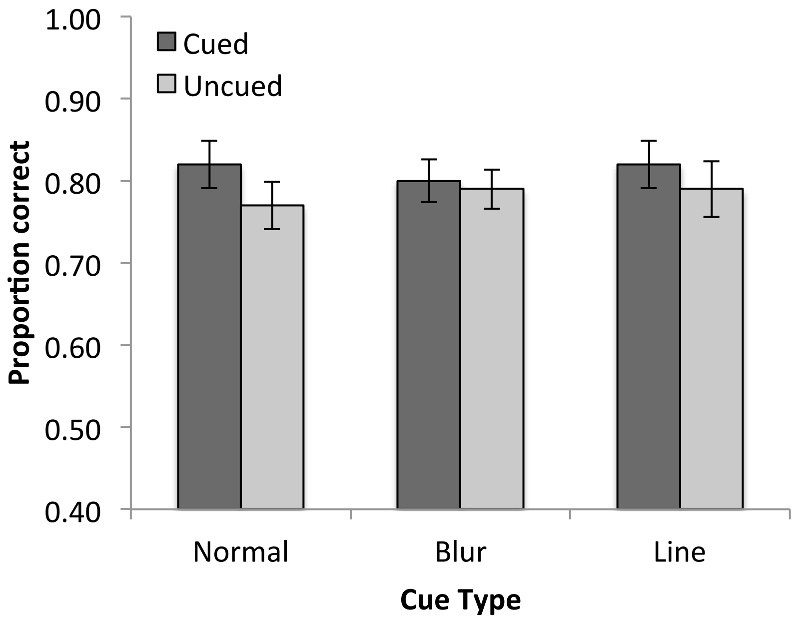

Fig. 4. Proportion of correctly identified targets in each condition of Experiment 1b. Error bars represent the standard error of the mean.

Participants correctly identified a higher proportion of targets at cued (M = .82) versus uncued locations (M = .78). A repeated measures ANOVA with cue type and trial type as factors supported this observation. This analysis yielded only a significant main effect of trial type, $F(1, 18) = 5.21$, $p < .05$, $\eta_p^2 = .22$. Neither the main effect of cue type nor the interaction between cue type and trial type reached significance (ps > .66)[2]. Because our hypothesis was specifically that line drawn images would yield more accurate target detection at cued than at uncued locations, a planned, one-tailed, paired samples t-test was conducted on the relevant data. This indicated a marginally significant advantage for cued targets (M = .82) over uncued targets (M = .79), $t(18) = 1.40$, $p = .09$.

3.3. Discussion

The results of this experiment indicate first, that a gaze following effect can be found with adult participants when accuracy is used as the main dependent variable. This result in itself is remarkable as it contradicts Prinzmetal, Leonhardt and Garrett’s (2008) claims that non-predictive gaze direction only has an effect on reaction time to targets, and does not enhance the accuracy with which targets are perceived. Our results clearly suggest that gaze direction *can* influence accuracy.

Second, although the gaze following effect did not interact statistically with the type of cue, the pattern of results suggests that gaze following in adults is primarily driven by images containing both luminance and geometrical cues, but can also be triggered on the basis of geometrical information alone: line drawn images produced a near-significant effect on target identification accuracy. The conclusion that line drawn images are capable of triggering gaze following in adults is bolstered by findings reported by Langton (2011), mentioned in section 2. Adult volunteers showed a similar pattern of data to that reported here, but with RT as the dependent measure[3]. The failure to observe gaze following on the basis of geometric cues in 2- and 3-year-olds in Experiment 1a is therefore not simply a consequence of the inability of these cues to generate an effect.

The results of Experiments 1a support our hypothesis that preschool children's gaze following relies on luminance cues to gaze direction. Our second hypothesis concerned explicit judgments about gaze direction. The suggestion was that children make use of geometrical information about gaze direction when making explicit judgments, which they do not do until around 3 years of age. Experiment 2 was designed to test this prediction.

4. Experiment 2

Children aged between 2 years 1 month and 4 years 11 months were asked which of four objects normal faces, blurred faces and line-drawn faces were looking at. Based on our hypothesis and previous findings (e.g., Anderson & Doherty, 1997; Doherty & Anderson, 1999; Doherty et al., 2009) we predicted that 2-year-olds would perform poorly with all kinds of images, but that children 3 years and older would succeed with all stimuli, including line-drawn images.

4.1. Method

4.1.1. Participants

Seventy-six children participated, in three age groups: 25 2-year-olds (17 girls, mean age = 2;7, *SD* = 3.5 months, range = 2;1 to 2;11), 24 3-year-olds (9 girls, mean age = 3;6, *SD* = 3.9 months, range = 3;0 to 3;11), and 27 4-year-olds (12 girls, mean age = 4;5, SD = 4.9 months, range = 4;0 to 4;11).

4.1.2. Materials and apparatus

Four greyscale images were obtained at the same time, under the same conditions of the same female as in Experiment 1. Each showed the eyes looking to one corner of the screen. Normal, blurred and line-drawn versions of each image were created as in Experiment 1 and rescaled to the same size (Fig. 5). Practice trials used three greyscale images of another female's face, looking left, right and straight ahead. These images measured 286 x 363 pixels and subtended a viewing angle of approximately 6º at a viewing distance of 70 cm.

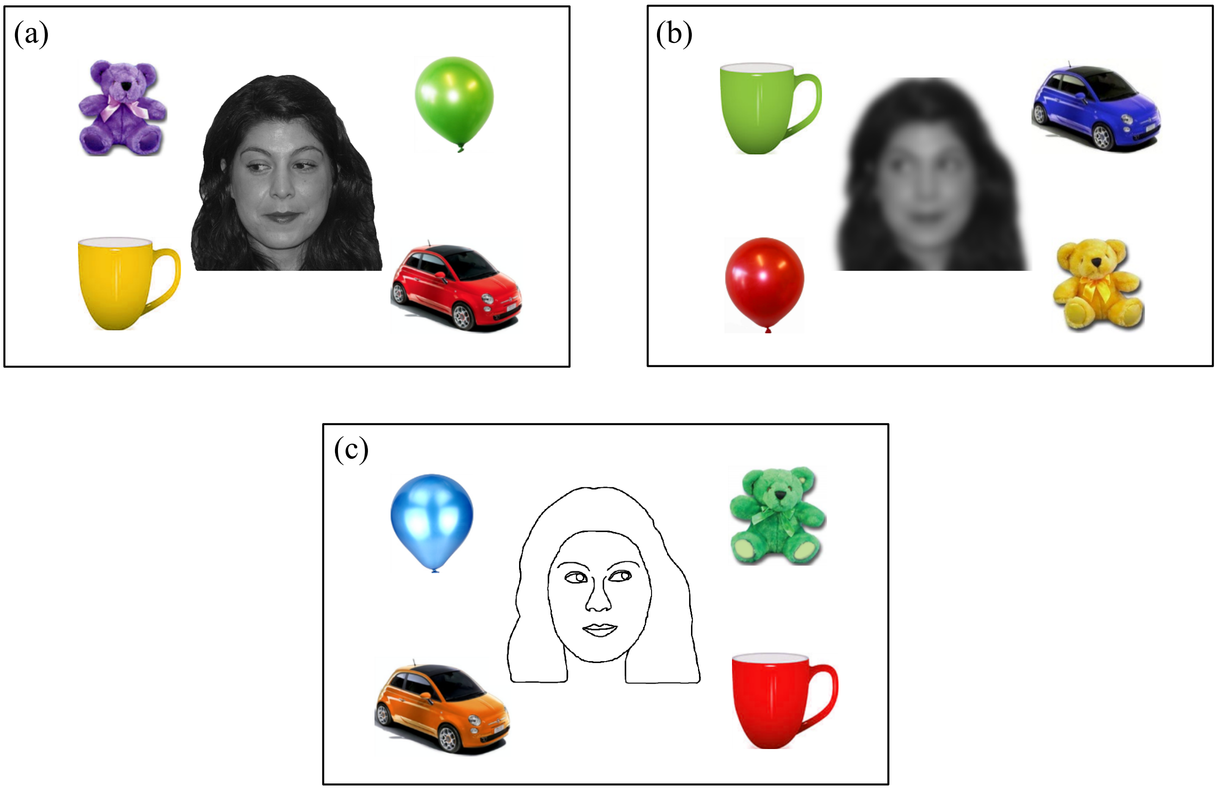

Fig.5. Examples of the displays used in the explicit gaze judgment task of Experiment 2. A normal face with a bottom-left gaze (a), a blurred face with a top-left gaze (b), and a line-drawn face with a top-right gaze (c).

Target images showing a mug, a balloon, a car, and a teddy bear were scaled to 227 x 239 and subtended a viewing angle of approximately 3°. A different version of each target image was created in red, yellow, orange, purple, green and blue, adjusted using Adobe Photoshop to ensure approximately equivalent hue. To control for potential colour and item preferences, 24 variations of item position and the colour were created, and sampled pseudo-randomly; each object differed in colour, and the same pattern of colour and target items never occurred twice for a given participant.

The experiment was presented using E-Prime 2.0 on a Toshiba Tecra laptop with a 17 inch screen at 1280 x 720 resolution; responses were recorded by the experimenter via the keyboard.

4.1.3. Design

The materials were tested in a 3 x 3 factorial design with a between-subjects factor of age group (2- vs. 3- vs. 4-year-olds) and a within-subjects factor of cue image (normal vs. blurred vs. line-drawn). The dependent variable was the proportion of correct identifications of the target item.

4.1.4. Procedure

Participants were invited to play a game with the experimenter individually in a room adjoining the main nursery. Practice trials began with an image of a Caucasian female looking left. Children were asked where the lady was looking. If they did not respond the experimenter pointed to the left side of the screen and asked “is she looking over here?” This sequence was repeated for the rightward and forward gazing faces. The final practice trial showed the four target images without a central face. The experimenter asked the child to point to each item in turn.

Each experimental trial showed a cue image in the centre of the screen looking at one of the target items, positioned in the corners of the screen (see Fig. 5). The experimenter asked the child to point to what the lady was looking at. If the child did not appear to understand, on the first trial they would also be asked what the lady’s eyes were looking at. Images remained on the screen until children responded.

Each child completed 8 trials with each of the 3 types of face image (normal, blurred and line-drawn), with each gaze direction seen twice for each type of face. Trials were blocked by image type; order of block presentation was counterbalanced across children. Trials were selected randomly within each block.

4.2. Results

Figure 6 shows the proportion of correct explicit judgements for each age group for each face type. The same pattern is evident across all ages: performance was superior with normal images compared with blurred and line drawn images.

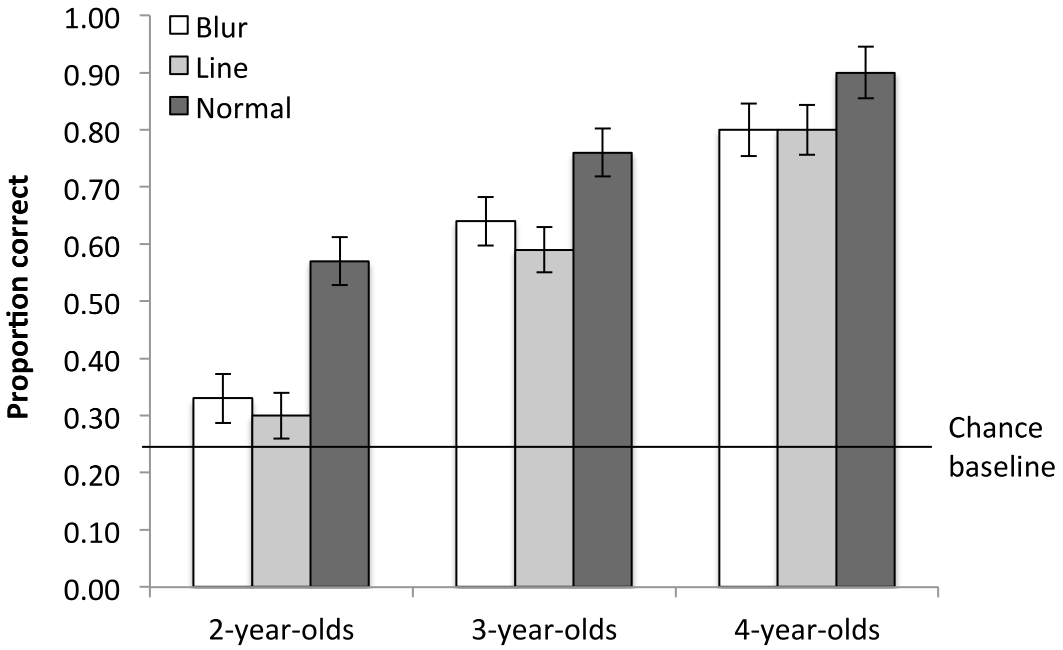

Fig. 6. Proportion of correct responses in each condition of the explicit judgement task in Experiment 2. Error bars represent the standard error of the mean.

Proportions of correct responses were entered into an ANOVA with age group as a between-subjects factor and face type as a within-subjects factor. This analysis yielded main effects of age, $F(2, 73) = 47.79$, $p < .001$, $\eta_p^2 = .57$, and of face type, $F(2, 146) = 22.72$, $p < .001$, $\eta_p^2 = .24$. The interaction between face type and age was not significant ($p = .15$). Fisher's LSD tests confirmed that performance was superior for normal faces ($M = .75$) than for line-drawn images ($M = .57$), $t(146) = 6.23$, $p < .001$, and blurred images ($M = .59$), $t(146) = 5.39$, $p < .001$, for which performance was equivalent ($p = .40$). Separate one-sample t-tests comparing proportion correct scores to chance (.25) for each face type indicated that the 2-

year-olds performed at chance for line-drawn images (*M* = .30), *t*(24) = 1.83, *p* = .08, exceeded chance for blurred images (*M* = .33), *t*(24) = 2.29, *p* = .03, and were comfortably above chance for normal images (*M* = .57), *t*(24) = 6.61, *p* < .01.

Incorrect responses were coded as either to the same or opposite side as gaze direction for each of type of face. For blurred faces, 37% of 2-year-olds' errors were to the gazed-at side of the screen. This figure was 35% for line-drawn faces. Neither figure differed significantly from the one-third errors expected by chance (binomial test, *p*s > .16, 1-tailed). Two-year-olds' errors to the gazed at side for normal faces, however, were significantly more frequent than expected by chance (50% of errors, binomial test, *p* < .001, 1-tailed). Three- and 4-year-olds' errors for all face types were also significantly more likely to the gazed-at side than would be expected by chance (binomial tests, all *p*'s < .001, 1-tailed).

4.3. Discussion

The results of Experiment 2 offer support for the hypothesis that success in making explicit judgments about gaze direction emerges at around 3 years of age, and involves the use of geometrical cues. As predicted, 2-year-olds performed poorly, and were at or only slightly above chance for the geometric and luminance stimuli. Furthermore, their errors on trials involving these faces were apparently random. However, on trials with normal faces, children tended to err by picking the incorrect object on the gazed-at side of the display. This suggests that the youngest children were able to extract some directional information from the normal images.

The 3-year-olds performed better. Their relatively good performance with line-drawn faces indicates that, as predicted, 3-year-olds are beginning to use geometrical cues in their gaze judgments. Three- and 4-year-olds' errors were more systematic, tending to be to the correct side. Performance with normal images was above chance for each age group, and superior to performance with images with either geometrical or luminance cues removed.

In summary, these data suggest that children from 2-years onwards rely on both sources of information to make explicit gaze judgments; when either luminance cues, or geometrical cues were unavailable, performance deteriorated, and each source of information on its own proved roughly equally useful.

5. General Discussion

The findings of the experiments reported here suggest that gaze following and explicit judgment about gaze rely on different sources of information during development. In Experiment 1a, normal greyscale photographs of faces produced gaze-cued orienting effects in 2- to 3-year-olds. This effect survived the removal of precise, geometric cues to gaze direction, but not the removal of luminance cues. The gaze-following of 2- to 3-year-olds therefore seems to be based on the gross luminance information in the eye. Adults, on the other hand, were cued by each type of image (Experiment 1b).

Three-year-olds but not 2-year-olds could make explicit gaze judgments based on the luminance-free line-drawn images (Experiment 2), suggesting the ability to use geometric cues in explicit judgments of gaze direction arises around this age. It is also clear that the explicit judgments of 3- and 4-year olds use *both* luminance cues and geometric information.

Together, these data suggest that children's gaze-following and explicit judgment use different cues: gaze-following is dominated by luminance cues, whereas gaze judgment uses both geometric and luminance information.

What do these findings suggest about the underlying psychological mechanisms that support gaze following and gaze judgment? Doherty et al. (2009; Doherty, 2006) hypothesised that there are developmentally distinct gaze processing systems, making a distinction similar to suggestions for two systems for reasoning about belief (Apperly & Butterfill, 2009) and two system cognitive theories in general (e.g., Kahneman, 2011): an innate, fast, automatic, but approximate system that initially supports gaze following (System 1); and a learned, relatively slow, computationally demanding, and precise system that supports gaze judgment (System 2). The present findings were predicted from this theory. The fast System 1 mechanism might compute gaze direction through an analysis of luminance cues and provide output to attention orienting systems. This mechanism would serve to orient infants' attention in the direction of others' gaze. At around three years of age, children begin to use the slower System 2 mechanism. This system uses spatial locations of relevant eye features to compute a more precise line of regard, and its output is available to explicit judgment. The data here suggest that the putative System 2 combines luminance and geometrical information.

5.1. One system or two?

However, do the data require postulation of two systems rather than a single system that over time incorporates a wider range of cues? A single system claim could proceed thus: the gaze following system functions from infancy, initially computing gaze direction using luminance cues in the eye. Later in development (e.g., at around 3 years of age) this system begins to incorporate geometrical cues. At around this age children also become reflectively aware that they are changing their own focus of attention as a result of gaze cues of others. This allows them also to use their gaze system to make judgements about others' attention, as in the gaze judgment task of Experiment 2[4]. This reflective awareness could plausibly be part of general theory of mind developments around the age of 3 years. The same theory of mind developments could also influence the incorporation of geometrical gaze cues as children begin to pay more attention to the attentional focus of others.

A difficulty for this account is that it makes clear predictions about the timing of developments that are inconsistent with the present data. If a single system begins to incorporate geometrical cues into gaze processing, geometrical cues should then either be available for both cuing and judgement, or available for cuing first, then judgement (if judgement requires additional factors such as late-developing reflective understanding). Present findings, however, suggest that geometrical cues are available for judgement *before* they are available for cuing. Three-year-old children failed to follow gaze on the basis of line drawn images (Experiment 1a), while children of the same age were able to make explicit judgments on the basis of these images (Experiment 2).

On the other hand, adult performance shows that at some point geometrical cues *are* incorporated into gaze following. This suggests that the dissociation in gaze processing shown in children is developmental rather than functional. Simply considering the child data only allows the conclusion that the two tasks rely on different cues. The full data show, however, that gaze following relies on luminance cues in childhood and a combination of luminance and geometrical cues in adulthood.

This fact potentially provides support for a single system account. The dissociation in development could be ascribed to perseveration: children can use geometrical cues, but for well-practiced behaviors like gaze following there is a period in which children continue using only luminance cues. For novel behaviors like judgment, all available cues are used immediately. This also produces a prediction. A key finding used to propose two systems was that the accuracy of fine-grained gaze judgment increases in roughly linear fashion from chance at 3 years to near adult levels around 6 years (Doherty et al., 2009; see also Vida & Maurer, 2012). Assuming this period is too long for perseveration to be plausible, the single system account should predict a corresponding increase in the use (or usefulness) of geometric cues in gaze following. According to the two systems account there should either be no specific relationship or a less specific relationship: the greater attention to gaze cues prompted by the development of system 2 might indirectly lead to learning in system 1, accounting for adult performance. This prediction has yet to be tested

6. Conclusion

To sum up present findings, preschool children rely on luminance cues when *following* eye direction, but make use of both luminance and geometrical gaze cues when making *judgements* of eye direction. We suggest that it is the nascent understanding of other people as agents with mental states that drives development of the use of more precise geometric information about gaze direction. By their third birthday, children begin to understand that things can appear in other people's minds, and that the moment-to-moment content of others' mental states can often be determined by where they are looking; in other words, attention begins to be understood as a representational mental state. This realisation prompts the need for more precise determination of gaze direction (see Doherty, 2011, for a discussion). This characterisation reverses what is more commonly assumed to be the developmental course of events. Rather than the mentalistic understanding of gaze serving as a precursor to the understanding of belief (e.g., Baron-Cohen, 1995, Gómez, 1996), we suggest that a representational understanding of mental states prompts a protracted period of learning to discriminate eye direction.

Footnotes

[1] In this paper we use the term "gaze following" to denote either an overt shift of attention in the gazed-at direction or a covert shift of attention which does not involve a movement of the eyes. Covert deployment of attention is usually inferred by some performance benefit in responding to targets toward which another's gaze has recently been directed, relative to targets that have not been cued in this way.

[2] According to the recommendation of Simmons, Nelson, and Simonsohn (2011) we also conducted an equivalent ANOVA including data from those participants that were removed in the original analysis. This also yielded a significant main effect of trial type, $F(1, 23) = 5.28$, $p < 0.05$, $\eta_p^2 = .19$, no significant effect of cue type ($p = .65$) and no interaction between these factors ($p = .32$). Our findings are therefore not reliant on the exclusion of data.

[3] Lanton (2011) used images produced by an edge detection algorithm, instead of the simple line-drawn images used here. We also conduced an additional experiment with the same design as Experiment 1b and using the same cues, but with RT as the main dependent variable. The letters T and F were used as targets instead of the TV characters, and these remained on the screen until participants (N = 24) made a keypress response. The main effect of trial type was significant, $F(1, 23) = 12.61$, $p < .01$, $\eta_p^2 = .19$, and, as in Experiment 1b, there was no interaction with cue type ($p = .81$). Critically, targets cued by line drawn faces received significantly faster responses ($M = 588$ ms) than uncued targets ($M = 615$ ms), $t(23) = 2.85$, $p < .01$.

[4] We thank an anonymous reviewer for this suggestion.

Authorship

The concept for the studies was developed by MJD and SRHL, who also designed the experiments. Data collection and analysis was carried out by AHM under the supervision of SRHL and MJD. SRHL drafted the paper, with some sections contributed by AHM. MJD then provided critical revisions. All authors approved the final version of the paper for submission.

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