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## The development of fine-grained sensitivity to eye contact after 6 years of age

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### ABSTRACT

Adults use eye contact as a cue to the mental and emotional states of others. Here, we examined developmental changes in the ability to discriminate between eye contact and averted gaze. Children (6-, 8-, 10-, and 14-year-olds) and adults ( $n = 18/\text{age}$ ) viewed photographs of a model fixating the center of a camera lens and a series of positions to the left/right or upward/downward and judged whether the model's gaze was direct or averted to the left/right or upward/downward. The horizontal range of fixation positions leading to the perception of direct gaze (the cone of gaze) was more than 50% larger in 6-year-olds than in adults, but it was adult-like and smaller than the vertical cone of gaze by 8 years of age. The vertical cone of gaze was large and statistically adult-like by age 6, with only a small linear reduction thereafter. In all age groups, the horizontal cone of gaze was centered on the bridge of the participant's nose and the vertical cone was centered slightly below the participant's eye height. These findings indicate that until after age 6, relatively poor sensitivity to direct versus averted gaze limits children's ability to use gaze cues to make social judgments.

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### Introduction

The direction of an individual's gaze can provide a useful cue to the target of his or her attention and thereby can allow inferences about the individual's interests and intentions. Dyadic gaze indicates whether an individual is making eye contact and hence attending to the observer, whereas triadic gaze

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indicates where else the person is looking (Symons, Lee, Cedrone, & Nishimura, 2004). In the current research, we investigated developmental changes in fine-grained sensitivity to dyadic gaze.

Eye contact plays an important role in human social interaction (see Senju & Johnson, 2009, for a review). Some authors have argued that eye contact triggers theory-of-mind computations, which support inferences about others' interests and intentions (Baron-Cohen, 1995; Baron-Cohen, Wheelwright, Hill, Raste, & Plumb, 2001; Senju & Johnson, 2009). Gaze directed toward an observer can signal the intent to communicate, interest in the observer, threat, or dominance, whereas deviations from eye contact can signal avoidance, deception, or attention toward an object or event in the environment (Argyle & Cook, 1976; Einav & Hood, 2008; Kendon, 1967). These signals modulate attention and person perception. For example, adults are faster to detect faces with direct gaze than they are to detect faces with averted gaze (Senju, Kikuchi, Hasegawa, Tojo, & Osanai, 2008). Eye contact also facilitates processing of facial expression (e.g., Bindemann, Burton, & Langton, 2007), identity (e.g., Smith, Hood, & Hector, 2006), and gender (Macrae, Hood, Milne, Rowe, & Mason, 2002). Eye contact also produces autonomic arousal (e.g., Hietanen, Leppänen, Peltola, Linna-aho, & Ruuhiala, 2008). Together, these results suggest that eye contact serves to regulate the onset of social interactions and facilitates processing of relevant social information during interactions.

Adults can detect approximately  $1^\circ$  horizontal shifts in the direction of gaze toward objects in the environment (Symons et al., 2004; Vida & Maurer, 2012), yet they perceive that someone is looking directly at them over a much wider range. For example, they judge that a live or virtual model is making eye contact with them even when gaze varies within a horizontal range  $5$  to  $9^\circ$  in width (Gamer & Hecht, 2007; Gibson & Pick, 1963; Lord & Haith, 1974). When the viewing distance is increased, the physical width of this "cone of gaze" increases to even larger values (Gamer & Hecht, 2007). Although there have been no formal measurements reported for the extent of the vertical cone of gaze, adults judge that someone is making eye contact even when they are in fact looking at the mouth or hairline (Lord & Haith, 1974).

Judgments of dyadic gaze require the observer to trace the direction of gaze along an invisible line running from the model's eyes toward the observer. When the eyes rotate while the head maintains a forward orientation, adults judge the direction of gaze from the position of the iris within the visible part of the sclera (Anstis, Mayhew, & Morley, 1969; Symons et al., 2004). The distribution of luminance across the eye can also influence perceived gaze direction because darkening the sclera on one side of the iris causes large shifts in the perceived direction of gaze toward the darkened region (Ando, 2004). Possible cues to the vertical direction of eye gaze include the position of the iris within the visible sclera, the distribution of luminance across the eye, and the positions of the upper and lower eyelids and the eyebrows. However, there has been no empirical work to measure whether and to what extent each of these cues influences adults' judgments.

### *Development of sensitivity to eye contact*

From birth, infants respond preferentially to direct gaze. For example, newborns shown pairs of faces, in which one face has gaze directed at the infant and the other does not, look longer at the face with direct gaze (Farroni, Csibra, Simion, & Johnson, 2002). At 2 weeks of age, crying infants are calmed by being given a sucrose solution, and by 4 weeks of age, oral sucrose is effective if accompanied by adult eye contact, but not if given alone (Zeifman, Delaney, & Blass, 1996). By 4 months of age, infants display a larger N240 ERP (event-related potential) component when viewing a face with direct gaze than when viewing a face with averted gaze (Farroni, Johnson, & Csibra, 2004). This may reflect greater cortical processing of faces with direct gaze. At around the same age, infants not only look longer but also smile for a longer duration when a person makes eye contact than when gaze is averted by as little as  $5^\circ$  to the left or right (Hains & Muir, 1996; Symons, Hains, & Muir, 1998). This effect was not observed for  $5^\circ$  vertical deviations (Symons et al., 1998), a failure that could reflect lower visual sensitivity to vertical differences in gaze direction than to horizontal ones and/or a difference in infants' interpretations of horizontal versus vertical shifts of gaze. By 4 or 5 months of age, infants will look in the same direction as a face with averted gaze (e.g., look to the left when the face looks to the left), but only after a period of mutual gaze (Farroni, Mansfield, Lai, & Johnson, 2003; Senju & Csibra, 2008). Together, these findings indicate that from a very young age, infants detect and respond

preferentially to eye contact. Infants' sensitivity to eye contact could contribute to the development of social cognition by providing input to theory of mind mechanisms (Baron-Cohen, 1995) and/or by drawing attention to faces, which provide opportunities for social interaction and provide input to mechanisms for person perception.

By 3 years of age, children can make explicit judgments about direct and averted gaze when deviations in gaze direction are large. When shown pairs of faces in which one face is making eye contact and the other is looking 25° away, 3-year-olds, but not 2-year-olds, are able to indicate which face is making eye contact with them (Doherty, Anderson, & Howieson, 2009). At 6 years of age, the horizontal cone of gaze appears to be quite wide. In the one previous study that included 6-year-olds, children responded that gaze was direct across fixation positions 10 to 30 cm to the left or right of the bridge of the participant's nose, suggesting a gaze cone at least 60 cm (17.06°) in width (Thayer, 1977). However, there was no adult comparison group tested with the same procedure. In the one previous study that included older children, adults and 7- and 11-year-olds viewed a live model fixating a series of positions on the participant's face. The authors analyzed the relative proportions of direct gaze responses for on-eye (eyes and bridge of nose) versus off-eye (mouth, ears, and hairline) fixation positions. Children's discrimination of the difference improved from 7 to 11 years of age but was not adult-like at age 11 (Lord, 1974). However, because the fixation positions were points on the child's own face and children's faces are smaller than those of adults, the task was inherently more difficult for the children.

By late childhood, perceived eye contact appears to influence cognition and person perception in the manner observed in adults. Both 9-year-olds and adults attribute deception to a person who fails to make eye contact (Einav & Hood, 2008; see also McCarthy & Lee, 2009). Like adults, 8- to 15-year-olds are faster at detecting faces presented with direct gaze than at detecting faces presented with averted gaze (Senju et al., 2008), and 6- to 11-year-olds are better at remembering facial identity when gaze is direct (Smith et al., 2006). In 9- to 14-year-olds, eye contact facilitates the perception of facial expressions associated with approach (e.g., anger), as it does in adults (Akechi et al., 2009).

Previous studies have not provided precise estimates of the width, height, and centering of the cone of gaze and have not used the same stimuli to compare sensitivity between adults and children. The purpose of the current study is to use a child-friendly procedure to measure the developmental trajectory of fine-grained sensitivity to eye contact along the horizontal and vertical axes from 6 years of age onward. We chose to include 6-year-olds because they were the youngest age group able to perform the child-friendly version of our task and to allow comparisons between our results and those of Thayer (1977). In the current experiment, adults and children (6-, 8-, 10-, and 14-year-olds) viewed photographs of faces fixating the center of the camera lens and a series of surrounding positions 1.6 to 8.0° to the left/right (horizontal blocks) or upward/downward (vertical blocks). Participants sat where the camera lens had been and performed a three-alternative forced-choice task in which they judged whether the model's gaze on each trial was direct, averted left (or up in vertical blocks), or averted right (or down). Any immaturity in children's ability to discriminate subtle differences between direct and averted eye gazes would affect their inferences about others' mental states (e.g., the desire to interact or to avoid interaction), which could in turn affect behavior during face-to-face interactions.

## Method

### Participants

Participants were 6-year-olds (6 years 6 months  $\pm$  3 months,  $M = 6.54$  years, 10 female and 8 male), 8-year-olds (8 years 6 months  $\pm$  3 months,  $M = 8.54$  years, 12 female and 6 male), 10-year-olds (10 years 6 months  $\pm$  3 months,  $M = 10.54$  years, 11 female and 7 male), 14-year-olds (14 years 6 months  $\pm$  3 months,  $M = 14.47$  years, 7 female and 11 male), and adults (18–21 years,  $M = 19.35$ , 13 female and 5 male) ( $n = 18$ /group). The adult participants were undergraduate students who received course credit for participation. Child participants were recruited from a database of children whose parents volunteered to participate in research at the time of their children's birth. All participants were visually screened and had normal or corrected-to-normal vision. Adults and children

8 years and older were required to have at least 20/20 Snellen acuity and normal stereoacuity as measured by the Titmus Stereo Fly test. The 6-year-olds met the same stereoacuity criterion, but the acuity criterion was relaxed to 20/25 because acuity is still maturing in this age range (Adams & Courage, 2002; Ellemberg, Lewis, Liu, & Maurer, 1999). An additional 5 children were tested but were replaced because they failed visual screening (3 8-year-olds and 1 14-year-old) or because a crossover point could not be calculated for data in one of the test blocks (1 8-year-old) (see Results for description of crossover point).

### Stimuli

Stimuli were full-color digital photographs of adults with a neutral expression fixating the middle of a camera lens and a series of positions ranging from 1.6° to 8.0° to the left, right, above, and below the camera lens in steps of 1.6° (see Fig. 1). All models had normal stereoacuity and were able to read three short passages of small text (2–3 mm letter height) at a distance of 75 cm. During the photography session, models used a head restraint to maintain a forward-facing, upright head position and an eye height of 120 cm. Fixation positions were marked with black stripes (5 mm wide and 25 mm tall) set against a white background. A Sigma SD14 digital camera fitted with a 50–150-mm lens was positioned so that the center of the lens was at a height of 120 cm (the eye height of the model). All models were photographed under identical lighting conditions (see Appendix A for details). Models used a wireless remote switch to trigger the camera when fixating each designated position. Models displaying blinks and/or noticeable variations in head position and/or facial expression were excluded from the stimulus set. We also conducted extensive pilot testing with photographs from all models. Models displaying a horizontal cone of gaze (see Results for description of this measure) centered further than 1° to the left or right of the central fixation were excluded.

The final stimulus set included three male and three female models (all Caucasian). Digital measurements of the stimuli confirmed that the position of the eyes moved linearly across fixation positions. All facial images were displayed at life size and at an eye height of 113 cm on a Dell P1130 Trinitron 19-inch monitor set to a resolution of 1152 × 870 and a refresh rate of 75 Hz. The experiment was run in MATLAB 7.6.0 (R2008a) (MathWorks, Natick, MA, USA) using the Psychophysics Toolbox extensions (Brainard, 1997) on an Apple Mac mini computer.

### Apparatus

Participants used a chin rest to maintain a consistent head position and an eye height of 113 cm at 150 cm from the computer monitor. Participants entered responses on a computer keyboard placed on a table directly in front of them. The experiment used six keys on the keyboard. In the horizontal condition, participants used the F key with a leftward-pointing arrow taped over the top to indicate left responses, the H key with a rightward-pointing arrow taped over the top to indicate right responses, the G key with a blue circle taped over the top to indicate direct responses, and the X key with the letter A taped over the top to respond to catch trials (see “Design” section for description). In the vertical condition, participants did not use the right and left buttons but instead used the T key with an

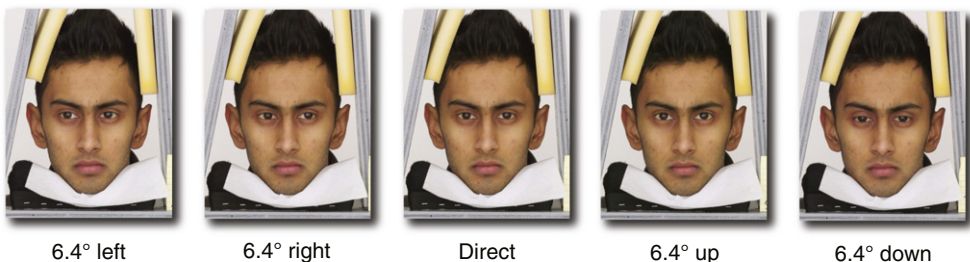


Fig. 1. Examples of stimuli for one model.

upward-pointing arrow to indicate up responses and the B key with a downward-pointing arrow to indicate down responses.

### *Design*

Every participant completed two different conditions, horizontal and vertical, involving the same model. The order in which the conditions were presented was alternated between participants so that half of the participants in each age group completed the horizontal condition first and half completed the vertical condition first. Before each test block, the participant received a practice block with a different model of the opposite sex. The presentation of models was counterbalanced across participants so that each of the six models appeared three times in test trials and three times in practice trials across all participants in a given age group. Each model was paired with every other model of the opposite sex, once as a practice model and once as a test model.

The practice block consisted of 12 trials, with the model fixating the center of the camera lens (4 trials) and the points farthest away from center (4 trials at 8.0° left/down and 4 trials at 8.0° up/right), presented in a pseudo-random order. During practice trials, participants received feedback indicating whether their responses were correct or not (a cartoon image of a happy face with a 1000-Hz tone for correct responses and a cartoon image of a sad face with a 400-Hz tone for incorrect responses). Participants were allowed to repeat each practice block up to two times to reach a criterion of 75% accuracy. Among the various age groups, 14 6-year-olds, 14 8-year-olds, 17 10-year-olds, 17 14-year-olds, and 18 adults were able to reach criterion on the first attempt in both the horizontal and vertical conditions. Of the remaining participants, 3 6-year-olds, 4 8-year-olds, 1 10-year-old, and 1 14-year-old needed an additional attempt to reach criterion for the vertical block, and 1 6-year-old needed an additional attempt to reach criterion for the horizontal block.

In each test block, the participant viewed the model fixating the camera lens and a series of 11 positions covering a range of 8.0° left/down to 8.0° right/up in steps of 1.6°, with 10 trials for each fixation position. Trials were presented in a pseudo-random order, with the constraint that the same image was never presented twice in a row. During test trials, participants received general encouragement but no trial-specific feedback. To assess attentiveness, we included 10 catch trials that appeared at random positions within each block, with the constraint that catch trials were never presented twice in a row. During each catch trial, a cartoon image of a meteoroid appeared on the screen. Participants were instructed to press the A button to sound an alarm when they saw this object. Each participant completed 120 trials per test block and received a break between test blocks.

### *Procedure*

Written consent was obtained from all adult participants and from a parent of each child participant. Verbal assent was also obtained from 8-, 10-, and 14-year-olds. After positioning the participant appropriately in the apparatus, the experimenter displayed a photograph of the model who would appear in the two target blocks. Before practice trials, the experimenter explained the task as follows (with appropriate adjustments if the test model was male and for the vertical version of the task): “This is Jenny. She is an astronaut, and she flies a special spaceship. Her spaceship is special because it takes two people to steer it. One person looks in different directions to show which direction they want to go, and another person watches their eyes and presses buttons to steer the spaceship in the direction that the person is looking. Do you want to press the buttons to help Jenny steer the ship? Okay, here’s how to do it: When Jenny is looking directly at you, press this blue button to make the spaceship go straight [points to blue button]. When Jenny is looking away from you in this direction [points to the left of the participant], press this button [points to left button] to make the spaceship go in this direction. When Jenny is looking away from you in the other direction [points to the right of the participant], press this button [points to right button]. If you get it right, the computer will show a happy face. If you get it wrong, the computer will show a sad face. Are you ready to try?”

The experimenter then initiated practice trials. At the start of each trial, a black fixation cross appeared at the center of a gray background. When the participant appeared to be looking at the fixation cross, the experimenter pushed a key in order to display a photograph of the model. The participant

pressed the central blue key or one of the surrounding arrow keys to indicate whether the model appeared to be making eye contact or looking away to the right (or up) or left (or down), depending on whether it was a horizontal or vertical block. The stimulus remained on the screen until the participant made a response. When the participant met the 75% accuracy criterion on the practice trials, the experimenter initiated test trials. Test trials had the same format as practice trials except for the absence of feedback. Participants typically completed each test block in approximately 10 min and completed the entire procedure in approximately 30 min.

## Results

### *Accuracy on catch trials*

All participants responded correctly on every catch trial with the exception of 2 children (a 14-year-old and a 6-year-old), each of whom responded incorrectly to a single catch trial (out of the 16 presented across the two test blocks). Because accuracy was at or near ceiling in all conditions, we did not carry out statistical analyses for these data.

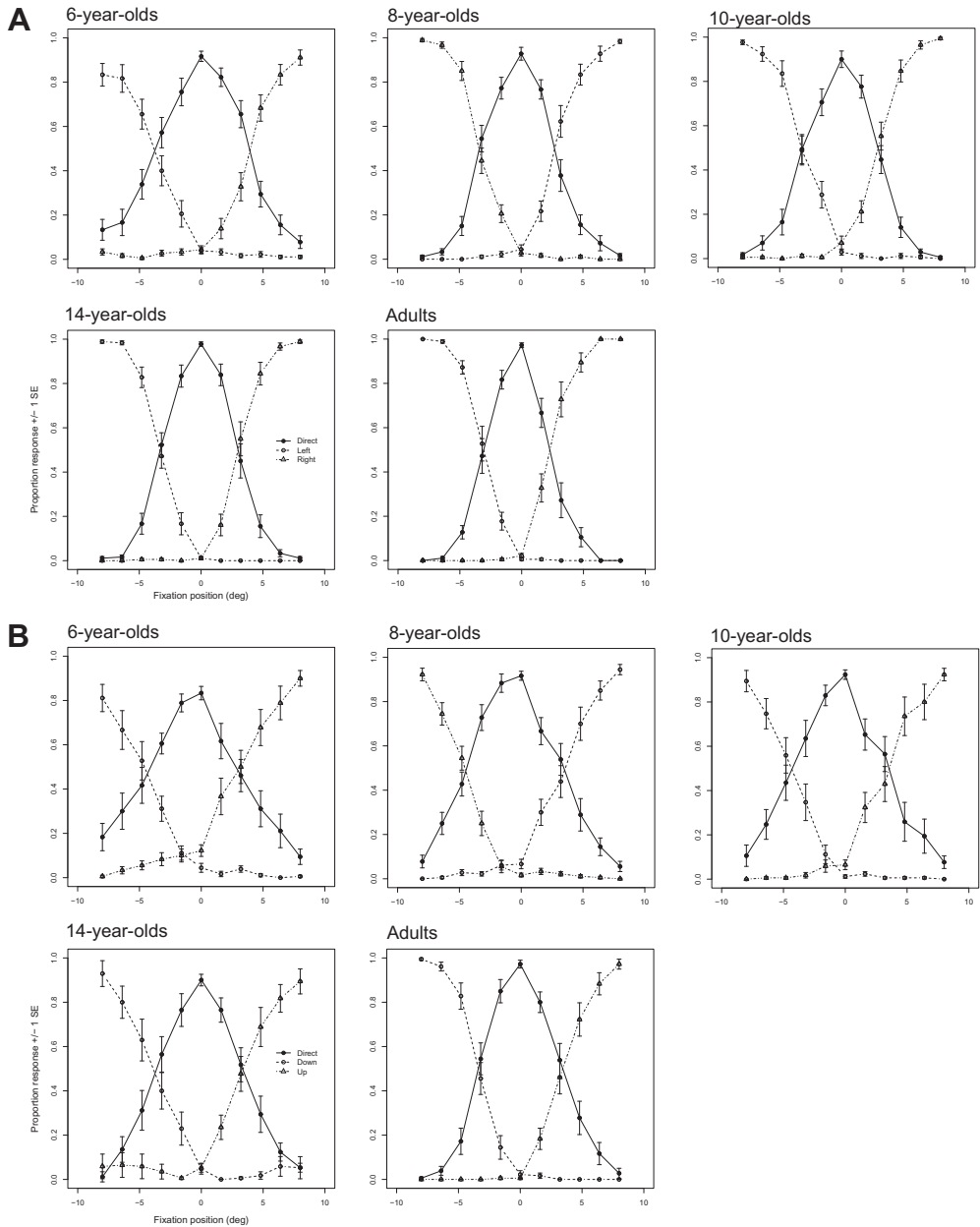
### *Curve fitting*

For each participant, we calculated the proportion of the 10 trials at each fixation position on which the model was judged to be looking directly toward the participant, left/down or up/right (see Fig. 2). To quantify sensitivity to dyadic gaze, we fit logistic functions relating each participant's proportion of left/down and up/right responses to the fixation positions. All fits were carried out using the *glmfit* routine from the Statistics Toolbox in MATLAB 7.6.0 (R2008a). The sum of the left/down and right/up fitted functions was then subtracted from 1 to define a third function fitting the proportion of direct responses. Goodness of fit was within acceptable parameters described in Appendix B for all fits.

We used the fitted functions to measure two aspects of each participant's performance: the size of the cone of gaze and its centering. Following Ewbank, Jennings, and Calder (2009), we calculated the size of the cone of gaze as the difference (in degrees) between the points of intersection between the fitted "direct" function and the left/down and up/right functions. These points of intersection correspond to the fixation positions where the participant was equally likely to judge that the model was making eye contact or looking off the face in a particular direction. The angular distance between the right and left points of intersection provides a measure of the horizontal cone of gaze. The angular distance between the up and down points of intersection provides a comparable measure of the vertical cone of gaze. We used two different measures of the centering of the cone of gaze: the maximum direct response and the midpoint of the cone of direct gaze. We calculated the maximum direct response from the peak of the direct response function. This represents the fixation position at which the participant would be most likely to indicate that the model was looking at him or her. We calculated the midpoint of the cone of gaze from the midpoint of a line connecting the outer edges of the cone of gaze. The data were coded so that a cone centered at the central fixation position (i.e., eye height in the vertical condition or the bridge of the nose in the horizontal condition) would receive a score of zero, whereas a cone centered to the left/down would receive a negative score and one centered to the right/up would receive a positive score. Thus, any horizontal or vertical response bias will lead to a nonzero score on these measures. When the cone of gaze is symmetrical with respect to the maximum direct response, the two measures of centering yield the same value. If the cone is asymmetrical, the two measures yield different values.

### *Size of gaze cone*

We carried out an age by axis mixed analysis of variance (ANOVA) with size of the gaze cone as the dependent variable (see Fig. 3). There were main effects of axis,  $F(1, 85) = 2.10$ ,  $p < .001$ ,  $f^2 = .21$ , and age,  $F(4, 85) = 3.69$ ,  $p < .005$ ,  $f^2 = .17$ , and an age by axis interaction,  $F(4, 85) = 3.47$ ,  $p < .02$ ,  $f^2 = .13$ . To follow up the age by axis interaction, we conducted separate one-way ANOVAs (one for each axis)



**Fig. 2.** (A) Proportion of each response type  $\pm 1$  standard error as a function of fixation position for the horizontal condition. Negative values represent fixation positions to the left of the participant's nose, and positive values represent fixation positions to the right of the participant's nose. Each plot displays the data for one age group. (B) Corresponding data for the vertical condition. Fixation positions with negative values represent fixation positions below the participant's eyes, and fixation positions with positive values represent fixation positions above the participant's eyes. For Panels (A) and (B), the legend displayed in the bottom left plot applies to all plots in the same panel.

with age as the independent variable and cone size as the dependent variable. There was a simple effect of age for the horizontal condition,  $F(4, 85) = 4.57, p < .005, f^2 = .21$ , but not for the vertical condition,  $p > .10, f^2 = .09$ . Post hoc Dunnett's tests for the horizontal and vertical conditions showed that horizontal cone width was significantly greater in 6-year-olds ( $M = 8.48^\circ, SD = 3.92$ ) than in adults ( $M = 5.49^\circ, SD = 1.69$ ),  $p < .002$ . There were no other significant differences,  $ps > .10$ . Although the ANOVA revealed no effect of age for the vertical condition and no differences between adults and children older than 6 years in the horizontal condition, Fig. 3 suggests that there may have been a slight reduction in vertical cone size after age 6 and in horizontal cone size after age 8. To evaluate these possibilities, we conducted linear trend analyses testing the null hypotheses that there was no linear reduction in vertical cone size after age 6 or in horizontal cone size after age 8. The test for the vertical condition was significant,  $t(85) = 2.51, p < .01, d = 0.60$ , indicating that vertical cone size decreased linearly after age 6. The test for the horizontal condition was not significant,  $p > .10$ , indicating that horizontal cone size did not decrease linearly after age 8.

### Centering of gaze cone

#### Maximum direct response

We carried out an age by axis mixed ANOVA with the maximum direct response as the dependent variable (Fig. 4). There was a main effect of axis,  $F(1, 85) = 14.50, p < .001, f^2 = .17$ ; the centering of the cone of gaze differed between the horizontal condition ( $M = 0.23, SD = 1.22$ ) and the vertical condition ( $M = -0.70, SD = 2.21$ ). However, there was no significant effect of age,  $p > .90$ , and no age by axis interaction,  $p > .60$ . We followed up the main effect of axis with two single-sample *t*-tests (one for each axis) comparing the maximum direct response with zero. In the vertical condition, the maximum direct response was significantly below zero (the participant's eye height),  $t(89) = -3.02, p < .005, d = 0.32$ . In the horizontal condition, the maximum direct response did not differ from zero (the bridge of the participant's nose),  $p > .07$ .

#### Midpoint

We carried out an age by axis ANOVA with the midpoint of the gaze cone as the dependent variable (Fig. 5). There was a marginally significant main effect of axis,  $F(1, 85) = 3.24, p = .076, f^2 = .03$ ; the

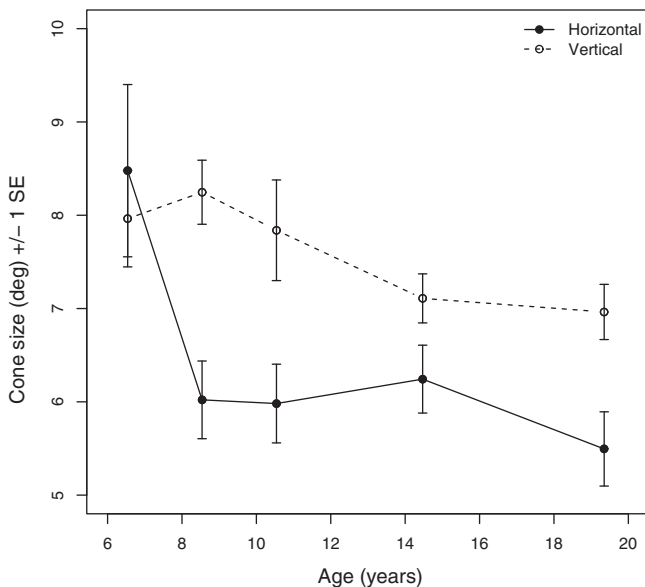
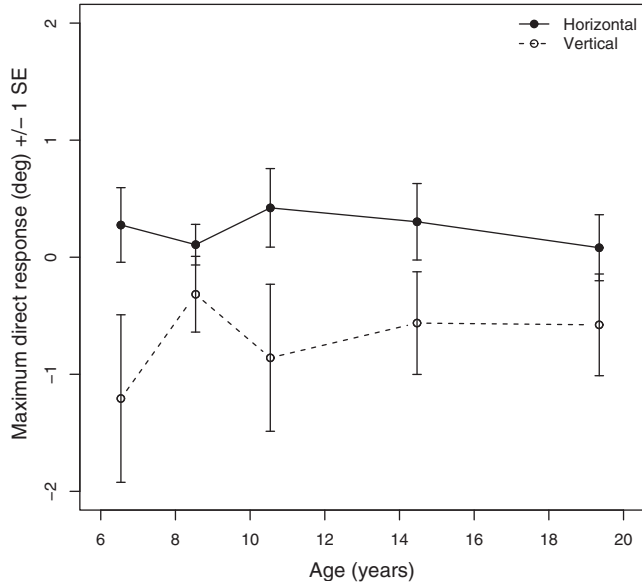
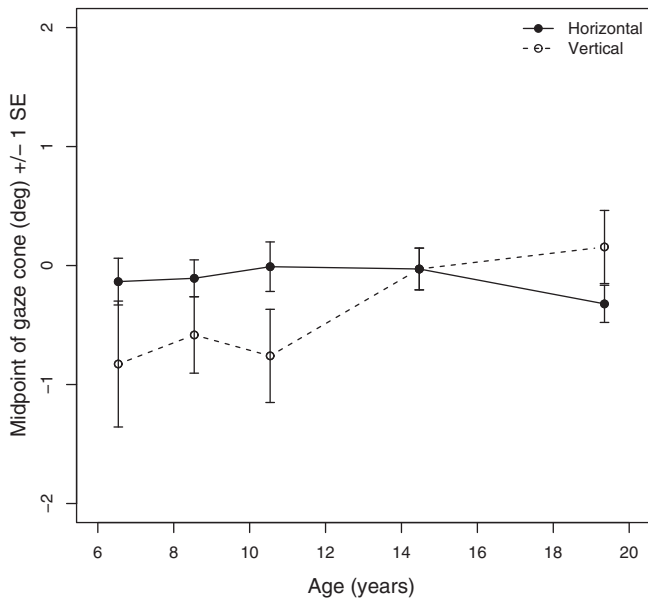


Fig. 3. Size of gaze cone  $\pm 1$  standard error (in degrees) as a function of age and axis. Higher values indicate a larger gaze cone.





**Fig. 4.** Maximum direct response  $\pm 1$  standard error (in degrees) as a function of age and axis. For horizontal judgments, positive values indicate fixation positions to the right of the participant's nose and negative values indicate fixation positions to the left of the participant's nose. For vertical judgments, positive values indicate fixation positions above the participant's eyes and negative values indicate fixation positions below the participant's eyes.



**Fig. 5.** Midpoint of gaze cone  $\pm 1$  standard error (in degrees) as a function of age and axis. Other details are as in Fig. 4.

centering of the cone of gaze differed slightly between the horizontal condition ( $M = -0.12^\circ$ ,  $SD = 0.75$ ) and the vertical condition ( $M = -0.47^\circ$ ,  $SD = 1.66$ ). However, there was no effect of age,  $p > .60$ , and no

age by axis interaction,  $p > .20$ . In the vertical condition, the midpoint of the cone was significantly below zero (the participant's eye height),  $t(89) = 2.70$ ,  $p < .01$ ,  $d = 0.28$ . In the horizontal condition, the midpoint of the cone did not differ from zero (the bridge of the participant's nose),  $p > .10$ . The similar patterns observed for the two measures of the centering of the cone suggest that the cone was, for the most part, symmetrical with respect to the point of maximum direct response.

## Discussion

### Adults

Adults in the current experiment judged that a model was looking at them over a wide horizontal range of fixation positions, such that their cone of gaze measured  $5.49^\circ$  (14.4 cm) in width. This corresponds well with the horizontal range of positions leading to adults' perception of eye contact in Gibson and Pick (1963) ( $5.6^\circ$ ) and Lord and Haith (1974) (fixation anywhere on the participant's eyes and bridge of nose, a region  $\sim 5^\circ$  wide). In those studies, like the current one, the boundaries represent the fixation positions where the participant judged gaze to be averted 50% of the time and judged it to be direct the other 50% of the time. It was only for fixations beyond these points that the participant was more confident that the model was looking away than they were that the model was making eye contact. When Gamer and Hecht (2007) measured the points where participants were confident that the model was looking away from himself or herself, not surprisingly, they found a slightly wider range ( $\sim 7\text{--}9^\circ$  at a testing distance of 100 cm). The current results provide the first precise measurements of the size of adults' cone of gaze along the vertical axis. The vertical height of their cone of gaze was  $6.96^\circ$  (18.2 cm), a value larger than the horizontal extent of  $5.49^\circ$  (14.4 cm). Our vertical measurements are consistent with findings that adults perceive eye contact when a live model fixates their mouth or hairline (Lord & Haith, 1974), each position of which is near the outer boundaries of the cone observed in the current experiment.

Adults' horizontal cone of gaze may have been smaller than their vertical cone because there is less visual information available for the discrimination of vertical differences in gaze direction than there is for horizontal differences. However, this seems unlikely given the results of previous studies showing that adults are equally sensitive to horizontal (e.g., Symons et al., 2004) and vertical (e.g., Bock, Dicke, & Thier, 2008) differences in the direction of gaze toward objects in the environment. Another possible explanation is that observers adopt a more relaxed decision criterion for vertical judgments of direct gaze than for horizontal ones. The vertical criterion may be relaxed because observers take into account the dimensions of their own faces, which are typically taller than they are wide. Observers may also take into account the fact that adults often fixate facial features that are distributed vertically across the face (e.g., eyes, nose, mouth) but rarely fixate features at the lateral edges of the face (e.g., ears) (Caldara, Zhou, & Mielle, 2010; Dahl, Wallraven, Bülhoff, & Logothetis, 2010). Observers' judgments may also be influenced by the fact that in their past experience, direct gaze has been broken much more frequently to look at a stimulus to the left or right than to look at something above their heads or below their chins. That differential exposure may lead to greater perceptual sensitivity to horizontal deviations from direct gaze than to vertical ones.

As in Gamer and Hecht (2007), adults' horizontal cone of gaze was centered on the fixation position for which the model's gaze was directed toward the bridge of the participant's nose, whether centering was measured from the maximum direct response or from the midpoint of the gaze cone. The current study is the first to measure the centering of adults' vertical cone, which was approximately  $1^\circ$  ( $\sim 2.5$  cm) below the eye height of the participant, near the vertical midpoint of the face. The vertical cone may be centered slightly below eye height because the perception of mutual gaze is strongest when gaze is directed toward the center of the face, a position that could hold special status as the mean of the facial positions typically fixated during social interactions. Alternatively, or in addition, there may be an asymmetry in the coding of upward versus downward deviations from eye contact. Previous work on the perception of head orientation indicates that vertical variations in head orientation are coded by at least three channels (for heads directed straight forward, upward, and downward) and that the direct channel may overlap more with the upward channel than it does with the downward channel (Lawson, Clifford, & Calder, 2011). A similar asymmetry for judgments of

eye direction would make viewers more sensitive to upward deviations, which may signal that attention is directed away from the viewer, than to downward deviations, which may signal attention to the viewer's body. Consistent with this possibility is the finding that, as in Lawson et al. (2011), the slope of direct responses appears to be slightly steeper for upward deviations from direct gaze than for downward ones (see Fig. 2B).

### *Development*

The current experiment provides the first information on the development of fine-grained sensitivity to eye contact along the horizontal and vertical axes from 6 years of age to adulthood. The size of the cone of gaze decreased with age, but this effect was much larger for horizontal judgments than for vertical judgments. For horizontal deviations from direct gaze, the width of the cone was  $8.47^\circ$  (22.2 cm) in 6-year-olds, which is more than 50% larger than the cone width of  $5.49^\circ$  (14.4 cm) observed in adults. However, cone width decreased to adult-like levels by age 8, remaining stable thereafter. For vertical judgments, the main analysis indicated that cone height was statistically adult-like by age 6. However, a trend analysis revealed that there was a slight linear decrease in the extent of the vertical cone with increasing age. Like adults, children's cone of gaze at all ages was centered on the bridge of the participant's nose for the horizontal axis and approximately  $1^\circ$  below the participant's eyes for the vertical axis.

Previous studies of sensitivity to eye contact at ages overlapping with those tested here have reported poorer sensitivity. The one previous study that included 6-year-olds found that children at this age perceive eye contact over a much larger horizontal range of fixation positions ( $17.06^\circ$  or 60 cm) (Thayer, 1977) than in the current study ( $8.47^\circ$  or 22.2 cm). The live model in Thayer (1977) was farther away than the photographed models in the current study (200 vs. 150 cm), so one would expect a slightly larger cone of gaze. However, there was no adult reference group in Thayer's study to allow evaluation of this possibility. The one previous study that included children older than 6 years showed that as late as age 11, children do not distinguish as well as adults between gaze directed toward their eye region and gaze directed at facial features beside the eye region (e.g., the ears) or above/below it (e.g., hairline, mouth) (Lord, 1974). However, because the fixation positions were points on the child's own face and children's faces are smaller than those of adults, the task was inherently more difficult for the children. In addition, unlike both Thayer (1977) and Lord (1974), the current experiment included a child-friendly cover story, a practice session, and criterion trials, which may have helped the younger children to understand the task and remain attentive, leading to more accurate measurements.

In the current experiment, the extent of the vertical cone was wide and nearly adult-like by 6 years of age, whereas the extent of the horizontal cone shrank between ages 6 and 8 to reach the smaller adult dimensions. A relaxed criterion and/or relatively low sensitivity to vertical differences in eye position could potentially explain why the vertical cone of gaze was nearly adult-like at age 6; at this age, judgments may be adult-like not because children are particularly sensitive but rather because adults' sensitivity is relatively crude. The narrowing of the horizontal cone between ages 6 and 8 is unlikely to result from an improvement in sensitivity to horizontal differences in eye position because by age 6, children can already detect horizontal differences of approximately  $2^\circ$  in gaze toward an object in the environment (Vida & Maurer, 2012), a smaller distance than the limit for adults' horizontal cone ( $2.74^\circ$  from center to edge). Another possible explanation is that children's representation of eye contact becomes more refined after age 6. At age 6, children might not have received enough experience with the social costs of incorrectly attributing mutual gaze to form a refined representation of eye contact. Subsequent experience with these costs could lead to refinements that allow children to better distinguish between direct and averted gaze.

The early acquisition of an adult-like cone of gaze has implications for understanding the development of social cognition. Adults use their perception of direct versus averted gaze to make social judgments; depending on the context, they associate direct gaze with interest, threat, dominance, and an attempt to establish a social interaction, and they associate averted gaze with attention directed toward a significant environmental event, deception, and avoidance (Argyle & Cook, 1976; Emery, 2000; Kendon, 1967). Our findings indicate that by 8 years of age, a child is as likely as an adult to infer

that a real-world partner is attending to the child when the person is fixating any part of his or her face. Thus, from 8 years of age onward, immaturity in distinguishing direct gaze from averted gaze will no longer limit children's interpretation of such social signals. In the current experiment, 6-year-olds perceived eye contact over a wider horizontal range of positions than did older children and adults and, thus, may be less sensitive to the social signals associated with averted gaze. This, along with less knowledge of the display rules associated with eye gaze (see McCarthy & Lee, 2009), could be why 6-year-olds are less likely than 9-year-olds and adults to attribute deception to a person displaying averted gaze (Einav & Hood, 2008). Children's sensitivity to the other social signals associated with averted gaze (e.g., attention toward an event in the environment, avoidance) has not been reported.

Although the wider horizontal gaze cone observed in 6-year-olds could potentially entail social costs (e.g., mistakenly attributing mutual gaze to a stranger who is in fact looking at a nearby object), it could also serve an adaptive function. The wider cone could also facilitate processing of facial characteristics (e.g., identity, facial expression) in the manner observed in older children and adults (Akechi et al., 2009; Senju et al., 2008; Smith et al., 2006). This could contribute to the refinement of perceptual abilities supporting social cognition.

### *Limitations and future research*

One limitation of the current study is that the stimuli were two-dimensional photographs that lack binocular depth cues. This is unlikely to have affected the results because when viewed frontally, the eye region contains little variation in depth. Moreover, the width of adults' horizontal cone of gaze in the current study corresponds quite well with the values reported in studies using live models (e.g., Gibson & Pick, 1963; Lord & Haith, 1974). Nevertheless, three-dimensional faces may appear to be more realistic than two-dimensional faces, a difference that might have more effect on children than adults and that might contribute to differences in the effects of eye contact on cognition, attention, and/or affect (Hietanen et al., 2008). Future studies could evaluate the extent to which the inclusion of binocular depth cues modulates the effects of eye contact.

Future studies could further investigate developmental changes in the representation of eye contact by comparing the results of the current procedure with those of one in which participants are asked to judge whether the model is looking to the left (or down) or right (or up) of straight ahead instead of whether the model is making eye contact or not. If the larger vertical cone at all ages or the larger horizontal cone at 6 years of age results primarily from differences in the representation of eye contact, those differences should disappear when participants are asked to judge the direction of gaze rather than eye contact.

Future studies could also extend our work by investigating the influence of context on the extent of the cone of gaze. It is possible that participants in the current experiment adopted a relatively relaxed criterion for direct gaze judgments because no other targets were present for the model to look at. Altering the cover story to include additional characters or objects located beside participants could influence participants to adopt a more conservative criterion for direct gaze judgments. An additional question is whether the vertical gaze cone, like the horizontal cone of adults (Gamer & Hecht, 2007), becomes wider with increasing testing distance and whether the effect of distance is the same in children and adults.

### **Summary**

This investigation has provided the first evidence on fine-grained sensitivity to eye contact along the horizontal and vertical axes from 6 years of age to adulthood. The horizontal cone of gaze was more than 50% larger in 6-year-olds than in adults but was adult-like and smaller than the vertical cone by age 8, whereas the vertical cone of gaze was large and statistically adult-like at age 6, with only a small linear reduction thereafter. These findings indicate that by age 8, children are as sensitive as adults to cues to mutual gaze that adults use to make judgments about another person's focus of interest, the probability of deception, and whether or not a person is avoiding or threatening them.

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## Appendix A. Lighting setup

The lighting setup was designed to symmetrically and evenly illuminate the face and eyes of the model. Two Paul C. Buff White Lightning X1600 flash units (Nashville, TN, USA) were positioned at a height of 138 cm, 60 cm to either side of the model at a distance of 300 cm from the model. Both lights were aimed away from the model toward two large reflective umbrellas positioned directly behind the lights so that their reflective surfaces were oriented toward the model. Light was further diffused by a 480 × 240-cm barrier of white corrugated plastic placed between the lighting/camera setup and the model. The barrier was arranged in a U shape so that the surface of the barrier surrounded the front of the model at a distance of approximately 300 cm. The camera lens was positioned in a small opening cut in the barrier 300 cm in front of the model.

## Appendix B. Fitting of logistic functions

We calculated the deviance residual for the predicted value corresponding with each data point in each fit. A more extreme deviance residual reflects a greater discrepancy between the predicted probability and the corresponding data point (Dalgaard, 2008; McCullagh & Nelder, 1989). We assessed the quality of the fit for each of the left/up and right/down functions by examining plots of the deviance residual for each data point against the predicted probability for the data point. For each fit, the deviance residuals tended to cluster around zero, indicating no systematic relation between the predicted values and the deviance residuals. We also calculated the overall residual deviance for each of the left/up and right/down functions. A larger overall residual deviance reflects greater overall discrepancy between the model and the data. The residual deviance and residual degrees of freedom for a fit correspond approximately to a  $\chi^2$  distribution (Dalgaard, 2008). A  $\chi^2$  probability less than .05 is typically taken as an indicator of a poor fit. The largest residual deviance across all fits in the current experiment was 2.28, which corresponds to a  $\chi^2$  probability of .99. Thus, there was no significant discrepancy between the data and the model for any of the fits in the current study.

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