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Gradual improvement in fine-grained sensitivity to triadic gaze after 6 years of age

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ABSTRACT

The current research compared the ability of adults and children to determine where another person is looking in shared visual space (triadic gaze). In Experiment 1, children (6-, 8-, 10-, and 14-year-olds) and adults viewed photographs of a model fixating a series of positions separated by 1.6° along the horizontal plane. The task was to indicate whether the model was looking to the left or right of one of three target positions (midline, 6.4° left, or 6.4° right). By 6 years of age, thresholds were quite small ($M = 1.94°$) but were roughly twice as large as those of adults ($M = 1.05°$). Thresholds decreased to adult-like levels around 10 years of age. All age groups showed the same pattern of higher sensitivity for central targets than peripheral targets and of misjudging gaze toward peripheral targets as farther from midline than it really was. In subsequent experiments, we evaluated possible reasons for the higher thresholds in 6- and 8-year-olds. In Experiment 2, the thresholds of 6-year-olds did not improve when the range of deviations from the target position that the model fixated covered a much wider range. In Experiment 3, 8-year-olds were less sensitive than adults to small shifts in eye position even though the task required only matching faces with the same eye position and not determining where the person was looking. These findings suggest that by 6 years of age, children are quite sensitive to triadic gaze, which may support inferences about others' interests and intentions. Subsequent improvements in sensitivity involve, at least in part, an increase in sensitivity to eye position.

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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 his or her interests and intentions. Dyadic gaze indicates whether an individual is making eye contact and, hence, attending to the observer. In contrast, triadic gaze indicates where someone is looking in shared visual space and, hence, which object he or she may be thinking about. In the current research, we investigated developmental changes in sensitivity to triadic gaze.

Judgments of triadic gaze require the observer to trace the direction of gaze along an invisible line running from the gazer's eyes to a position in shared visual space. When the eyes rotate while the head maintains a forward orientation, adults judge the horizontal position of the eyes from the position of the iris within the visible part of the sclera. The distribution of luminance across the eye can also influence adults' perception of 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). In tasks restricting head movement, adults are able to detect horizontal deviations of gaze of 0.3° to 2° (depending on viewing distance and stimulus quality) from a target at midline. For targets in the near periphery, adults have slightly poorer sensitivity (Symons, Lee, Cedrone, & Nishimura, 2004) and tend to overestimate the direction of gaze as being more peripheral than it actually is (e.g., gaze toward a target 10° from midline is judged to be 15° from midline) (Anstis, Mayhew, & Morley, 1969).

Development of sensitivity to triadic gaze

From an early age, infants shift their gaze in the direction of an adult's eye movements, but over the first 4 months the critical cue seems to be lateral motion rather than changes in gaze direction (Farroni, Mansfield, Lai, & Johnson, 2003). Newborns (Farroni, Massaccesi, Pividori, & Johnson, 2004) and 4-month-olds (Farroni, Johnson, Brockbank, & Simion, 2000) look more quickly toward a peripheral target when it is preceded by an eye movement in that direction in a centrally presented face. At both ages, eliminating motion by having the eyes move behind closed eyelids eliminates the cuing effect. Even at 4 or 5 months of age, infants shift their gaze in the direction of a lateral movement of the head even when the eyes did not move (Farroni et al., 2000). Lateral motion of the eyes could even account for why by 6 months of age infants reliably follow gaze to the correct side of the visual field, locating the true target of gaze when it appears first in the scanning path but not when it is farther to the side (Butterworth & Cochran, 1980; Butterworth & Jarrett, 1991). It could also reflect imitation of the adult's eye/head orientation (Meltzoff & Moore, 1977).

After 6 months of age, infants respond to more than lateral motion of the head/eyes; they follow gaze to specific objects outside their visual field even if the object of fixation is not first in the scanning path (Butterworth & Cochran, 1980; Butterworth & Jarrett, 1991; Corkum & Moore, 1998). By 8 months of age, infants respond as though they expect gaze to be directed to an object that is visible to the looker that need not be visible to the infant. This was evident in an experiment that presented infants with an experimenter repeatedly looking toward the right side or left side behind an occluder and then lifted the occluder to reveal an object on either the fixated or nonfixated side. Although they spent more time looking at the object than at the empty side, both 8- and 12-month-olds looked longer at the empty side when the observer had been fixating it than when he or she had not (Csibra & Volein, 2008). By 9 months of age, infants appear to encode the relation between the direction of gaze and a specific object. After viewing an experimenter repeatedly fixating one of two objects, 9-month-olds looked longer when the experimenter fixated the same object in a different location than when the experimenter fixated the other object in the previous location of fixation (Johnson, Ok, & Luo, 2007; see also Senju, Csibra, & Johnson, 2008). At 18 (but not 12) months of age, infants follow an adult's gaze to objects located behind the infant when the visual field is empty (Butterworth & Jarrett, 1991). These patterns may reflect an understanding of gaze as the act of looking toward a point of interest (e.g., Butler, Caron, & Brooks, 2000), but they could merely reflect an adjustment of the infant's gaze-following strategy to better reflect the conditions under which gaze following has led to objects that interest the infant (e.g., Csibra & Volein, 2008). Collectively, the findings suggest that sensitivity to triadic gaze increases throughout infancy but do not indicate the extent to which infants understand gaze as a cue to the target of others' interest.

By 2 or 3 years of age, children can make explicit judgments of triadic gaze, and the accuracy of these judgments improves throughout early childhood. In one study, 2- to 4-year-olds were presented with video displays of a live model moving her eyes alone or moving her eyes and head together toward one of several widely spaced objects (Lee, Eskritt, Symons, & Muir, 1998, Experiments 4 and 5). In all conditions, 3- and 4-year-olds exceeded chance in determining the correct target of gaze, but 2-year-olds exceeded chance only when feedback was provided and the model moved her eyes and head together. In another study, 2- to 4-year-olds were presented with targets placed in the corners of a rectangular frame. Stimuli were a live model, photographs, and cartoon images, in each case with the eyes directed at one of the corners. In all versions of the task, only the endpoint of the eye movement was displayed and feedback was not presented. A majority of 3- and 4-year-olds, but not 2-year-olds, passed each version (Doherty, Anderson, & Howieson, 2009, Experiment 1).

Although young children can make explicit judgments of gaze, finer-grained sensitivity appears to develop gradually. Only half of 4-year-olds are able to determine which of a set of targets spaced 10° or 20° apart an adult is looking at (Butterworth & Itakura, 2000; Leekam, Baron-Cohen, Perrett, Milders, & Brown, 1997). In the one previous study comparing sensitivity between children and adults, 3- to 6-year-olds and adults were presented with three targets spaced 10° or 15° apart on one side of midline. The model fixated one of the targets by moving either the eyes alone or the eyes and the head together. The 3-year-olds exceeded chance only when the head and eyes moved together and the targets were 15° apart. By 6 years of age, accuracy was adult-like in all conditions except when the model moved the eyes alone and the targets were 10° apart (Doherty et al., 2009, Experiment 2). These gradual refinements in sensitivity to the direction of triadic eye gaze may support more accurate inferences regarding the interests and intentions of others. However, even at age 6, sensitivity appears to be much poorer than that of adults, who can detect a difference of 0.3° to 2°.

Previous studies have not examined sensitivity to triadic gaze after 6 years of age and have not tested children with objects spaced less than 10° apart. The purpose of the current study was to extend previous work by measuring the developmental trajectory of fine-grained sensitivity to triadic gaze from age 6 onward. In Experiment 1, instead of asking children which of three targets a model was fixating (Doherty et al., 2009), we used a simpler task in which children (6-, 8-, 10-, and 14-year-olds) and adults judged whether the model was looking to the right or left of a specified target, with deviations spaced 1.6° apart for children and 0.8° apart for adults. In Experiment 2, we investigated whether 6-year-olds' accuracy could be improved by adding easier trials in which the model was looking farther away from the target than in Experiment 1. In Experiment 3, we asked whether the precision of younger children's triadic gaze judgments in Experiments 1 and 2 was limited by an immaturity in sensitivity to differences in eye position. We evaluated this hypothesis by testing adults and 8-year-olds on a gaze matching task.

Experiment 1

Method

Participants

Participants were 18 6-year-olds (6 years 6 months ± 3 months, M = 6.46 years, 10 girls and 8 boys), 18 8-year-olds (8 years 6 months ± 3 months, M = 8.55 years, 12 girls and 6 boys), 18 10-year-olds (10 years 6 months ± 3 months, M = 10.56 years, 11 girls and 7 boys), 18 14-year-olds (14 years 6 months ± 3 months, M = 14.58 years, 7 girls and 11 boys), and 18 adults (18–21 years, M = 18.62 years, 13 women and 5 men). 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 replaced because they failed visual screening (1 8-year-old), because their data file was corrupt (1 8-year-old), because their data were best fit by a function with a negative slope (2 6-year-olds), or because of a threshold value more than 3 standard deviations above the mean (1 6-year-old). A negative slope or statistically deviant threshold value was taken as an indication of inattentiveness or poor understanding of the task.

Materials

Stimuli. Stimuli were digital color photographs of adult models fixating a series of positions marked on a horizontal board 75 cm in front of them and 20 cm below eye height (120 cm) (see Fig. 1 and Appendix A for details). The final stimulus set for each model contained photographs of the model fixating 37 positions ranging from 14.4° to the left of midline through 14.4° to the right in 0.8° steps. All facial images were displayed at life size with the model's eyes 115 cm above the floor 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 Cedrus Superlab on an Apple Mac mini computer. To allow some generality of the results, the final stimulus set included three male models (one Asian and two Caucasian) and three female models (one Asian and two Caucasian). Each participant was tested with only one model, counterbalanced across participants at each age, such that each of the six models appeared three times in test trials and three times in practice trials. Each model was paired with every other model of the opposite sex, once as a practice model and once as a test model.

Apparatus. The apparatus was geometrically identical to that used during the photography sessions, with the model replaced by a computer monitor (see Fig. 2) positioned 150 cm in front of the participant, the distance from which the models had been photographed. Participants used a chin rest to maintain a consistent head position and an eye height of 115 cm. The horizontal board with the marked positions was placed 75 cm in front of the participant with the fixation positions facing the participant at a height of 95 cm. Three target positions (midline, 6.4° right, and 6.4° left) were marked by printed paper cutouts displaying small images of Earth's moon and the planets Venus and Mars. The images of the moon, Venus, and Mars always marked the target positions presented in the first, second, and third blocks, respectively. During each test block, the marker image was flanked by printed images of blue and red space stations. All marker images irrelevant to the current block were occluded by a white piece of paper folded over the top.

Participants entered responses on a computer keyboard placed on a table directly in front of them. The experiment used three keys on the keyboard: the B key with a piece of red paper taped over the top (for eye deviations toward the red space station), the V key with a piece of blue paper taped over the top (for eye deviations toward the blue space station), and the G key with a piece of paper bearing the letter "A" taped over the top (for catch trials). The experimenter used a separate computer keyboard to advance the experiment and enter responses for practice trials.

Design

Participants completed a test block for each of three target positions (6.4° left, midline, and 6.4° right) using the same model on every test trial. Before each test block, there was a practice block with a different model of the opposite sex. The practice block consisted of eight trials with the model fixating the farthest position from the target (four trials at 6.4° to the left of the target and four trials at 6.4° to the right). Practice trials were presented in a pseudorandom order. During practice blocks, participants received

Fig. 1. Stimuli for one model presented in the midline target block.

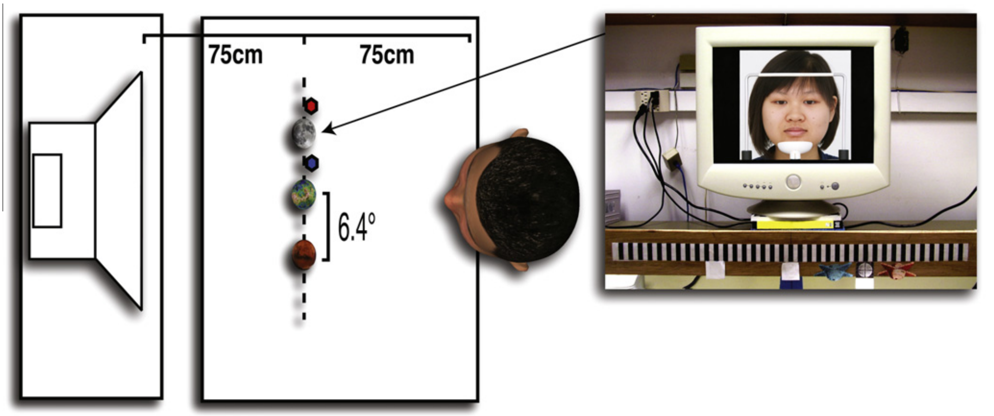

Fig. 2. Schematic representation of the apparatus used in Experiment 1. The photograph displays the configuration of targets and fixation positions for a block during which the observer judged whether the model was looking to the right or left of a target 6.4° to the right of midline. The arrow shows the relevant target in the version of the apparatus depicted in the accompanying photograph.

verbal feedback indicating whether each response was correct or not. Participants were allowed to repeat each practice block up to two times to achieve a criterion of 75% accuracy on either the first four or last four trials in the practice block. All adults, 8-year-olds, and 10-year-olds met criterion on the first attempt, but two 6-year-olds and one 14-year-old required a second attempt to meet it.

The order of the three target positions was counterbalanced across participants. In each test block, the participant viewed photographs of a single model fixating a series of horizontal positions covering a range of 6.4° to each side of the target, with 10 repetitions of each fixation position. Adults received photographs corresponding to the model fixating 17 positions (the target and 8 positions on either side) in 0.8° steps, whereas children received photographs corresponding to the model fixating 9 positions (the target and 4 positions on either side) in 1.6° steps. During test blocks, participants received no feedback. To assess attentiveness, we included five catch trials that appeared at random positions within each block and never more than twice in a row. In 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.

Procedure

Written consent was obtained from all adult participants and from a parent of each child participant. Verbal assent was also obtained from 10- and 14-year-olds. After positioning each participant appropriately in the apparatus, the experimenter displayed a photograph of the model that would appear in all target blocks. The experimenter explained the task as follows (with appropriate adjustments if the test model was male):

> This is Jenny. She is an astronaut that has just been chosen for a special space mission to Mars!

After pressing a key to present a cartoon spaceship, the experimenter continued:

> On this mission, she will be traveling in a brand new spaceship. To steer this new spaceship, she will have to move her eyes in the direction she wants the spaceship to go.

The experimenter then pressed a key to display a photograph of Earth's moon and gave the following instruction:

> Jenny is trying to steer her spaceship toward the moon. To stay on course, she has to look at the center of the tip of the black stripe above the moon. Sometimes, she goes off course by looking

Table 1
Accuracy on catch trials as a function of age group and target position.

	6-year-olds	8-year-olds	10-year-olds	14-year-olds	Adults
Midline	.99 (.05)	.99 (.05)	.99 (.05)	1.00 (.00)	1.00 (.00)
Right	.97 (.09)	.97 (.07)	.99 (.05)	1.00 (.00)	.99 (.05)
Left	1.00 (.00)	.96 (.08)	.96 (.15)	.99 (.05)	1.00 (.00)

Note: Standard deviations are in parentheses.

too far toward the blue or red space station. She needs your help to stay on course. If Jenny is looking too far toward the red space station, press the red button. If she is looking too far toward the blue space station, press the blue button.

The experimenter then pressed a key to display the picture of the meteoroid that was used for catch trials and explained the response protocol. The experimenter then initiated practice trials. The participant responded to practice trials by saying whether the model appeared to be looking toward the blue station (left of target) or red station (right of target). Once the participant reached criterion, test trials at that target location began.

At the start of each test trial, a black fixation cross appeared at the center of a white background. When the participant appeared to look at the fixation cross, the experimenter pressed a key to display a photograph of the model. The participant pressed a blue or red button with his or her dominant hand to indicate whether the model appeared to be looking toward the blue space station (left side of the target) or the red space station (right side of the target). The stimulus remained on the screen until the participant entered an appropriate response.

After completion of the first and second test blocks, a photograph of Venus (end of first block) or Mars (end of second block) appeared on the screen and the participant was given a break before beginning the practice block for the next target position.

Results

Accuracy on catch trials

Accuracy on catch trials was high at all ages and for blocks testing all target positions (see Table 1). An analysis of variance (ANOVA) on accuracy revealed no effect of age, no effect of target position and no interactions, *p*s > .10. Thus, children of all ages appeared to be as attentive as adults.

Estimates of sensitivity to triadic gaze

Curve fitting. For each participant, we calculated the proportion of the 10 trials at each eye deviation that were judged to be to the left or right of the target (see Fig. 3). To quantify sensitivity to triadic gaze cues, we fit a cumulative Gaussian function relating each participant's judgments in each target position to the fixation positions (see Appendix B for details). Although adults were tested with finer steps (0.8°) than children (1.6°), we based the analyses only on the fixation positions tested in common.[1] We used the fitted cumulative Gaussian functions to calculate two measures of interest: threshold and point of subjective equality (PSE). The PSE is the fixation position corresponding to the 0.5 point on the function. This represents the position in degrees at which the participant was unable to reliably classify the direction of gaze as either left or right of the target position. A participant with perfect calibration would yield a PSE of 0°. We calculated thresholds for each participant from the difference in fixation positions corresponding to the 0.50 and 0.75 points on the fitted curve. This measure provides an estimate of the participant's precision that is independent of the location of the PSE. When a participant is very precise, this part of the function is very steep because a small shift farther left or right is picked up accurately. A participant with perfect precision would yield a threshold of 0.30°.

[1] To determine whether using the data for positions spaced 0.8° or 1.6° apart affected the shape of the fitted functions, we fit functions to adults' data for both step sizes. There was no difference in threshold or PSE between 0.8° and 1.6° step sizes, *p*s > .50.

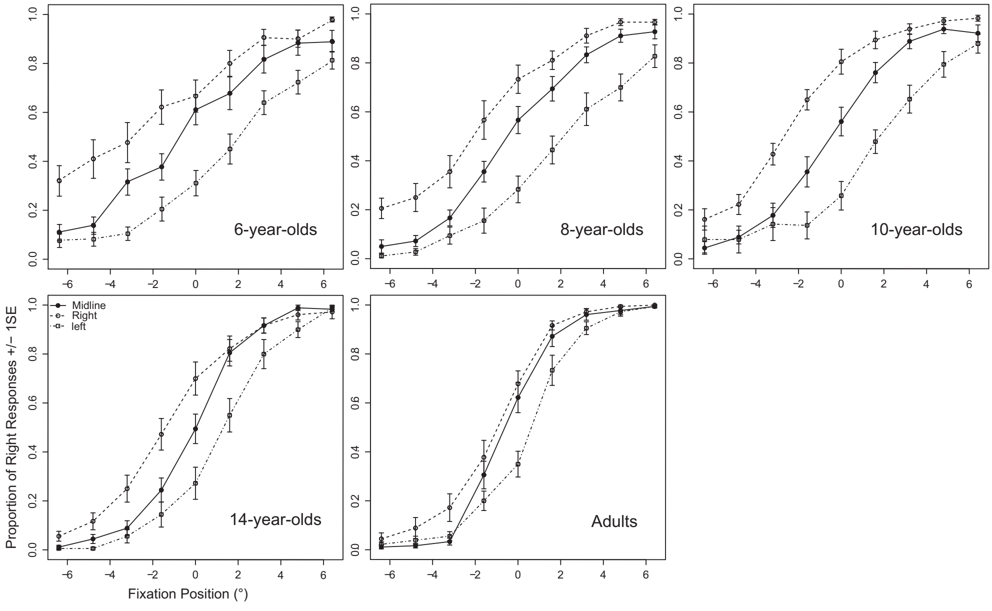

Fig. 3. Mean proportion of trials (±1 SE) during which children (6-, 8-, 10-, and 14-year-olds) and adults indicated that the model appeared to look to the right of the target as a function of fixation position. Positive values on the abscissa refer to fixation positions to the right of the target. Negative values refer to fixation positions to the left of the target.

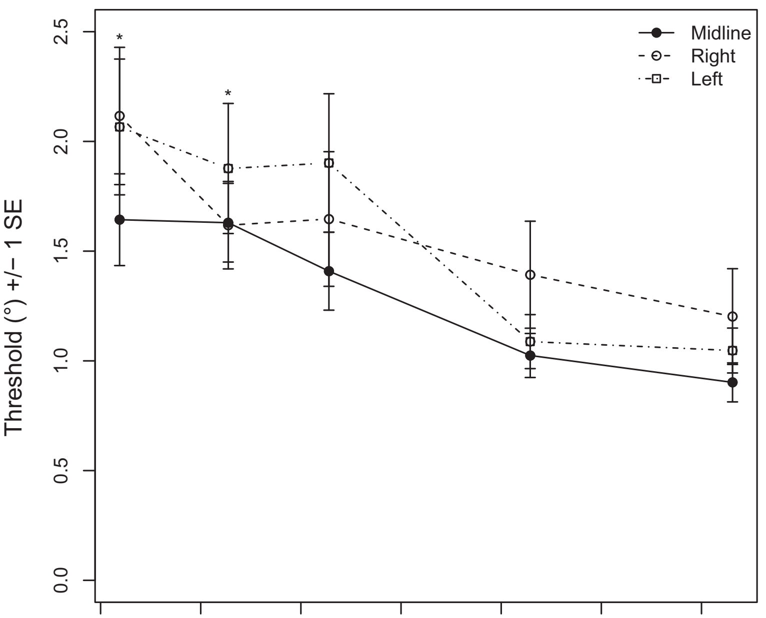

Fig. 4. Mean threshold (±1 SE) in degrees as a function of age. Higher values indicate lower sensitivity. *$p < .05$ compared with adults.

Threshold. The threshold values are shown in Fig. 4. To assess the effects of age and target position on threshold sensitivity to triadic gaze, we conducted an age by target position mixed ANOVA with threshold as the dependent variable. When appropriate, the Greenhouse–Geisser estimate of epsilon, $\hat{\epsilon}$, was used to adjust p values of F tests conducted on within-participant variables. There was a significant main effect of age, $F(4, 85) = 5.09$, $p < .01$, $f^2 = .23$. Post hoc Dunnett's tests showed that thresholds were significantly lower in adults ($M = 1.05$, $SD = 0.37$) than in 6-year-olds ($M = 1.94$, $SD = 0.92$), $p < .01$, or 8-year-olds ($M = 1.71$, $SD = 0.82$), $p < .02$. There was no significant difference in threshold between 10-year-olds ($M = 1.42$, $SD = 0.99$) and adults, $p > .20$, or between 14-year-olds ($M = 1.17$, $SD = 0.72$) and adults, $p > .90$. The ANOVA also revealed a significant main effect of target position, $F(2, 170) = 3.63$, $p < .05$, $f^2 = .04$, which did not interact with age, $p > .50$. We followed up the main effect of target position with three paired-samples t tests (Bonferroni-corrected $\alpha = .017$) comparing each possible pair of target positions. Thresholds were significantly lower for the midline target position ($M = 1.28$, $SD = 0.71$) than for the right target position ($M = 1.56$, $SD = 1.04$), $t(89) = 2.44$, $p = .017$, $d = 0.31$, and the left target position ($M = 1.52$, $SD = 1.04$), $t(89) = 2.43$, $p = .017$, $d = 0.27$. However, there was no significant difference in threshold between the left and right target positions, $p > .80$.

Point of subjective equality. Fig. 5 shows the PSE for each age group and target position. For central targets the PSE is close to zero (i.e., near the actual position of the target), but for peripheral targets the plot indicates a systematic bias. To assess the effects of age and target position on any bias in perceiving the direction of gaze judgments, we conducted an age by target position mixed ANOVA with PSE as the dependent variable (see Fig. 5 for plot). There was no target by age interaction, $p > .10$, and no main effect of age, $p > .50$. There was a significant main effect of target, $F(1.58, 134.47) = 59.28$, $\hat{\epsilon} = .791$, $p < .001$, $f^2 = .69$. We followed up the main effect of target with three paired-samples t tests (Bonferroni-corrected $\alpha = .017$) comparing every combination of target positions. Participants overestimated the direction of gaze toward peripheral targets: they judged the model to be looking to the left of the actual fixation position when the target was to the left of midline ($M = 1.43$,

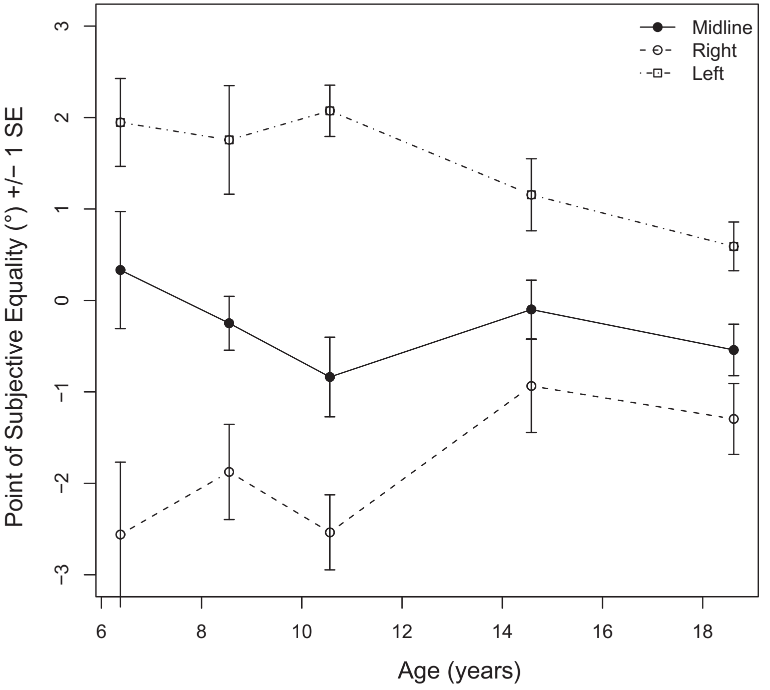

Fig. 5. Mean PSE (±1 SE) in degrees as a function of age. Zero corresponds to the actual position of the target. Positive values indicate fixation positions to the right of the target. Negative values indicate fixation positions to the left of the target.

$SD = 0.89$) and judged the model to be looking to the right of the actual fixation position when the target was to the right of midline ($M = -1.78$, $SD = 2.35$), $t(89) = 8.62$, $p < .001$, $d = 1.80$. Both biases were significantly greater than that shown at midline ($M = -0.40$, $SD = 1.71$), $ps < .001$.

Relationship between threshold and PSE

The threshold and PSE measures used in the current investigation are mathematically independent, but a cognitive or perceptual variable (e.g., attention, motivation) could affect both, leading to covariance between the two measures. We tested this hypothesis by conducting Pearson correlations between threshold and absolute PSE scores for each target position and age group. There were no significant correlations, $ps > .05$.

Changes in performance across and within blocks

The greater precision of judgments in adults than in children could be a result of age differences in fatigue and/or learning across trials. Either possibility would predict age-related differences in performance across successive blocks. To test this hypothesis, for each target position we conducted an age by block number (first, second, or third) ANOVA with threshold as the dependent variable. There was a main effect of age in each ANOVA, $ps < .02$, but these effects are redundant with the previous threshold analysis and, therefore, will not be discussed further. For all ANOVAs, there was no age by target interaction, $ps > .30$. There was a main effect of order for the central target, $F(2, 75) = 3.50$, $p < .05$, $f = .23$, but not for the right or left targets, $ps > .30$. A Tukey HSD post hoc test following up the main effect of order for the central target revealed a significant difference in threshold between the second block ($M = 1.12$, $SD = 0.65$) and the third block ($M = 1.54$, $SD = 0.73$), $p < .05$, but not between the first block ($M = 1.19$, $SD = 0.70$) and the second or third blocks, $ps > .10$. Although there was some evidence of fatigue for the central target only, the absence of an age by order interaction suggests that fatigue and/or learning do not account for the observed effects of age on thresholds.

The greater precision of judgments in adults than in children might also have resulted from age differences in the rate of learning of the task within blocks. To examine this possibility statistically, we compared within-block changes for the two most extreme age groups: 6-year-olds and adults. We conducted a mixed ANOVA with fixation position, target position, and block half (first half or last half) as within-participant variables, age (6-year-olds or adults) as a between-participant variable, and the proportion of "right" responses as the dependent variable. There was no main effect of block half, and there were no interactions involving block half and age, $ps > .05$. These results suggest that different rates of within-block learning do not account for the observed age differences in the precision of judgments.

Discussion

Adults in the current experiment were highly sensitive to triadic gaze, as indicated by a mean threshold of 1.05°. Assuming an eyeball radius of 12.5 mm, this threshold corresponds to an iris shift of 31.5″[2] from the perspective of the observer. Previous research has reported thresholds of 30″ in adults using a live looker (Symons et al., 2004, Experiment 1), 8.6′ (i.e., 516″) using low-quality photographs (Symons et al., 2004, Experiment 2), and 24.4″ using high-quality photographs (Symons et al., 2004, Experiment 3). Thus, the current results correspond well to previous findings obtained using stimuli of comparable quality.

As in Symons and colleagues' (2004, Experiment 3) study, adults in the current experiment displayed lower sensitivity for peripheral targets than for the midline target: their thresholds were 1.05° for the left target and 1.20° for the right target compared with 0.90° for the midline target. These results are consistent with the hypothesis that observers rely on different cues to eye position at different fixation positions (Symons et al., 2004). According to this hypothesis, observers may judge eye position from the amount of sclera visible on either side of the iris at positions near midline. When the eyeball rotates to fixate a position in the periphery, part (as in this experiment) or all (with more peripheral fixation) of the sclera is occluded on the side of fixation as well as part of the iris for more

[2] Here ″ refers to seconds of arc, and ′ refers to minutes of arc (1′ = 1/60° and 1″ = 1/3600°).

extreme target locations. In this case, observers may use the position and/or shape of the visible iris to infer the direction of gaze, a cue that may be more difficult to judge accurately than the visible sclera on both sides of the iris. Lower precision at peripheral targets could also result from the greater angle between the target and the center of the pupil. Estimating the target of gaze across a greater lateral distance may require more elaborate spatial processing, which could lead to lower precision.

As in Anstis and colleagues' (1969) study, adults in the current experiment overestimated the direction of gaze toward peripheral targets: they judged the model to be looking 1° to 2° farther in the periphery than he or she actually was. One possible explanation for this arises from the fact that the model altered eye position while maintaining a forward head orientation. Adults are known to make detectable head movements when asked to fixate targets 25° from midline even when asked to maintain a forward head orientation (Doherty & Anderson, 2001). Adults may also tend to move the head and eyes together when fixating less extreme peripheral fixation positions such as those tested in the current experiment (up to 12.8° from midline). Thus, adults may typically see others move their eyes less than the full amount when shifting gaze to position 6° to 12° in the periphery, with the missing amount coming from a head rotation. The eye shifts shown here may be more typical of those used for shifts of fixation farther off to the side. As a result, adults in the current experiment may have overestimated the target of fixation as farther off to the side than it actually was. A second possibility is that the blocked design (e.g., a block of trials with the left target) led to shifts of spatial attention. Adults reflexively orient toward the location of a peripheral target when the gaze of a centrally presented face cues the location of the object (e.g., Friesen & Kingstone, 1998). During each peripheral target block in the current experiment, the model looked in the direction of the target on 80 of 90 trials, with the only variation being in whether the eyes under- or overshot the target location. Thus, orienting in the direction of gaze could have recentered participants' sense of straight ahead in the direction of the target, resulting in the observed bias.

The current experiment provides the first information on the developmental trajectory of fine-grained sensitivity to triadic gaze from 6 years of age to adulthood. Children were highly sensitive to eye deviations, displaying a mean threshold of 1.92° by age 6, compared with an adult mean threshold of 1.05°. Like adults, children at all ages had better thresholds for central targets than for peripheral targets and overestimated the direction of gaze toward peripheral targets. The similar patterns suggest that the system for decoding triadic gaze is functioning in an adult-like manner by age 6, the youngest age tested. It is only the precision of the system that appears to change after age 6. Both 6- and 8-year-olds displayed statistically higher thresholds than adults. The thresholds of 10-year-olds were also higher than those of adults, but the difference was not statistically significant. Thresholds were well within the range established by adults at 14 years of age, suggesting that the precision of triadic gaze judgments improves gradually, reaching maturity at or above 10 years of age.

The one previous study of sensitivity to triadic gaze at an age overlapping with the ages studied here seemingly found much poorer sensitivity: in that study, 6-year-olds were as accurate as adults at using eye position alone to judge which of three objects spaced 15° apart a model was looking at but were less accurate than adults with 10° spacing (Doherty et al., 2009). However, the previous study did not distinguish between errors resulting from limitations in precision and those resulting from systematic biases (e.g., overestimation). The current results suggest that adults and children as young as 6 years overestimate the direction of gaze toward peripheral targets. This could have reduced the accuracy reported by Doherty and colleagues (2009). In the current experiment, we made independent estimates of precision and bias and, hence, may have obtained a more accurate assessment of precision at age 6. However, it is also possible that at age 6, children's precision is better at judging whether an observer is fixating to the left or right of a single target (our task) than at judging which of three targets is being fixated (Doherty et al., 2009), a judgment that may require more elaborate spatial processing.

The observed effects of age on sensitivity could potentially result from differences in attention or motivation between children and adults. However, this seems unlikely given that age did not affect accuracy on catch trials and that the effects of block number on thresholds did not interact with age. Age-related differences in sensitivity could also result from poorer understanding of the task in children than in adults. However, this too seems unlikely given that children with deviant threshold values or negative slopes were replaced, that the same effect of target position on thresholds and PSEs was found at all ages, and that children reached criterion on practice trials as quickly as adults.

Poor performance in young children could also arise if the range of fixation positions was too small to allow children to respond reliably. As shown in Fig. 3, the youngest age groups failed to reach the lower and upper asymptotes established by adults at fixation positions farthest from the target. The narrow range of fixation positions might have prevented children from applying a consistent response strategy, resulting in low precision. Alternatively, fitting functions to data that did not reach asymptote may have resulted in inaccurate estimates of slope.

Experiment 2

In Experiment 2, we tested 6-year-olds on the midline target from Experiment 1 using fixation positions covering a much wider range, namely 14.4° left to 14.4° right of midline in increments of 1.6°. With this larger range, we expected children's performance to be more likely to reach asymptotic values near the extreme deviations and, hence, perhaps allow a more accurate estimate of slope. We also thought that children might respond more reliably when the stimulus set included extreme deviations they could judge more easily. To evaluate these possibilities, we compared the estimated thresholds for central targets for 6-year-olds tested in Experiment 1 with those obtained in Experiment 2. We also compared the response functions for the overlapping positions.

Method

Participants

Participants were 18 6-year-olds (6 years ± 3 months, $M = 6.56$ years, 9 girls and 9 boys) who met the same screening criteria as in Experiment 1. No additional children were excluded.

Materials, design, and procedure

Stimuli came from the same set as those used in Experiment 1 for the central target except that more peripheral fixation positions were included for a total of 19 positions (midline and nine positions on either side in steps of 1.6°). The apparatus was identical to that in Experiment 1 with the exception that the peripheral targets were removed and the central target position was always marked by an image of the planet Mars. The procedure was the same except for splitting the single block in half to provide a break. In each half, participants received five trials at each fixation position and five catch trials. The experimenter administered visual screening during the break between halves.

Results

Curve fitting

We fit psychometric functions to each participant's data using the fitting regime applied in Experiment 1 (see Fig. 6). Goodness of fit was within the acceptable parameters described in Appendix B for Experiment 1 for all fits.

Threshold, PSE, and accuracy on catch trials

As shown in Fig. 6, the responses of 6-year-olds in Experiments 1 and 2 were very similar within the range of overlapping fixation positions. There was no significant difference in thresholds between Experiment 1 ($M = 1.64$, $SD = 0.98$) and Experiment 2 ($M = 2.15$, $SD = 1.02$), $p > .10$, nor did PSE differ significantly between Experiment 1 ($M = 0.34$, $SD = 2.72$) and Experiment 2 ($M = 1.23$, $SD = 2.01$), $p > .20$. Accuracy on catch trials was high in both experiments, with no significant difference (Experiment 1: $M = .99$, $SD = .05$; Experiment 2: $M = .98$, $SD = .05$), $p > .40$.

Discussion

Including more extreme deviations in Experiment 2 altered the shape of the response functions for 6-year-olds so that they reached the upper and lower asymptotes shown by adults. Nevertheless, the estimated thresholds and PSE were similar to those from Experiment 1, a result suggesting that the

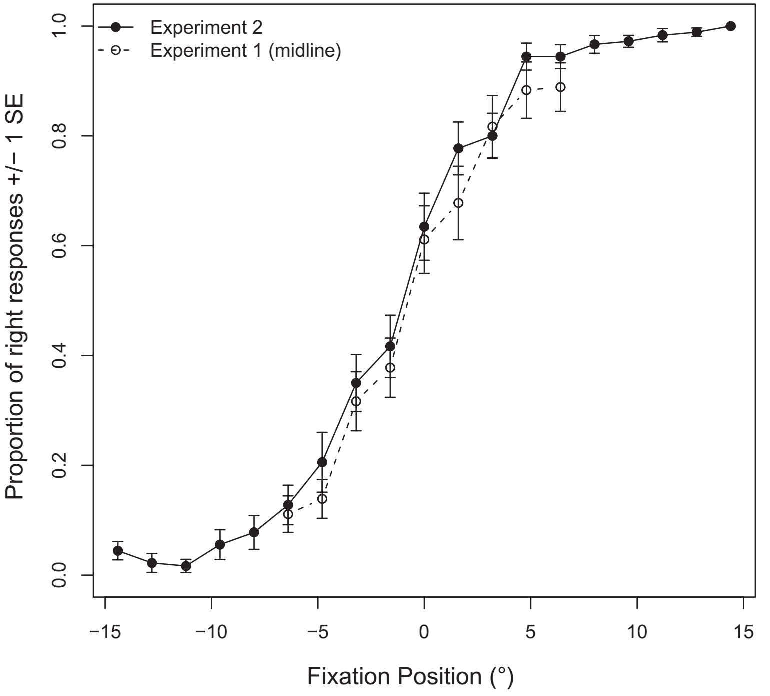

Fig. 6. Mean proportion of trials (±1 SE) on which 6-year-olds indicated that the model appeared to look to the right of the target as a function of fixation position in Experiments 1 and 2. Positive values on the abscissa refer to fixation positions to the right of the target. Negative values on the abscissa refer to positions to the left of the target.

adjustment of upper and lower asymptotes for curve fitting in Experiment 1 did not lead to inaccurate estimates. Moreover, the similarity between the response functions for overlapping positions indicates that the inclusion of the easier positions did not lead children to respond more reliably. Thus, Experiment 2 confirms the conclusion of Experiment 1 that sensitivity to triadic gaze improves after 6 years of age.

Experiment 3

The results of Experiment 1 suggest that fine-grained sensitivity to triadic gaze does not reach maturity until around 10 years of age. The limitation observed in younger children could reflect an immaturity in the ability to detect small differences in eye position and/or an immaturity in the ability to determine which object in the environment the eyes are looking toward. In Experiment 3, we investigated the former hypothesis by presenting the stimuli from the previous experiments in a matching task. We tested 8-year-olds because this was the oldest age at which children had significantly higher thresholds than adults in Experiment 1 and because the immaturity observed in 8-year-olds was similar in magnitude to that of 6-year-olds.

The detection of small differences in eye position involves fine spatial judgments of the relative size of the sclera to the right and left of the iris for more central targets and of the size of the still visible sclera or the shape of the visible iris for more peripheral targets (Symons et al., 2004). Children are not as sensitive as adults to the alignment of abutting lines (Vernier acuity) (see Skoczenski & Norcia, 1999) or to the distance between the eyes (Baudouin, Gallay, Durand, & Robichon, 2010). Given the protracted developmental trajectory for those skills, we suspected that children might also not be as sensitive to small shifts in eye position.

Method

Participants

Participants were 18 8-year-olds (8 years 6 months ± 3 months, $M = 8.47$ years, 11 girls and 7 boys) and 18 adults (18–26 years, $M = 20.41$ years, 11 women and 7 men) who met the same screening criteria as in Experiment 1. An additional 5 8-year-olds were replaced because they failed to pass visual screening ($n = 3$) or because their data in one target condition (see "Design" section below) was best fit by a function with a negative slope ($n = 2$).

Materials

Stimuli. The stimuli were the same as those presented in the previous experiments and were displayed at life size, with the model's eye height at 110 cm. The stimuli were displayed on a 30-inch Dell 3007WFP monitor set to a resolution of 2560 × 1600 pixels. The experiment was run in MATLAB (MathWorks, Natick, MA, USA) using the Psychophysics Toolbox extensions (Brainard, 1997) on an Apple Mac Pro computer.

Apparatus. The monitor was positioned 150 cm in front of the participant. The participant's sitting position was adjusted so that his or her height was 110 cm. The participant entered responses on a computer keyboard placed on a table directly in front of him or her. The F and J keys with stickers placed over the top were used to indicate left and right responses, respectively, and the B key with a piece of paper bearing the letter "A" taped over the top was used to indicate the detection of a catch trial.

Design

Each participant completed one practice block and one test block. The presentation of models was counterbalanced across participants as in the previous experiments. Three images of the model were presented simultaneously (see Fig. 7 for an example). Adjacent images were spaced 2.7 mm (0.10°) apart, and the outer edges of the peripheral images were 3 mm (0.11°) from the edges of the screen. During the practice block, the central image displayed the model looking at a "target" position at midline or 6.4° to the left or right of midline (four trials per direction) except that no target was physically present. The central image was identical to one of the peripheral choices. The other peripheral choice displayed the model fixating a position 8° to the left or right of the target position. The task was to indicate in which picture the model was looking in a different direction from that of the central image. Practice trials were presented in a pseudorandom order with the constraint that the central image did not fixate the same target position for more than two trials in a row. The participant was allowed to repeat the practice block up to two times to meet the criterion of at least 75% accuracy. In total, 12 8-year-olds and 13 adults were able to meet the criterion on the first attempt. The remaining 6 8-year-olds and 5 adults required two attempts to meet the criterion.

Fig. 7. Example of the images displayed on a single trial in Experiment 3. The left and center images show the model fixating a target at midline. The right image shows the model fixating a target 6.4° to the right of midline.

Following the practice block, the participant completed a single test block composed of 240 trials that was identical to practice blocks except that in the nonmatching peripheral choice the model fixated a position 1.6°, 3.2°, 4.8°, 6.4°, or 8.0° to the left or right of the position fixated in the central image. Each level of mismatch was presented 16 times (half to each side of the target position) for each target position. Trials were presented in a pseudorandom order with the constraint that the central image did not fixate the same target position for more than two consecutive trials. Trials were divided into three sets of 80. The experimenter carried out visual screening after the first set of trials and offered a break after the second set. Within each set, the participant received 5 catch trials. Catch trials were presented and scored as in Experiment 1 with the exception that consecutive catch trials were at least 8 trials apart.

At the beginning of each practice or test trial, a black fixation cross appeared at the center of a gray background. When the participant was judged to be attending to the fixation point, the experimenter pressed a key to display three images of the model. The participant was instructed to press the key corresponding to the location of the mismatch. The participant received feedback following each response (cartoon image of a happy face and 1000-Hz tone for correct responses, cartoon image of a sad face and 400-Hz tone for incorrect responses). On each trial, the images remained on the screen until the participant responded.

Procedure

The experimenter obtained written consent from adult participants and from a parent of each child participant. The experimenter adjusted the chair height so that the participant's eye height was 110 cm. As in the previous experiments, instructions were adjusted to reflect the sex of the model. The experimenter introduced the test model and spaceship as in Experiment 1. The experimenter then displayed three images of the test model. The left and center images displayed the model fixating a target at midline. The right image displayed the model fixating a target 8° to the left of midline. To explain the task, the experimenter delivered the following instruction:

> Jenny needs your help to stay on course. I'll show you three pictures of Jenny on the monitor like the ones you see here. The middle picture will always show Jenny looking in the correct direction. One of the other two pictures will show Jenny looking in the wrong direction, and one of the other two will show her looking in the correct direction. If the picture of Jenny that is looking the wrong way shows up on this side [points to left side], press this button [points to left button]. If the picture of Jenny looking in the wrong direction is on this side [points to right side], press this button [points to right button].

The experimenter then introduced the catch trials as in Experiment 1 and initiated test trials.

Results

Accuracy on practice and catch trials

There was no significant difference in accuracy on practice trials between 8-year-olds ($M = .78$, $SD = .15$) and adults ($M = .84$, $SD = .12$), $p > .10$. Accuracy was high on catch trials, with no significant difference between adults ($M = .98$, $SD = .04$) and 8-year-olds ($M = .99$, $SD = .02$), $p > .20$.

Accuracy on test trials

We attempted to fit functions to each participant's data. Although each participant's responses displayed a positive slope, there were only five data points per mismatch magnitude and the shape of the response function tended to vary between participants. Thus, we were unable to obtain fits of sufficient quality for confident estimation of individual thresholds and instead used group analyses based on individual mean accuracy for each magnitude of mismatch.

To assess the effects of age, mismatch level, and target position on accuracy, we conducted an age by mismatch level mixed ANOVA with accuracy as the dependent variable (see Fig. 8 for plot). There was a significant mismatch level by age interaction, $F(2.98, 100.24) = 3.64$, $\hat{\epsilon} = .748$, $p < .02$, $f = .11$. No other interactions were significant, $ps > .20$. There were main effects of target, level and age, $F(1.89, 64.35) = 4.26$, $\hat{\epsilon} = .737$, $p < .05$, $f = .12$, $F(2.95, 100.23) = 131.73$, $\hat{\epsilon} = .748$, $p < .001$, $f = 3.88$, and $F(1, 34) = 10.98$, $p < .005$, $f = .32$, respectively.

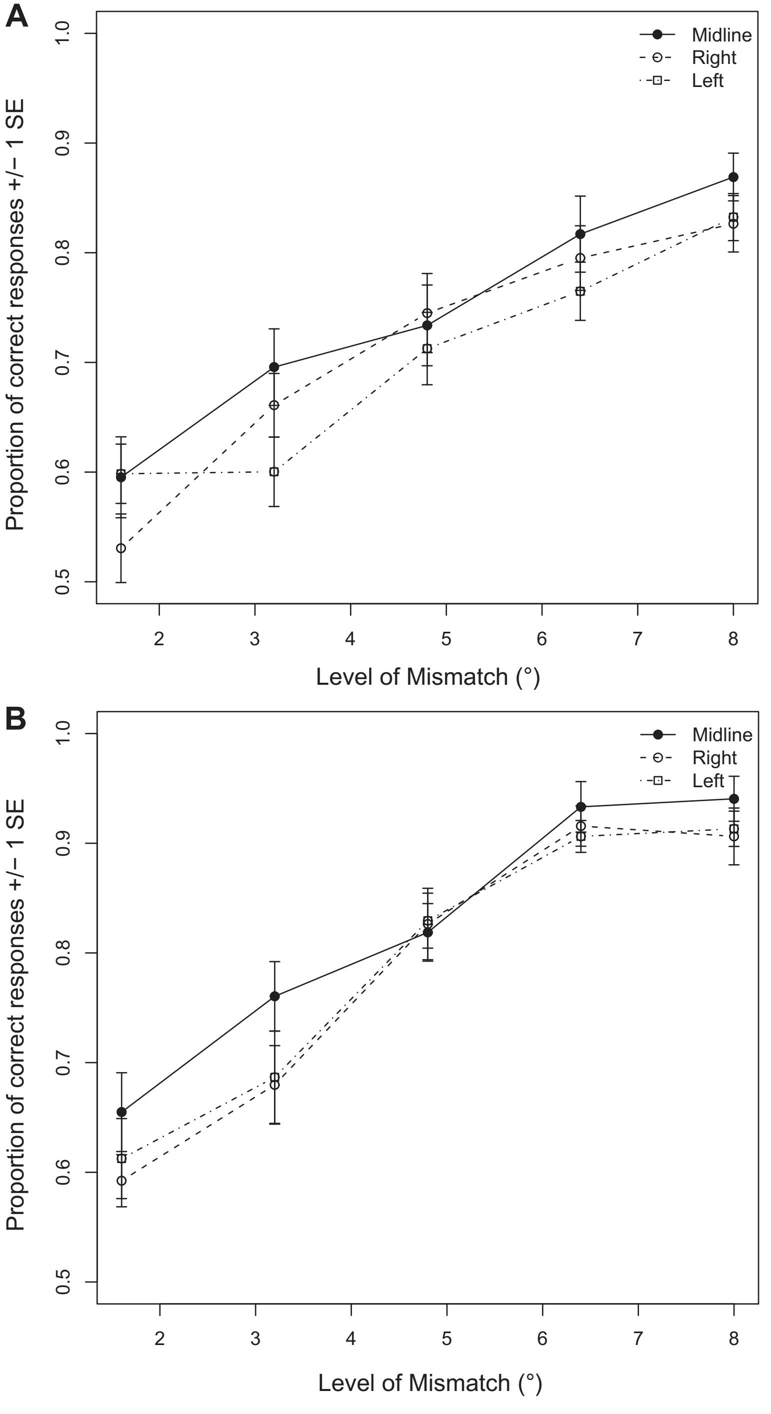

Fig. 8. (A) Mean proportion (±1 SE) of correct responses as a function of the level of mismatch in degrees for 8-year-olds for each of the three target positions. (B) Corresponding data for adults.

To follow up the age by mismatch level interaction, we conducted independent-samples t tests (Bonferroni-corrected $\alpha = .01$) comparing accuracy between 8-year-olds and adults at each level of mismatch. To determine the level of mismatch at which participants were able to reliably detect the mismatch, we conducted one-tailed single-sample t tests (one for each age group and level of mismatch) testing the alternative hypothesis that accuracy was significantly greater than .75 (Bonferroni-corrected $\alpha = .005$). At the two lowest levels of mismatch (1.6° and 3.2°), there was no significant difference in accuracy between adults and 8-year-olds, $ps > .05$, and neither age group was significantly above .75, $ps > .08$. At the three higher levels of mismatch, adults were significantly more accurate than 8-year-olds, $ps < .01$, and were significantly above .75, $ps < .001$. In 8-year-olds, accuracy was not significantly greater than .75 at the 4.8° and 6.4° mismatches, $ps > .08$, but was significantly greater than .75 at the 8.0° mismatch, $t(17) = 5.42$, $p < .001$, $d = 2.63$.

To follow up the main effect of target, we conducted paired-samples t tests (Bonferroni-corrected $\alpha = .017$) comparing accuracy between each possible pairing of targets. Accuracy was slightly greater for the midline target ($M = .78$, $SD = .09$) than for the left target ($M = .74$, $SD = .08$), $t(35) = 2.48$, $p = .018$, $d = 0.47$, and the right target ($M = .75$, $SD = .10$), $t(35) = 2.40$, $p = .022$, $d = 0.31$. There was no significant difference in accuracy between the left and right target conditions, $p > .50$. The reduction in accuracy for peripheral target positions was not explained by the incongruency on some trials between the direction of gaze of the target face and the location of the mismatch.[3]

Discussion

The results of Experiment 3 provide the first comparison of the ability to detect small differences in eye position between children and adults. The 8-year-olds required a much greater mismatch in the direction of gaze than the adults to reliably detect the mismatch. This is consistent with findings that children in this age range are less sensitive than adults in making other judgments about spatial relations in both faces and non-face stimuli (Baudouin et al., 2010; Hadad, Maurer, & Lewis, 2010a; Hadad, Maurer, & Lewis, 2010b).

As in Experiment 1, adults were approximately twice as sensitive as 8-year-olds. This indicates that an immaturity in sensitivity to eye position may be the primary factor limiting sensitivity to triadic gaze at 8 years of age. In addition, as in Experiment 1, both age groups displayed a reduction in accuracy for peripheral targets. This suggests that the reduction in precision at peripheral targets in Experiment 1 at both ages can be at least partially explained by reductions in sensitivity to eye position given that the sclera is partially occluded by eye rotation. Although the data from Experiment 3 seem adequate to explain the patterns observed in Experiment 1, difficulties in triangulating accurately to estimate the spatial relation between the eyes and a target in the environment might also contribute to the imprecision observed at age 8 and for targets in the periphery at all ages.

The observed effects of age on precision could result from differences in attention or understanding of the task between 8-year-olds and adults. However, this seems unlikely given the lack of an age difference in accuracy on practice and catch trials. Another issue is whether participants in the current experiment used non-eye cues (e.g., small differences in mouth position) to detect the mismatch between faces. This too seems unlikely given that adults displayed the same pattern of data on the pilot version of the current experiment regardless of whether the full face or the eye region alone was presented and that children's accuracy varied with target position in a way similar to that of adults.

General discussion

The results indicate that by 6 years of age, children are quite sensitive to triadic gaze, as indicated by a mean threshold of 1.92°, roughly double that of adults. Like adults, children overestimate the direction of gaze toward peripheral targets and display lower sensitivity for peripheral target positions

[3] We conducted a three-way mixed ANOVA on accuracy scores with congruency (matching faces looking toward mismatch or matching faces looking away from mismatch) and mismatch level as within-participant variables and age as a between-participant variable. There was no effect of congruency, nor did congruency interact with any other variable, $ps > .05$.

than for a midline target. The latter effect was observed at all ages tested for the triadic gaze judgment task (Experiment 1) and in both the 8-year-olds and adults tested on the gaze matching task (Experiment 3), patterns suggesting that children and adults use similar perceptual cues to judge eye position across target positions. Together, these findings suggest that by age 6, children's sensitivity to gaze direction is qualitatively similar to that of adults.

Although children were quite sensitive to triadic gaze by 6 years of age, our results show that sensitivity develops slowly thereafter. Thresholds decreased from approximately twice those of adults at ages 6 and 8 to reach adult-like levels at or after age 10. In addition, 8-year-olds required a greater mismatch in the direction of gaze than adults to reliably detect a difference in eye position. This suggests that the immaturity observed in young children's triadic gaze judgments is driven, at least in part, by an immaturity in sensitivity to eye position. Combined with previous research (e.g., Butterworth & Itakura, 2000; Doherty et al., 2009; Lee et al., 1998; Leekam et al., 1997), the results indicate that explicit judgments of triadic gaze improve gradually from approximately 3 to 10 years of age. This pattern suggests that in real-world social interactions, younger children may experience greater uncertainty about the target of others' attention and that this uncertainty will diminish gradually throughout childhood. The observed improvement in sensitivity to triadic gaze could be related to sharper tuning of neurons in brain areas associated with processing of low-level visual information relevant to gaze discrimination (e.g., neurons in primary visual cortex involved in contour detection and integration; see Hess, Hayes, & Field, 2003, for a review) or in brain areas implicated in processing of eye gaze in both adults and children, such as the superior temporal sulcus (Mosconi, Mack, McCarthy, & Pelphrey, 2005; Nummenmaa & Calder, 2009).

The current results leave open a number of questions for future research. First, although it is clear that young children are not as sensitive as adults to triadic gaze, the relation between the development of sensitivity to triadic gaze and other forms of spatial vision (e.g., contour integration/interpolation) remains unclear. Future studies could address this issue by using a correlational approach to evaluate the statistical relation between gaze processing and other aspects of spatial vision. A second direction arises from the limitation in the current study that each gaze direction was presented statically for an extended period of time and that there was no social context for gaze judgments. In real-world interactions, the direction of gaze moves from one target to another and the social context may provide a cue to the location of probable objects of fixation. Thus, future research could investigate the development of sensitivity to gaze direction under conditions that represent the temporal and social dynamics of gaze behaviors during real-world interactions. The added cues simulating real-world interactions could potentially help the precision of children's judgments, but their complexity might also hinder that precision. Finally, it would be interesting to test sensitivity to triadic gaze at other distances. The current distance of 150 cm is within the range of typical interactions. It is possible that sensitivity is poorer for close distances where the triangulation is more challenging or at farther distances where the shifts in eye position are hard to detect.

Summary

This investigation has provided the first evidence of fine-grained sensitivity to triadic gaze from 6 years of age onward. Children were quite sensitive to triadic gaze by age 6, as indicated by a mean threshold of 1.92°. Like adults, children displayed a reduction in sensitivity at peripheral target positions and overestimated the direction of gaze toward peripheral targets. Sensitivity improved gradually after age 6, reaching adult-like levels around age 10. Children's lower sensitivity to triadic gaze is attributable, at least in part, to an immaturity in sensitivity to eye position. Collectively, these findings suggest that although children's sensitivity to triadic gaze is qualitatively similar to that of adults by age 6, sensitivity improves gradually thereafter.

Acknowledgments

We thank Kathleen Lee and Tiffany Mintah for their valuable assistance in data collection. This research was supported by Grant 9797 from the Natural Sciences and Engineering Council of Canada (NSERC) to D.M. and an NSERC Vanier Canada Graduate Scholarship (CGS-V) to M.D.V.

Appendix A

A.1. Details of stimuli

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 chin and forehead rest to maintain a forward-facing upright head position and an eye height of 120 cm. Fixation positions were marked on the board with black stripes (5 mm wide, 25 mm tall) set against a white background at a height of 100 cm. A digital camera fitted with a 50- to 150-mm lens was positioned at eye height, 150 cm in front of the model. All models were photographed under the same lighting conditions, which were designed to symmetrically and evenly illuminate the face and eyes of the model. Two Paul C. Buff (Nashville, TN, USA) White Lightning X1600 flash units were positioned at a height of 138 cm, 60 cm to either side of the model at a distance of 160 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 150 cm. The camera lens was positioned in a small opening cut in the barrier. Models used a wireless remote switch to trigger the camera and lights when they were fixating each designated position. Models displaying blinks and/or noticeable variations in head position and/or facial expression were excluded from the stimulus set. Digital measurements of the stimuli confirmed that the position of the eyes moved linearly across fixation positions.

Appendix B

B.1. Details of curve fitting and goodness of fit

B.1.1. Curve fitting

The cumulative Gaussian function is defined by

$$f(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right],$$

where μ determines the mean of the function and σ determines the slope of the function. All fits were carried out using the psignifit toolbox (Wichmann & Hill, 2001) in MATLAB 7.6.0 (R2008a, MathWorks), which employs constrained maximum likelihood estimation to implement the procedure described in Wichmann and Hill (2001). The youngest children's psychometric functions occasionally failed to reach the lower and upper asymptotes established by adults. For this reason, we allowed the lower and upper bounds to vary between 0 and 0.2 (lower) and between 0.8 and 1.0 (upper) (Wichmann and Hill, 2001)

B.1.2. Goodness of fit

We used the procedures described by Wichmann and Hill (2001) to assess the goodness of fit of the fitted functions. First, we assessed the extent to which data points were significantly farther from the fitted curve than expected (overdispersion). We calculated deviance (D), a measure of overdispersion defined as

$$D = 2\log\left[\frac{L(\theta_{\max}; y)}{L(\theta; y)}\right],$$

where $L(\theta_{\max};y)$ denotes the likelihood of a model with no residual error between the model prediction and the observed data and $L(\hat{\theta}; y)$ denotes the likelihood of the best-fitting model. We used the psignifit toolbox (Wichmann and Hill, 2001) for MATLAB to generate 10,000 Monte Carlo simulated data sets. We then calculated the cumulative probability estimate for deviance [$CPE(D)$], defined as

$$CPE(D) = \frac{\{\#(D_i \leqslant D)\}}{B+1},$$

where B denotes the number of simulated data sets in the deviance distribution, D_i denotes a deviance value from the deviance distribution, and D denotes the observed deviance of the fit. $CPE(D)$ indicates the proportion of deviance values in the deviance distribution that are less than or equal to D. If $CPE(D)$ exceeds .975, the agreement between the data and the fit is poor. For all fits in the current experiment, $CPE(D)$ never exceeded .975 and it did not show a systematic pattern of variation across target conditions or age groups. In cases where a given fitting regime does not produce significant overdispersion, it may nevertheless produce a fit that is biased by a systematic relation between the values predicted by the model and the deviance residuals d_i, defined as

$$d_i = \mathrm{sgn}(y_i - p_i)\sqrt{2\left[n_i y_i \log\left(\frac{n_i}{y_i}\right) + n_i(1 - y_i)\log\left(\frac{1 - y_i}{1 - p_i}\right)\right]},$$

where y_i denotes the observed value, n_i denotes the number of trials for a given block, and p_i denotes the predicted value. Using the procedure described by Wichmann and Hill (2001), we calculated the correlation coefficient between the deviance residuals and predicted values for each of 10,000 Monte Carlo simulated data sets. We then calculated the cumulative probability estimate for rPD as described above. A $CPE(rPD)$ of .975 or greater reflects a poor fit resulting from a linear relation between the model prediction and the deviance residuals. $CPE(rPD)$ never exceeded .975 in any experiment and showed no systematic pattern across age groups.

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