DEVELOPMENT OF SENSITIVITY TO THE DIRECTION OF EYE GAZE

THE TYPICAL AND ATYPICAL DEVELOPMENT OF FINE-GRAINED SENSITIVITY TO THE DIRECTION OF EYE GAZE

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree Ph.D.

McMaster University PH.D. (2014) Hamilton, Ontario (Psychology)

TITLE: The Typical and Atypical Development of Fine-grained Sensitivity to the Direction of Eye Gaze AUTHOR: Mark Donald Vida, B.A. (McMaster University) SUPERVISOR: Dr. Daphne Maurer NUMBER OF PAGES: xvi, 259

Abstract

Typical adults use gaze cues to make inferences about people's mental and emotional states. I investigated the development of fine-grained sensitivity to the direction of gaze during middle childhood, and how development differs in high-functioning adults with autism spectrum disorder (ASD). In Study 1, sensitivity to deviations of gaze from an object in the environment improved after age 6, becoming adult-like by age 10. This improvement may allow more precise inferences about others' interests and/or intentions. In Study 2, the horizontal range of directions of gaze perceived as direct (the cone of gaze) narrowed considerably after age 6, becoming adult-like by age 8. This narrowing may reduce social costs associated with erroneously perceiving direct gaze. In contrast, the vertical cone of gaze was adult-like at age 6. In Study 3, 6-year-olds' horizontal cone of gaze was narrower when they heard object-directed voice cues (e.g., "I see that.") than when they heard participant-directed voice cues (e.g., "I see you.") or no voice, a result suggesting that object-directed voice cues can allow more adult-like judgments of gaze. In Study 4, face inversion increased the width of the cone of gaze in typical adults, but not in those with ASD. However, the cone of gaze was normally modulated by facial expression in the ASD group. This pattern suggests that in adults with ASD, sensitivity to the direction of gaze is not tuned to be finer for upright faces, but that information is nevertheless integrated across expression and gaze. Together, these results suggest that although some aspects of sensitivity to the direction of gaze are adult-like at age 6, immaturities in other aspects of sensitivity will limit children's social judgments until at least age 8. The results also suggest that adults with ASD use atypical visual processing to discriminate the direction of gaze.

Acknowledgements

I am deeply grateful to Daphne Maurer (supervisor and member of supervisory committee) for her excellent guidance in all aspects of my work as a graduate student, and for her tremendous patience and generosity. I thank Pat Bennett and M. D. Rutherford (members of supervisory committee) for their excellent guidance in many aspects of my work as a graduate student. I thank Tiffany Mintah, Erica D'Angelo, Kathleen Lee, Desiree Law, and the staff of the McMaster University Visual Development Laboratory for their assistance in data collection. I also thank Daphne Maurer, M. D. Rutherford, Gillian Rhodes, Andy Calder, Jennifer Walsh, and Matthew Pachai for their valuable contributions to the ASD project (Study 4). The research included in the current thesis was supported by a Natural Sciences and Engineering Research Council (NSERC) Canada Graduate Scholarship (CGS-M) to Mark Vida, an NSERC Vanier Canada Graduate Scholarship (CGS-V) to Mark Vida, a grant from NSERC (9797) to Daphne Maurer, a grant from the Australian Research Council (ARC) Centre of Excellence in Cognition and its Disorders (project number CE110001021) to Gillian Rhodes, Daphne Maurer, and M. D. Rutherford, and an ARC Professorial Fellowship (project number DP087737) to Gillian Rhodes.

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List of all Abbreviations and Symbols

°: Degree, a unit of angular measurement. 1° = 1/360 of a circle.

′: Minute of arc, a unit of angular measurement. 1′ = 1/60°.

″: Second of arc, a unit of angular measurement. 1″ = 1/3600°.

α: In statistical hypothesis testing, α is the probability of making a type I error (i.e., rejecting the null hypothesis when it is in fact true). It is common practice to reject the null hypothesis when the value of *p* (see below for definition) is less than α.

$\hat{\epsilon}$: The Greenhouse-Geisser estimate of ϵ. In statistical hypothesis testing, $\hat{\epsilon}$ is used to adjust *p* values of *F*-tests conducted on within-subject variables, to correct for violations of the assumption of sphericity.

η_p^2: A common measure of effect size in statistical hypothesis testing. A larger value of η_p^2 indicates a larger effect.

ANOVA: Analysis of variance, a statistical model used to evaluate the influence of one or more independent variables on a dependent variable.

ASD: Autism spectrum disorder, a developmental disorder characterized by deficits in social communication and interactions, and by repetitive and restricted behaviours and interests.

aSTS: Anterior superior temporal sulcus, a brain region located in the temporal lobe of the cerebral cortex.

cm: Centimetre, a unit of length. 1 cm = 1/100 of a metre.

d: Cohen's *d*, a common measure of effect size in statistical hypothesis testing. A larger value of *d* indicates a larger effect.

D: Deviance, a measure of the goodness-of-fit of a fitted model (see p. 75-77 and p. 116 for details). A larger value of *D* indicates greater discrepancy between the fitted model and the observed data.

f^2: Cohen's f^2, a common measure of effect size in statistical hypothesis testing. A larger value of f^2 indicates a larger effect.

F: The test statistic for an *F*-test, which is used to evaluate the influence of one or more independent variables on a dependent variable.

FG: Fusiform gyrus, a brain region located in the temporal lobe of the cerebral cortex.

Hz: Hertz, a measure of frequency. 1 Hz = 1 cycle/second.

m: Metre, the fundamental unit of length in the International System of Units.

M: Arithmetic mean. For a set of values, *M* is the sum of all values in the set divided by the number of values in the set.

mm: Millimetre, a unit of length. 1 mm = 1/1000 of a metre.

mPFC: Medial prefrontal cortex, a brain region located in the frontal lobe of the cerebral cortex.

ms: Millisecond, a unit of time. 1 ms = 1/1000 of a second.

p: In statistical hypothesis testing, *p* is the probability of obtaining the observed data or data more extreme, assuming that the null hypothesis is true.

PSE: Point of subjective equality. In a task in which participants are required to classify a stimulus in one of two ways (e.g., classifying the direction of gaze as left or right), the PSE is the configuration of the stimulus (e.g., the direction of gaze) for which participants are unable to reliably classify the stimulus (see p. 37-38 for details).

pSTS: Posterior superior temporal sulcus, a brain region located in the temporal lobe of the cerebral cortex.

r: The Pearson correlation coefficient. A more extreme value of *r* indicates a stronger linear association between two variables.

RMS: Root mean square (i.e., the quadratic mean), a measure of the magnitude of a varying quantity. The RMS of a set of values is the square root of the mean of the squared values (see p. 212 for further details).

SD: Standard deviation, a measure of the spread of a set of values around the mean. A larger value of *SD* indicates a larger spread.

SE: Standard error of the mean, an estimate of how far a sample mean is likely to be from the population mean. A smaller value of *SE* indicates that the sample mean is a better estimate of the population mean.

t: The test statistic for a *t*-test, which is used to evaluate differences between two means.

Declaration of Academic Achievement

For Study 1, I designed the experiments with Daphne Maurer (supervisor), and collected and analyzed the data with assistance from Kathleen Lee (independent study student supervised by me). I wrote the paper and revised it in response to comments and suggestions from Daphne Maurer. For Study 2, I designed the experiment with Daphne Maurer, and collected and analyzed the data with assistance from Tiffany Mintah (independent study student supervised by me). I wrote the paper and revised it in response to comments and suggestions from Daphne Maurer. For Study 3, I designed the experiments with Daphne Maurer, and collected and analyzed the data with assistance from Erica D'Angelo (independent study student supervised by me) and Desiree Law (volunteer supervised by me). I wrote the paper and revised it in response to comments and suggestions from Daphne Maurer. For Study 4, I designed the experiment with Daphne Maurer, Mel Rutherford (supervisory committee member), and Andy Calder (Senior Research Fellow, Medical Research Council Cognition and Brain Sciences Unit). I collected the data with assistance from Jennifer Walsh (graduate student), and analyzed the data with assistance from Matthew Pachai (graduate student). I wrote the paper and revised it in response to comments from Daphne Maurer, Mel Rutherford, Andy Calder, and Gillian Rhodes (Professor, University of Western Australia). Hence, I was the primary contributor to each study included in the current thesis.

Chapter 1 - Introduction

Typical human adults use the direction of a person's gaze to make inferences about that person's mental and emotional states. For example, direct gaze can signal the intent to communicate, dominate, or threaten, whereas averted gaze can signal avoidance, deception, or attention toward a target in the environment (Argyle & Cook, 1976; Kendon, 1967). Typical adults can detect very small (approximately 1º) differences in the direction of gaze relative to an object in the environment (triadic gaze) (e.g., Bock, Dicke, & Thier, 2008; Symons, Lee, Cedrone, & Nishimura, 2004; also see Cline, 1967). This high sensitivity suggests that adults are likely to be very precise in using the direction of gaze to judge the focus of others' attention. However, the range of gaze directions over which adults perceive direct gaze (known as the "*cone of gaze*") is relatively wide (around 5.5º; e.g., Gamer & Hecht, 2007; Gibson & Pick, 1963). Adults' relatively wide cone of gaze may reduce social costs associated with attributing averted gaze when gaze is actually direct (e.g., missing an opportunity to interact with a person).

In the current thesis, I examined the development of fine-grained sensitivity (i.e., the ability to detect small differences) to the direction of gaze during childhood, and how development differs in high-functioning adults with autism spectrum disorder (ASD). Specifically, I investigated fine-grained sensitivity to horizontal differences in gaze toward objects in the environment (triadic gaze) during middle childhood (Study 1), fine-grained sensitivity to horizontal (Studies 2 and 3) and vertical (Study 2) differences between direct and averted gaze during middle childhood, and the influence of voice cues on fine-grained sensitivity to horizontal differences between direct and averted gaze during middle childhood (Study 3). Finally, I examined the influence of facial expression on judgments of direct and averted gaze in high-functioning adults with and without ASD, and measured the influence of face inversion (i.e., turning the face upside down) on these judgments, to compare perceptual specialization for upright faces between the two groups (Study 4).

The results have important implications for social interactions involving typically developing children and/or individuals with ASD. Specifically, immature or abnormal sensitivity to differences between direct and averted gaze may lead an individual to make incorrect judgments about whether a person is paying attention to the individual or not, which could in turn lead to inappropriate social behaviour (e.g., attempting to establish an interaction with a person who is not interested in doing so, missing opportunities to interact with a person who wishes to do so, or failing to notice someone who is threatening or hostile). Also, immature sensitivity to triadic gaze may lead to errors in judgments of the target of others' visual attention, which could in turn lead to errors in inferences about others' interests and/or intentions (e.g., inferring that a stranger is looking at an object belonging to oneself when the stranger is in fact looking at another object in the environment), and/or errors in learning language (e.g., hearing a person saying a novel noun, and associating the noun with the wrong object). The results also have implications for understanding the visual, cognitive and neural mechanisms underlying developmental changes in judgments of gaze. Specifically, different developmental trajectories during childhood for different types of judgments (e.g., triadic gaze, direct and averted gaze), and/or differences in judgments of gaze between adults with and without ASD (e.g., a difference in the width of the cone of gaze) may imply differences in these mechanisms between types of judgments and/or between individuals with and without ASD.

In the remainder of the current chapter, I will i) describe visual cues to the direction of gaze; ii) summarize what is known about adults' sensitivity to the direction of eye gaze, and about the neural basis of this sensitivity; iii) describe what is known about the typical development of sensitivity to the direction of gaze during childhood; iv) summarize evidence on sensitivity to eye gaze in individuals with ASD, from studies reporting both behavioural and neural indices; v) and finally, outline the purpose and implications of each study included in the current thesis.

Visual Cues to the Direction of Gaze

In humans, shifts of gaze involve changes in the orientation of the eyes, head, and/or body. Since each of these body parts can move independently in humans, accurate judgments of people's gaze are likely to involve the integration of information from more than one of these sources (Emery, 2000). Differences in facial morphology between human and non-human primates make eye position a more important cue to the direction of gaze among humans than among non-human primates (Emery, 2000). Whereas non-human primates have a dark iris and brown sclera (i.e., the visible part of the eyeball surrounding the iris), humans have a white sclera and dark iris (Kobayashi & Kohshima, 1997). The high contrast between the iris and sclera in humans facilitates discrimination of the direction of eye gaze, especially at large viewing distances. This high contrast may have evolved to allow more effective nonverbal communication based on eye gaze cues (Kobayashi & Kohshima, 1997).

The morphology of the human face leads to differences between the horizontal and vertical axes in visual cues to the direction of eye gaze. For horizontal shifts of gaze, the rotation of the eyeball leads to changes in the apparent position of the iris within the surrounding white sclera. Hence, it is possible to decode the direction of gaze along the horizontal axis from the position of the iris within the visible sclera, and/or from deviations from bilateral symmetry within the eye region. Vertical shifts of gaze also involve changes in the position of the iris within the surrounding sclera. However, unlike horizontal shifts of gaze, vertical shifts are accompanied by asymmetrical changes in the position of the eyelids. The upper eyelid tracks the position of the iris closely, whereas the lower eyelid does not. Upward shifts of gaze cause the eyes to open wider, exposing more of the iris and sclera, whereas downward shifts of gaze cause the eyes to close, occluding more of the iris and sclera (Anstis, Mayhew, & Morley, 1969). Therefore, humans may rely on different visual cues to discriminate horizontal and vertical shifts of gaze.

Developmental changes in children's sensitivity to the direction of gaze may involve tuning to these different cues used by adults.

Typical Adults

Gaze toward objects in the environment. Human adults are highly sensitive to horizontal shifts of gaze toward objects in the environment (triadic gaze): they can detect shifts of around 1º from an object at midline. For targets in the near periphery, adults have slightly poorer sensitivity (Symons, et al., 2004) and tend to estimate the direction of gaze as more peripheral than it actually is (e.g., gaze toward a target 10° from midline is judged to be 15° from midline; Anstis et al., 1969). Adults can also detect differences of 1-2º in the direction of gaze toward objects arranged in a circle, a pattern suggesting that adults are quite sensitive to vertical and/or oblique shifts of triadic gaze (Bock et al., 2008). Adults' high sensitivity suggests that they are likely to be quite precise in using differences in triadic gaze to make inferences about others' interests, preferences, and/or intentions.

Direct and averted gaze. The perception of direct gaze modulates perceptual and cognitive processing, and influences physiological arousal, a phenomenon known as the "*eye contact effect*" (Senju & Johnson, 2009). For example, compared to perceived averted gaze, perceived direct gaze enhances face memory (Smith, Hood, & Hector, 2006), and increases galvanic skin response, a measure of physiological arousal (e.g., Nichols & Champness, 1971). Perceived direct gaze also influences judgments of facial expression (see Graham & Labar, 2012, for review). Some studies indicate that direct gaze facilitates the perception of facial expressions associated with approach (e.g., anger), and impairs the perception of expressions associated with avoidance (e.g., fear; Adams & Kleck 2003; Milders, Hietanen, Leppänen, & Braun, 2011). However, other studies report that direct gaze facilitates the perception of facial expressions generally (e.g., Bindemann, Burton, & Langton, 2008).

Although adults can detect shifts of approximately 1º in the direction of gaze relative to objects in the environment, the range of directions of gaze leading to the perception of direct gaze (the cone of gaze) is relatively large, at approximately 5.5º in width (e.g., Gibson & Pick, 1963). This range corresponds to the width of an adult human's face, viewed from a typical social distance of approximately 1.5 m (e.g., Hall, 1966). Hence, an adult is likely to perceive direct gaze when a person is looking at a point anywhere between the lateral edges of the adult's own face. Adults' relatively wide cone of gaze may minimize social costs associated with attributing averted gaze when a person's gaze is actually direct (e.g., missing an opportunity to interact).

Adults' perception of direct versus averted gaze is influenced by contextual information in the visual and auditory modalities. For example, adults' cone of gaze is wider for angry faces than for fearful or neutral faces (Ewbank, Jennings, & Calder, 2009). This pattern may reflect a bias to interpret threatening signals as being directed toward oneself. In addition, the cone of gaze is wider when adults hear their own name than when they hear a different person's name, even when participants are told that the names are not informative for the task (Stoyanova, Ewbank, & Calder, 2010). This pattern may arise because hearing one's own name increases the width of the cone of gaze, and/or because hearing a different person's name decreases it.

Effect of face inversion. Typical adults' ability to decode the direction of eye gaze from faces appears to be specialized for upright faces. Face inversion (i.e., turning a face image upside down) impairs sensitivity to the direction of gaze, as indicated by higher thresholds for discriminating between leftward and rightward gaze for inverted faces than for upright faces (Jenkins & Langton 2003; Schwaninger, Lobmaier, & Fischer, 2005). This effect appears to be driven, at least in part, by the inversion of the eyes. When the orientation of the eye region (including eyebrows, eyelids, and part of the bridge of the nose) and that of the outer face context are manipulated independently, inversion of the eye region impairs sensitivity to the direction of gaze to a similar extent whether the face context is upright or inverted (Jenkins & Langton 2003). Also, typical adults' ability to discriminate small differences in the direction of gaze is equal for full faces and for eyes isolated by occluding all but the visible surface of the eyeball (the palpebral fissure) and the lower eyelid, and this ability is equally impaired for full faces and isolated eyes when these stimuli are inverted (Schwaninger et al., 2005). These results highlight the importance of visual cues in and around the palpebral fissure, as viewed in an upright orientation.

The neural basis of gaze perception.

Separable coding of different directions of gaze. Single-cell recordings in macaque cortex have revealed cells in primarily anterior superior temporal sulcus (aSTS) that are tuned to the direction of the head and eyes (Perrett, Hietanen, Oram, & Benson, 1992; Perrett et al., 1991; Perrett et al., 1985). The majority of these cells respond selectively to a particular direction of the head and/or eyes, with the preferred direction varying between cells. A subset of these cells were found to respond to the same direction of gaze, whether this information was conveyed by an actor's eye or head orientation, a pattern suggesting that these cells may code the direction of an actor's attention, independent of the cue used to convey this information. Together, these results provide evidence that aSTS contains separable mechanisms for coding different directions of gaze.

Behavioural studies in humans have provided further evidence for separable coding of different directions of gaze. Following adaptation to leftward or rightward gaze, human adults show repulsive aftereffects in which the perceived direction of gaze shifts in a direction opposite to the adapting direction (Calder, Jenkins, Cassel, & Clifford, 2008). In addition, alternating adaptation to leftward and rightward gaze leads to an increase in the range of directions of gaze perceived as direct, whereas adaptation to direct gaze has the opposite effect (Calder et al., 2008). This pattern is consistent with the predictions of a multichannel model in which the direction of gaze is coded by at least three populations of neurons, which respond selectively to leftward, direct, and rightward gaze. The increased perception of direct gaze following alternating left/right adaptation may reflect a reduction in the response of neurons tuned to leftward and rightward gaze, whereas the decreased perception of direct gaze following direct adaptation may reflect a reduction in the response of neurons tuned to direct gaze (Calder et al., 2008).

Functional neuroimaging studies in humans have provided further evidence that STS is involved in separable coding of different directions of gaze. Adaptation to a particular direction of averted eye gaze leads to a reduction of responses in anterior STS (aSTS) to gaze in the same direction, with an increased response to gaze in the opposite direction and an intermediate response to direct gaze (Carlin, Rowe, Kriegeskorte, Thompson, & Calder, 2012). This pattern suggests that aSTS includes separable representations of leftward and rightward gaze. aSTS also appears to code the direction of a person's attention (i.e., the perceived direction of gaze, taking into account the orientations of the eyes and head), even when the direction is conveyed by physically dissimilar combinations of head and eye orientation. In one study, participants viewed combinations of multiple head orientations and directions of eye gaze (Carlin, Calder, Kriegeskorte, Nili, & Rowe, 2011). Multi-voxel pattern analysis was used to decode the direction of the actor's attention from the pattern of activation in pSTS and aSTS. It was possible to decode the perceived direction of the actor's attention from responses in aSTS, even when the direction was conveyed by physically dissimilar combinations of head and eye orientation. In contrast, responses in pSTS did not predict the perceived direction of attention independent of head orientation. This pattern is consistent with findings that human pSTS is sensitive to differences in head orientation (e.g., Fang, Murray, & He, 2010; Natu et al., 2010), and suggests that responses in human aSTS may be similar to cells in macaque STS (primarily aSTS) that respond to the direction of an actor's attention, whether this information is conveyed by eye or head orientation (Perrett et al., 1992; Perrett et al., 1991; Perrett et al., 1985).

Direct and averted gaze. Neuroimaging and electrophysiological studies in humans have identified a network of brain regions that respond more strongly to direct gaze than to averted gaze, including brain regions implicated in processing of biological motion (e.g., STS; Calder et al., 2002; Conty, N'Dyiaye, Tijus, & George, 2007; Wicker, Perrett, Baron-Cohen, & Decety, 2003; Pelphrey, Singerman, Allison, & McCarthy, 2003; but also see Engell, & Haxby, 2007), emotionally salient stimuli (e.g., amygdala; Kawashima et al., 1999; Sato, Yoshikawa, Kochiyama, & Matsumura, 2004; Wicker et al., 2003), face processing (e.g., fusiform gyrus [FG]; Calder et al., 2002; George, Driver, & Dolan, 2001; Pageler et al., 2003), and reasoning about the mental states of others (e.g., medial prefrontal cortex [mPFC]; Kampe, Frith, & Frith, 2003; Schilbach et al., 2006). Although some of these responses (e.g., those in STS) could reflect the visual analysis of gaze signals, it seems possible that some of these responses (e.g., those in amygdala and mPFC) reflect modulation of arousal and/or cognition in response to perceived eye contact (see Senju & Johnson, 2009).

Gaze toward objects in the environment. Neuroimaging studies in humans indicate that at least two brain areas are sensitive to the relationship between the direction of a person's averted gaze and the location of an object in the environment. pSTS responds more strongly when a model looks away from an object (toward empty space) than when the model looks toward the object. This result may reflect more extensive processing when gaze does not terminate at an obvious target (Pelphrey et al., 2003). Also, mPFC responds more strongly when the participant and an actor attend to the same object (i.e., joint attention) than when they do not (Redcay et al., 2010; Redcay, Kleiner, & Saxe, 2012; Schilbach et al., 2010). This response is stronger when joint attention is initiated by an actor looking toward an object before the participant does than when it is initiated by the participant looking toward the object before the actor does (Redcay et al., 2012; Schilbach et al., 2010).

Comparison of dyadic and triadic gaze. Judgments of both dyadic and triadic gaze require sensitivity to differences in eye position. Consistent with this idea, the neuroimaging studies described above indicate that brain regions typically implicated in processing of the direction of gaze (e.g., pSTS, mPFC) are recruited in tasks involving judgments of either dyadic or triadic gaze. However, dyadic and triadic gaze seem likely to involve different cognitive and/or visual processing. Judgments of triadic gaze involve triangulating the position of the target of gaze by judging the direction of a person's gaze and drawing an imaginary line from the person to the target. In contrast, judgments of dyadic gaze do not require this triangulation, but instead require one to estimate the spatial relation between the direction of a person's gaze and oneself, and to form an impression about whether or not one is being looked at. This impression may be based, at least in part, on the subjective interpretation of gaze cues, independent of visual processing of the direction of gaze. Consistent with this idea, the width of the cone of gaze is modulated by relevant social contextual information, including hearing one's own name (e.g., Stoyanova et al., 2010) and facial expression (e.g., Ewbank et al., 2009; Rhodes et al., 2012). Also, the amygdala, a brain region recruited in processing of emotionally relevant stimuli, has been repeatedly implicated in processing of dyadic (e.g. Senju & Johnson, 2009) but not triadic gaze. In addition, adults' horizontal cone of gaze (approximately 5.5º; e.g., Gibson & Pick, 1963) is over five times wider than their threshold for discriminating horizontal shifts of triadic gaze (approximately 1º; e.g., Symons et al., 2004). Hence, judgments of triadic and dyadic gaze are likely to depend to some degree on visual sensitivity to the direction of gaze, but judgments of dyadic gaze may depend to a greater extent than judgments of triadic gaze on the subjective interpretation of gaze cues.

Typical Development

Direct and averted gaze. From birth, infants can discriminate differences between direct and averted gaze, provided the difference is large. For example, when shown pairs of faces in which gaze is direct in one face and averted far to one side in the other, newborns look longer at the face with direct gaze (Farroni, Csibra, Simion, & Johnson, 2002). By 4 months of age, infants not only look but also smile longer at faces with direct gaze (Hains & Muir, 1996; Symons, Hains, & Muir, 1998). At 4-5 months of age, the N240 ERP (event-related potential) component is larger for faces displaying direct gaze compared to faces with averted gaze (Farroni, Johnson, & Csibra, 2004), a result that could reflect more elaborate processing of faces with direct gaze. Infants' preferential responses to eye contact and other cues indicating that a person is paying attention to the infant (e.g., infant-directed speech) may support early social and/or physical development by allowing the infant to respond selectively to individuals (e.g., potential caregivers) who interact with the infant.

By 3 years of age, children can make explicit judgments about differences between direct and averted gaze when the differences are large. When shown pairs of faces in which gaze is direct in one face and averted 25° in the other, 3-year-olds, but not 2-year-olds, are able to report which face is making eye contact (Doherty, Anderson, &

Howieson, 2009). At 6 years of age, the horizontal cone of gaze may be quite wide. In the one previous study that included 6-year-olds, children judged that gaze was direct across fixation positions 10 to 30 cm to the left or right of the bridge of the participant's nose, a result suggesting a cone of gaze of 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 (a region including the eyes and bridge of the nose) versus off-eye (a region including the mouth, ears, and hairline) fixation. 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. Previous studies have not examined the development of fine-grained sensitivity to direct and averted gaze during childhood, and have not used the same stimuli to compare children's and adults' sensitivity.

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, children aged 8-15 years are faster at detecting faces presented with direct gaze than faces with averted gaze (Senju et al., 2008) and children aged 6-11 years 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).

Developmental changes in children's sensitivity to direct and averted gaze could reflect improvements in visual sensitivity to eye position (i.e., the perception and interpretation of the position of the iris within the visible sclera), which could in turn reflect refinements in brain regions implicated in the visual analysis of gaze signals (e.g., STS, see Carlin & Calder, 2012). Changes in children's sensitivity to direct and averted gaze could also reflect changes in children's interpretation of gaze signals (e.g., whether to interpret a small deviation from straight gaze as direct or averted), which could in turn reflect the accumulation of experience with the social properties of gaze signals (e.g., the social costs of attributing direct gaze when gaze is actually averted). Changes in children's interpretation of gaze signals could reflect refinements in mPFC, a brain area implicated in the detection of eye contact and other self-relevant signals (e.g., hearing one's own name), and in reasoning about the mental states of others (see Carlin & Calder, 2012, for review). Refinements in children's sensitivity to direct and averted gaze may influence children's behaviour during social interactions by allowing children to make more adult-like judgments about whether a person is attending to the child or not. For example, a decrease in the width of children's cone of gaze could lead children to be less likely to erroneously infer that a person is paying attention to the child when the person is actually attending to something else in the environment.

Gaze toward objects in the environment. Sensitivity to the direction of gaze toward objects in the environment (triadic gaze) may contribute to development during childhood by providing a cue to the location of relevant objects in the environment, and/or by facilitating links between words spoken by others and objects in the environment (see Tomasello & Farrar, 1986). Newborns (Farroni, Massacessi, 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, a result suggesting that the eye movement captured the infant's attention. However, this effect disappears when apparent motion of the eyes is eliminated (Farroni et al., 2000). Also, at 4-5 months of age, a lateral movement of the head with no displacement of the eyes triggers shifts of attention in 4- to 5-month-olds in the direction of the head, rather than the eyes (Farroni et al., 2000). Hence, these effects may be driven, at least in part, by cuing of attention by lateral motion.

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). In one study, 8- and 12-month-olds viewed an actor repeatedly looking toward the right (or to the left) side behind an occluder. The actor then lifted the occluder to reveal an object either on the fixated or non-fixated side. Although they spent more time looking at the object than 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/she had not (Csibra & Volein, 2008). This pattern suggests that infants expect a person's gaze to be directed to an object that is visible to the person, even if the object is not visible to the infant. In another study, 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, also see Senju, Csibra, & Johnson, 2008). This pattern suggests that by 9 months, infants encode the relationship between the direction of gaze and a specific object. At 18 (but not 12) months, infants follow an adults' gaze to objects located behind the infant when the visual field is empty (Butterworth & Jarrett, 1991). Collectively, these results 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. Instead, these results 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).

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 (e.g., Lee, Eskritt, Symons, & Muir, 1998, Experiments 4 and 5; Doherty, Anderson, & Howieson, 2009). For example, 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. 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).

Improvements in children's sensitivity to triadic gaze could reflect improvements in sensitivity to eye position, which could in turn reflect refinements in brain areas implicated in the visual analysis of gaze signals (e.g., STS; Carlin & Calder, 2012). Improvements in sensitivity to triadic gaze could also reflect improvements in children's ability to triangulate the target of gaze from the direction of the model's gaze, which could reflect refinements in brain areas implicated in joint attention (e.g., mPFC; Carlin & Calder, 2012). Improvements in children's sensitivity to triadic gaze could allow more accurate judgments of the focus of others' attention, which may in turn support more accurate inferences about others interests, preferences, and/or intentions.

Atypical Development

Autism spectrum disorder (ASD) is a developmental disorder characterized by deficits in social communication and interactions, and by repetitive and restricted behaviours and interests (American Psychiatric Association, 2013). Abnormal eye contact during face-to-face social interactions is a characteristic of autism (American Psychiatric Association, 2013). Individuals with autism are known to have impairments in their ability to perceive mental state information from the direction of gaze (Baron-Cohen, Baldwin, & Crowson, 1997; Baron-Cohen et al., 1995; Baron-Cohen & Goodheart, 1994; Baron-Cohen et al., 2001), show autonomic hyper-arousal to eye contact (Kaartinen et al., 2012; Kyläiinen & Hietanen, 2006, but also see Joseph, Ehrman, McNally, & Keehn, 2008), and, at least under some circumstances, spend less time than controls fixating the eye region when viewing faces (e.g., Dalton et al., 2005; Jones, Carr, & Klin, 2008; Klin, Jones, Schultz, Volkmar, & Cohen, 2002; Pelphrey et al., 2002; Spezio, Adolphs, Hurley,

& Piven, 2007, but also see Falck-Ytter & von Hofsten, 2011). These characteristics of autism could lead to abnormal experience with gaze cues, which could in turn lead to or exacerbate abnormal visual perception of eye gaze.

Previous studies have found that sensitivity to the direction of gaze is abnormally low in individuals with ASD, at least under some circumstances. When differences in the direction of gaze are large, and the duration of exposure to the face is long, individuals with ASD can judge the direction of gaze as precisely as typical individuals (Ashwin, Ricciardelli, & Baron-Cohen, 2009; Senju, Kikuchi, Hasegawa, Tojo, & Osanai, 2008). For example, high-functioning adults with ASD are as precise as typical adults in discriminating between direct gaze and gaze averted 30° to the left or right (Ashwin et al., 2009). However, when differences in the direction of gaze are small and/or the duration of exposure is short, high-functioning adults with ASD are less precise (Campbell et al., 2006; Dratsch et al., 2013; Gepner et al., 1996; Howard et al. 2000; Webster & Potter, 2008; 2011) and slower (Wallace, Coleman, Pascalis, & Bailey, 2006, but also see Dratsch et al., 2013) than controls. Also, Senju and colleagues (2008) found that performance on a visual search task involving judgments of eye gaze is distorted by face inversion in typically developing children, but not in children with ASD. These results suggest that the ability to discriminate the direction of gaze may be abnormal in individuals with ASD.

Neural responses to differences in the direction of gaze appear to be abnormal in

ASD. In one study, high-functioning adults with and without ASD viewed images of a person looking toward an object in the periphery or away from the object (toward empty space), while brain activity was recorded with fMRI (Pelphrey et al., 2005). Activation in pSTS was greater when the model looked toward empty space than when the model looked toward the object, but only in the typical group, a result suggesting that processing of the relation between the direction of a person's gaze and the location of a nearby object may be abnormal in ASD. There also is evidence for abnormal neural responses to the difference between direct and averted gaze in ASD (Grice et al., 2005; Senju, Tojo, Yahuchi, & Hasagawa, 2005). For example, in one study, children aged 3-7 years with and without ASD viewed faces with direct gaze or gaze averted to the side (Grice et al., 2005). The amplitude of the face-sensitive N170 ERP component over midline channels was larger for direct than averted gaze, but only in the ASD group. The difference over midline channels was previously observed in typically-developing 4-month-olds (Farroni et al., 2002), and may therefore reflect a delay in processing of direct and averted gaze in ASD. Finally, there is evidence of abnormal neural responses to dynamic shifts of gaze in ASD. In one study, 6- to 10-month-olds at risk for ASD and age-matched controls viewed dynamic faces in which gaze shifted toward the infant or away from the infant (Elsabbagh et al., 2012). The amplitude of the P400 ERP component was larger for shifts of gaze away from the infant than toward the infant, but only for the control group. Together, these results suggest that neural mechanisms involved in processing several aspects of sensitivity to eye gaze may be abnormal in ASD.

Although previous studies have not investigated the influence of social contextual information on judgments of eye gaze in individuals with ASD, previous research suggests that the effects of the direction of gaze on processing of facial expression may be atypical in children with ASD. In one study, typically developing 9- to 14-year-old children were faster to recognize fearful and angry faces when they were paired with a motivationally congruent direction of gaze (e.g., anger with direct gaze, fear with averted gaze) than when gaze and expression were incongruent. This congruency effect was absent in children with ASD (Akechi et al. 2009). In a second study, typically developing 9- to 14-year-old children showed greater amplitude in the N170 ERP component for congruent combinations of expression and gaze than for incongruent combinations. This congruency effect, which may reflect more extensive cortical processing of expressions presented with a congruent direction of gaze, was absent in children with ASD (Akechi et al. 2010). In sum, children with ASD do not show evidence of typical interactions between perceptions of expression and gaze, when measured by either behavioural or neural indices.

Summary

In sum, previous studies indicate that typical adults are sensitive to small differences in the direction of gaze toward objects in the environment (e.g., Symons et al., 2004), but that adults nevertheless perceive direct gaze over a relatively wide range of directions of gaze (e.g., Gibson & Pick, 1963). Also, typical adults' judgments of gaze are modulated by several factors, including face inversion (e.g., Jenkins & Langton 2003; Schwaninger et al. 2005), voice cues (e.g., Stoyanova et al., 2010), and facial expression (e.g., Ewbank et al., 2009). In typical development, the ability to detect large differences in the direction of gaze is present from early in infancy (e.g., Farroni et al., 2000; 2002; 2004), and children's sensitivity may be partially refined during early childhood (e.g., Doherty et al., 2009). Sensitivity to the direction of gaze appears to be abnormally low in individuals with ASD (e.g., Dratsch et al., 2013; Wallace et al., 2006), and the influence of gaze on judgments of facial expression (Akechi et al., 2010; 2011), and that of face inversion on judgments of gaze (Senju et al., 2008) appear to be abnormal in children with ASD. Previous studies do not indicate whether fine-grained sensitivity to triadic gaze or to differences between direct and averted gaze is refined during middle childhood, and do not indicate when children's sensitivity becomes adult-like, or whether contextual information has the same effect on judgments of gaze in children and adults. Also, previous studies do not indicate whether sensitivity to the direction of gaze is normally modulated by factors such as face inversion and facial expression in high-functioning adults with ASD, that is, whether the deficits identified in children with ASD persist into adulthood. The purpose of the current thesis was to investigate these questions.

In Study 1, I carried out the first investigation of the development of fine-grained sensitivity to horizontal differences in triadic gaze in 6-, 8-, 10-, 14-year-olds, and adults.

In Study 2, I carried out the first investigation of the development of fine-grained sensitivity to horizontal and vertical differences between direct and averted gaze in the same age groups as in Study 1. In view of a finding in Study 2 that 6-year-olds perceived direct gaze over a wider range of directions of gaze than older children and adults, it was of interest whether adding social contextual information could allow more adult-like judgments of direct and averted gaze in young children. In Study 3, I investigated this question by measuring the cone of gaze in 6-, 8-year-olds, and adults while participants heard object-directed voice cues (e.g., “I see that.”), participant-directed voice cues (e.g., “I see you.”), or no voice. For Studies 1-3, I chose to test 6-year-olds as the youngest age group because this was the youngest age group able to perform each task, and because starting at this age allowed comparison to one age group included in a previous study of sensitivity to triadic gaze (Doherty et al., 2009) and one age group included in a previous study of sensitivity to direct and averted gaze (Thayer, 1977). In Study 4, I carried out the first investigation of the influences of facial expression and face inversion on sensitivity to direct and averted gaze in high-functioning adults with and without ASD.

The results have important implications for understanding real-world social interactions involving typically developing children or individuals with ASD. Specifically, immature or abnormal sensitivity to differences between direct and averted gaze may limit an individual's ability to make accurate judgments about whether a person is paying attention to the individual or not, whereas immature sensitivity to triadic gaze may lead to inaccurate judgments of the target of others' visual attention. The results may also allow inferences about visual, cognitive, and/or neural mechanisms underlying developmental changes in judgments of gaze. Specifically, different developmental trajectories for different types of judgments (e.g., triadic gaze, direct and averted gaze), and/or different outcomes in adults with and without ASD may imply differences in these mechanisms.

Chapter 2 - Study 1

Vida, M. D., & Maurer, D. (2012). Gradual improvement in fine-grained sensitivity to triadic gaze after 6 years of age. *Journal of Experimental Child Psychology, 111*, 299-318.

The direction of people's gaze toward objects in the environment (triadic gaze) provides cues to the focus of others' attention, and can thereby allow inferences about others' interests and/or intentions. Hence, accuracy in discriminating differences in triadic gaze is likely to affect a person's precision in making inferences about the mental states of others in real-world social situations. Adults are highly sensitive to differences in triadic gaze: they can detect differences of approximately 1° in the direction of gaze toward a target at midline (Bock et al., 2008; Symons et al., 2004), but are slightly less sensitive for targets in the near periphery (e.g., Symons et al., 2004). Adults' high sensitivity suggests that they are likely to be highly accurate in using differences in triadic gaze to make social judgments.

Children first exceed chance in making explicit judgments of large differences in triadic gaze by age 2-3 (e.g., Doherty et al., 2009; Lee et al., 1998), and their sensitivity improves gradually throughout early childhood. However, even at age 6, children's are less accurate than adults in judging which of three objects spaced 10° apart an adult is looking at (Doherty et al., 2009), a result suggesting that their sensitivity is poorer than that of adults. Previous studies do not indicate how fine-grained sensitivity to triadic gaze develops after age 6. The purpose of Study 1 was to investigate this question. In Experiment 1, children (6-, 8-, 10-, and 14-year-olds) and adults judged whether a 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, I 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, I investigated whether the precision of younger children's judgments of triadic gaze in Experiments 1 and 2 was limited by immature sensitivity to differences in eye position. I evaluated this hypothesis by testing adults and 8-year-olds on a matching task in which participants were asked to detect differences in the direction of gaze between simultaneously presented faces. The results provide the first information about the development of fine-grained sensitivity to triadic gaze from age 6 onward. Improvements in children's sensitivity may allow children to make more accurate judgments of the focus of others' attention, which may in turn lead to more accurate inferences about others' interests and/or intentions.

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-yearolds) 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.

Introduction

The direction of an individual's gaze can provide a useful cue to the target of his/her attention and can thereby allow inferences about his/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/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, as 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 0.3-2° (depending on viewing distance and stimulus quality) from a target at midline. For targets in the near periphery, adults have slightly poorer sensitivity (Symons et al., 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 et al., 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, Massacessi, 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- 5 months, 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, 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 & Cochrane, 1980; Butterworth & Jarrett, 1991). It could also reflect imitation of the adults' 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 (Corkum & Moore, 1998; Butterworth & Cochrane, 1980; Butterworth & Jarrett, 1991). 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 (or to the left) side behind an occluder, and then lifted the occluder to reveal an object either on the fixated or non-fixated side. Although they spent more time looking at the object than 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/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, also see Senju, Csibra, & Johnson, 2008). At 18 (but not 12) months, infants follow adults' 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 et al., 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 2-3 years of age, children can make explicit judgments of triadic gaze, and the accuracy of these judgments improves throughout early childhood. In one study, children aged 2-4 years were presented with video displays of a live model moving her eyes alone or eyes and head together toward one of several widely spaced objects (Lee et al., 1998, Experiments 4-5). In all conditions, 3- and 4-year-olds exceeded chance in determining the correct target of gaze, but 2-year-olds only exceeded chance when feedback was provided and the model moved the eyes and head together. In another study, 2-, 3- and 4-year-olds were presented with targets placed in the corners of a rectangular frame. Stimuli were a live model, photographs or 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 et al., 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 et al., 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. Three-year-olds only exceeded chance when the head and eyes moved together and the targets were 15° apart. By age 6, accuracy was adult-like in all conditions except when the model moved the eyes alone and 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 0.3-2°.

Previous studies have not examined sensitivity to triadic gaze after age 6, and have not tested children with objects spaced less than 10° apart. The purpose of the current study is 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 adults and children aged 6, 8, 10, and 14 years 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 6-year-olds (6 years, 6 months ± 3 months, *M* = 6.46 years, 10 female), 8-year-olds (8 years, 6 months ± 3 months, *M* = 8.55 years, 12 female), 10-year-olds (10 years, 6 months ± 3 months, *M* = 10.56 years, 11 female), 14-year-olds (14 years, 6 months ± 3 months, *M* = 14.58 years, 7 female) and adults (18-21 years, *M* = 18.62, 13 female) (*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 the child'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. Six-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 five children were replaced because they failed visual screening (one 8-year-old), because their data file was corrupt (one 8-year-old), because their data was best fit by a function with a negative slope (two 6-year-olds), or because of a threshold value more than three standard deviations above the mean (one 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 colour 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 Figure 1, 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 21 inch monitor set to a resolution of 1152 x 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 (1 Asian, 2 Caucasian) and three female (1 Asian, 2 Caucasian) models. Each participant was tested with only one model, counterbalanced across subjects 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 Figure 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 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 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 top (for eye deviations toward the red space station), the V key with a piece of blue paper taped over top (for eye deviations toward the blue space station) and the G key with a piece of paper bearing the letter "A" taped over 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, 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 furthest 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 pseudo-random order. During practice blocks, participants received 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 eight on either side) in 0.8° steps, whereas children received nine positions (the target and four 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, 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-year-olds and 14-year-olds. After positioning the 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 an appropriate adjustment 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 the 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 centre of the tip of the black stripe above the moon. Sometimes, she goes off course by looking 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. Participants responded to practice trials by saying whether the model appeared to be looking toward the blue station (left of target) or red (right of target) station. 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 centre 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. Participants pressed a blue or red button with their dominant hand to indicate whether the model appeared to be looking toward the blue space station (left side of the target) or red space station (right side). The stimulus remained on the screen until the participant entered an appropriate response.

After the 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 ANOVA on accuracy revealed no effect of age, no effect of target position and no interactions, ps > .10. Thus, children of all ages appeared to be as attentive as adults.

Estimates of sensitivity to triadic gaze. 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 Figure 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). 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 subject from the difference in fixation positions corresponding to the 0.5 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 participants are 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 .30°.

Threshold. The threshold values are shown in Figure 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 ϵ, $\hat{\epsilon}$, was used to adjust p values of F tests conducted on within-subject variables. There was a significant main effect of age, $F(4, 85) = 5.09$, $p < .01$, $f^2 = .20$. 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, $F(2, 170) = 3.63$, $p < .05$, $f^2 = .14$, 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 α = 0.017) 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), $t(89) = 2.44$, $p = .017$, $d = .31$, and the left target position (*M* = 1.52, *SD* = 1.04), $t(89) = 2.43$, $p = .017$, $d = .27$. However, there was no significant difference in threshold between the left and right target positions, $p > .80$.

Point of subjective equality (PSE). Figure 5 shows the point of subjective equality for each age group and target position. For central targets, the PSE is close to zero, that is, 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 Figure 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, $F(1.58, 134.47) = 59.28$, $\hat{\epsilon} = .791$, $p < .001$, $f^2 = .66$. We followed up the main effect of target with three paired-samples t-tests (Bonferroni-corrected $\alpha = 0.017$) 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 ($M = 1.43$, $SD = 0.89$) and 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 > 0.05.

Changes in performance across and within blocks. The greater precision of judgments in adults than 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, 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, *p*s > 3. There was a main effect of order for the central target, $F(2, 75) = 3.50$, $p < .05$, $f^2 = .23$, but not for the right or left targets, *p*s $> .3$. 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 ($M = 1.12$, $SD = .65$) and third ($M = 1.54$, $SD = .73$) blocks, $p < .05$, but not between the first ($M = 1.19$, $SD = .70$) block and the second or third blocks, *p*s $> .10$. 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 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, last half) as within-subject variables, age (6-year-olds, adults) as a between-subject 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, *p*s $> .05$. 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″[1] 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 et al. (2004, Experiment 3), adults in the current experiment displayed lower sensitivity for peripheral targets than for the midline target: their thresholds were 1.05° for the left and 1.20° for the right target compared to .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 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

[1] ″ refers to seconds of arc and ′ refers to minutes of arc. 1′ = 1/60° and 1″ = 1/3600°

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 centre 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 et al. (1969), adults in the current experiment overestimated the direction of gaze toward peripheral targets: they judged the model to be looking 1-2° farther in the periphery than he/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, 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 6-12° 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 and 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 re-centered the 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 age 6 to adulthood. Children were highly sensitive to eye deviations, displaying a mean threshold of 1.92° by age 6, compared to an adult mean threshold of 1.05°. Like adults, children at all ages had better thresholds for central than 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. Six- and 8-year-olds displayed statistically higher thresholds than adults. The thresholds of 10-year-olds were also larger 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 after age 10.

The one previous study of sensitivity to triadic gaze at an age overlapping with those 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 overestimate the direction of gaze toward peripheral targets. This could have reduced the accuracy reported in Doherty et al. (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 in 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 which 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 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 Figure 3, the youngest age groups failed to reach the lower and upper asymptotes established by adults at fixation positions furthest 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 to 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 female) 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 of 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 Figure 6). Goodness of fit was within the acceptable parameters described in Appendix B for Experiment 1 for all fits.

Threshold, point of subjective equality, and accuracy on catch trials. As shown in Figure 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 Experiments 1 ($M = 1.64$, $SD = 0.98$) and 2 ($M = 2.15$, $SD = 1.02$), $p > .10$, nor did PSE differ significantly between Experiments 1 ($M = 0.34$, $SD = 2.72$) and 2 ($M = 1.23$, $SD = 2.01$), $p > .2$. Accuracy on catch trials was high in both experiments, with no significant difference (Experiment 1: $M = .99$, $SD = 0.05$; Experiment 2: $M = .98$, $SD = 0.5$), $p > .40$.

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 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 conclusions of Experiment 1 that sensitivity to triadic gaze improves after age 6.

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 pointing 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 female) and 18 adults (18-26 years, *M* = 20.41 years, 11 female) who met the same screening criteria as in Experiment 1. An additional five 8-year-olds were replaced because they failed to pass visual screening (*n*=3) or because their data in one target condition (see Design) was best fit by a function with a negative slope (*n*=2).

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 Dell 3007WFP monitor set to a resolution of 2560x1600 pixels. The experiment was run in Matlab (The Mathworks, Natick, MA.) 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/her height was 110 cm. Participants entered responses on a computer keyboard placed on a table directly in front of them. The F and J keys with stickers placed over 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 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 subjects as in the previous experiments. Three images of the model were presented simultaneously (see Figure 7 for 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 (4 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 pseudo-random order with the constraint that the same target position was not presented more than twice in a row. Participants were allowed to repeat the practice block up to two times in order to meet the criterion of at least 75% accuracy. Twelve 8-year-olds and 13 adults were able to meet criterion on the first attempt. The remaining six 8-year-olds and five adults required two attempts to meet criterion.

Following the practice block, participants completed a single test block comprised of 240 trials which was identical to practice blocks except that in the non-matching peripheral choice, the model fixated a position 1.6°, 3.2°, 4.8°, 6.4° or 8° 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 pseudo-random order with the constraint that the same target position was not presented on 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, participants received five 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 centre 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. Participants were instructed to press the key corresponding with the location of the mismatch. Participants received feedback following each response (cartoon image of a happy face and 1000 Hz tone for correct responses, 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 space ship as in Experiment 1. The experimenter then displayed three images of the test model. The left and centre 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 = 0.98, SD = 0.04) and 8-year-olds (M = 0.99, SD = 0.02), 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 based the group analyses of 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 Figure 8 for plot). There was a significant mismatch level by age interaction, $F(2.98, 100.24) = 3.64$, $\hat{\epsilon} = .748$, $p < .02$, $f^2 = .22$. No other interactions were significant (ps > .20). There were significant main effects of target, $F(1.89, 64.35) = 4.26$, $\hat{\epsilon} = .737$, $p < .05$, $f^2 = .24$, level, $F(2.95, 100.23) = 131.73$, $\hat{\epsilon} = .748$, $p < .001$, $f^2 = 1.70$ and age, $F(1, 34) = 10.98$, $p < .005$, $f^2 = .37$.

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 smallest levels of mismatch (1.6º 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 4.8º and 6.4º mismatch, ps > .08, but was significantly greater than .75 at 8º 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 = 0.78, SD = 0.09) than for the left (M = 0.74, SD = 0.08), $t(35)$ = 2.48, p = .018, d = .47, and right targets (M = 0.75, SD = 0.10), $t(35)$ = 2.40, p = .022, d = .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.

Discussion. The results of Experiment 3 provide the first comparison of the ability to detect small differences in eye position between children and adults. Eight-year-olds required a much greater mismatch in the direction of gaze than 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 both in faces and non-face stimuli (Baudouin et al., 2010; Hadad, Maurer, & Lewis, 2010a; 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 age 8. Also, 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 as 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 in order 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 age six, 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 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 age 6, our results show that sensitivity develops slowly thereafter. Thresholds decreased from approximately twice those of adults at age 6 and 8 to reach adult-like levels at or after age 10. In addition, 8-year-olds also 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 3-10 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 review), or in brain areas implicated in processing of eye gaze in both adults and children, such as the superior temporal sulcus (Nummenmaa & Calder, 2009; Mosconi, Mack, McCarthy, & Pelphrey, 2005).

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 behaviours 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 on fine-grained sensitivity to triadic gaze from 6 years of age. 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.

References

Adams, R. A., & Courage, M. L. (2002). Using a single test to measure human contrast sensitivity from early childhood to maturity. *Vision Research, 42*, 1205-1210.

Ando, S. (2004). Perception of gaze direction based on luminance ratio. *Perception, 33,* 1173-1183.

Anstis, S. M., Mayhew, J. W., & Morley, T. (1969). The perception of where a face or television 'portrait' is looking. *The American Journal of Psychology, 82*, 474-489.

Baudouin, Y. Y., Gallay, M., Durand, K., & Robichon, F. (2010). The development of perceptual sensitivity to second-order relations in children. *Journal of Experimental Child Psychology, 107*, 195-206.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10,* 433-436.

Butterworth, G., & Cochran, E. (1980). Towards a mechanism of joint visual attention in human infancy. *International Journal of Behavioral Development, 3*, 253–272.

Butterworth, G., & Itakura, S. (2000). How the eyes, head and hand serve definite reference. *British Journal of Developmental Psychology, 18*, 25-50.

Butterworth, G., & Jarrett, N. (1991). What minds have in common is space. Spatial mechanisms serving joint visual attention in infancy. *British Journal of Developmental Psychology, 9*, 55–72.

Corkum, V., & Moore, C. (1998). The origins of joint visual attention in infants. *Developmental Psychology, 34*, 28–38.

Csibra, G., & Volein, A. (2008). Infants can infer the presence of hidden objects from referential gaze information. *British Journal of Developmental Psychology, 26,* 1-11.

Doherty, M. J., & Anderson, J. R. (2001). People don't move their heads when looking to one side, and other people can tell. *Perception*, *30*, 765-767.

Doherty, M. J., Anderson, J. R., Howieson, L. (2009). The rapid development of gaze judgment ability at 3 years. *Journal of Experimental Child Psychology*, *104*, 296-312.

Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research*, *39*, 2325-2333.

Farroni, T., Johnson, M. H., Brockbank, M., & Simion, F. (2000). Infants'use of gaze direction to cue attention: The importance of perceived motion. *Visual Cognition*, *7*, 705–718.

Farroni, T., Mansfield, E. M., Lai, C., & Johnson, M. H. (2003). Infants perceiving and acting on the eyes: Tests of an evolutionary hypothesis. *Journal of Experimental Psychology*, *85*, 3, 199-212.

Farroni, T., Massaccesi, S., Pividori, D., & Johnson, M. H. (2004). Gaze following in newborns. *Infancy, 5*, 39–60.

Friesen, C. K., & Kingstone, A. (1998). The eyes have it! Reflexive orienting is triggered by nonpredictive gaze. *Psychonomic Bulletin Review, 5*, 490–495.

Hadad, B., Maurer, D., & Lewis, T. L. (2010a). The effects of spatial proximity and collinearity on contour integration in adults and children. *Vision Research, 50,* 772-778.

Hadad, B., Maurer, D., Lewis, T. L. (2010b). The development of contour interpolation: Evidence from subjective contours. *Journal of Experimental Child Psychology, 106*, 163-176.

Hess, R. F., Hayes, A., & Field, D. J. (2003). Contour integration and cortical processing. *Journal of Physiology, 97*, 105-119.

Johnson, S., Ok, S., & Luo, Y. (2007). The attribution of attention: 9-month-olds' interpretation of gaze as goal-oriented action. *Developmental Science, 10*, 530-537.

Lee, K., Eskritt, M., Symons, L. A., & Muir, D. (1998). Children's use of triadic eye gaze information for ‘‘mind reading”. *Developmental Psychology, 34*, 525–539.

Leekam, S., Baron-Cohen, S., Perrett, D., Milders, M., & Brown, S. (1997). Eye-direction detection: A dissociation between geometric and joint attention skills in autism. British *Journal of Developmental Psychology, 15*, 77–95.

Meltzoff, A. N., & Moore, M. K. (1977). Imitation of facial and manual gestures by human neonates. *Science, 198*, 75-78.

Mosconi, M. W., Mack, P. B., McCarthy, G., & Pelphrey, K. A. (2005). Taking an “intentional stance” on eye-gaze shifts: A functional neuroimaging study of social perception in children. *NeuroImage, 27,* 247-252.

Nummenmaa, L., & Calder, A. J. (2009). Neural mechanisms of social attention. *Trends in Cognitive Sciences, 13*, 135-143.

Senju, A., Csibra, G., & Johnson, M. H. (2008). Understanding the referential nature of looking: Infants' preference for object-directed gaze. *Cognition, 108*, 303-319.

Skoczenski, A. M., & Norcia, A. M. (1999). The development of VEP Vernier acuity and grating acuity in human infants. *Investigative Ophthamology and Vision Science, 40*, 2411-2417.

Symons, L. A., Lee, K., Cedrone, C. C., & Nishimura, M. (2004). What are you looking at? Acuity for triadic eye gaze. *The Journal of General Psychology, 131*, 451-469.

Wichmann, F. A. & Hill, N. J. (2001). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception and Psychophysics, 63*, 1293-1313.

Tables

Table 1

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

Group	*6-year-olds*	*8-year-olds*	*8-year-olds*	*14-year-olds*	*Adults*
Midline (*SD*)	0.99 (0.05)	0.99 (0.05)	0.99 (0.05)	1.00 (0.00)	1.00 (0.00)
Right (*SD*)	0.97 (0.09)	0.97 (0.07)	0.99 (0.05)	1.00 (0.00)	0.99 (0.05)
Left (*SD*)	1.00 (0.00)	0.96 (0.08)	0.96 (0.15)	0.99 (0.05)	1.00 (0.00)

Figures

Figure 1

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

Figure 2

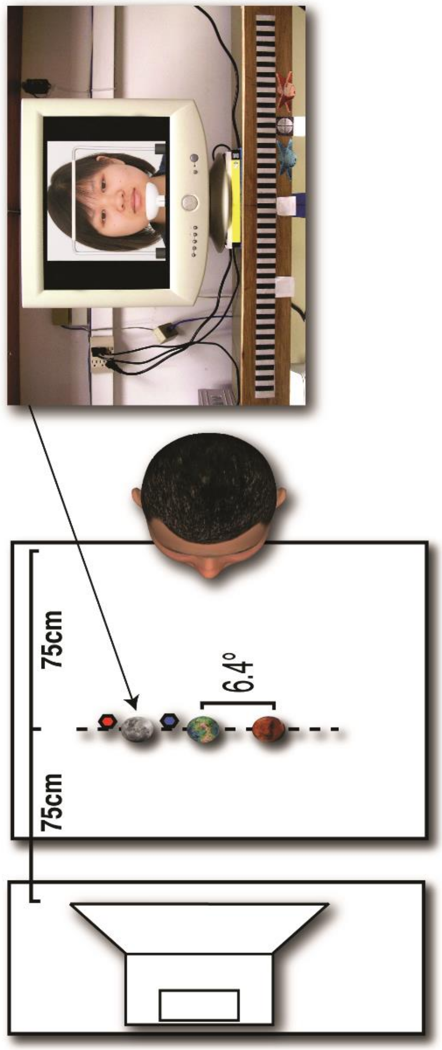


Figure 2. Schematic representation of the apparatus used in Experiment 1. The photograph displays the configuration of targets and fixation positions for a block during which the observer judged whether the model was looking to the right or left of a target 6.4° to the right of midline.

Figure 3

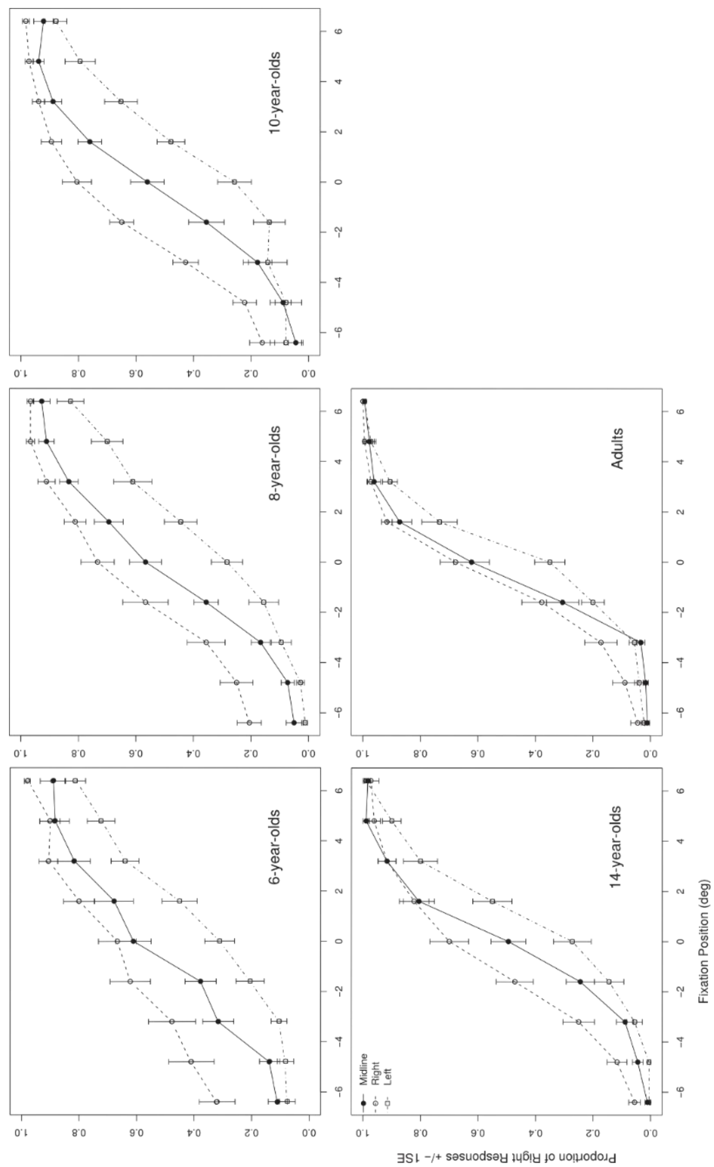


Figure 3. Mean proportion of trials (± 1 *SE*) during which 6-, 8-, 10-, 14-year-olds and adults indicated that the model appeared to look to the right of the target as a function of fixation position. Positive values on the abscissa refer to fixation positions to the right of the target. Negative values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

Figure 4

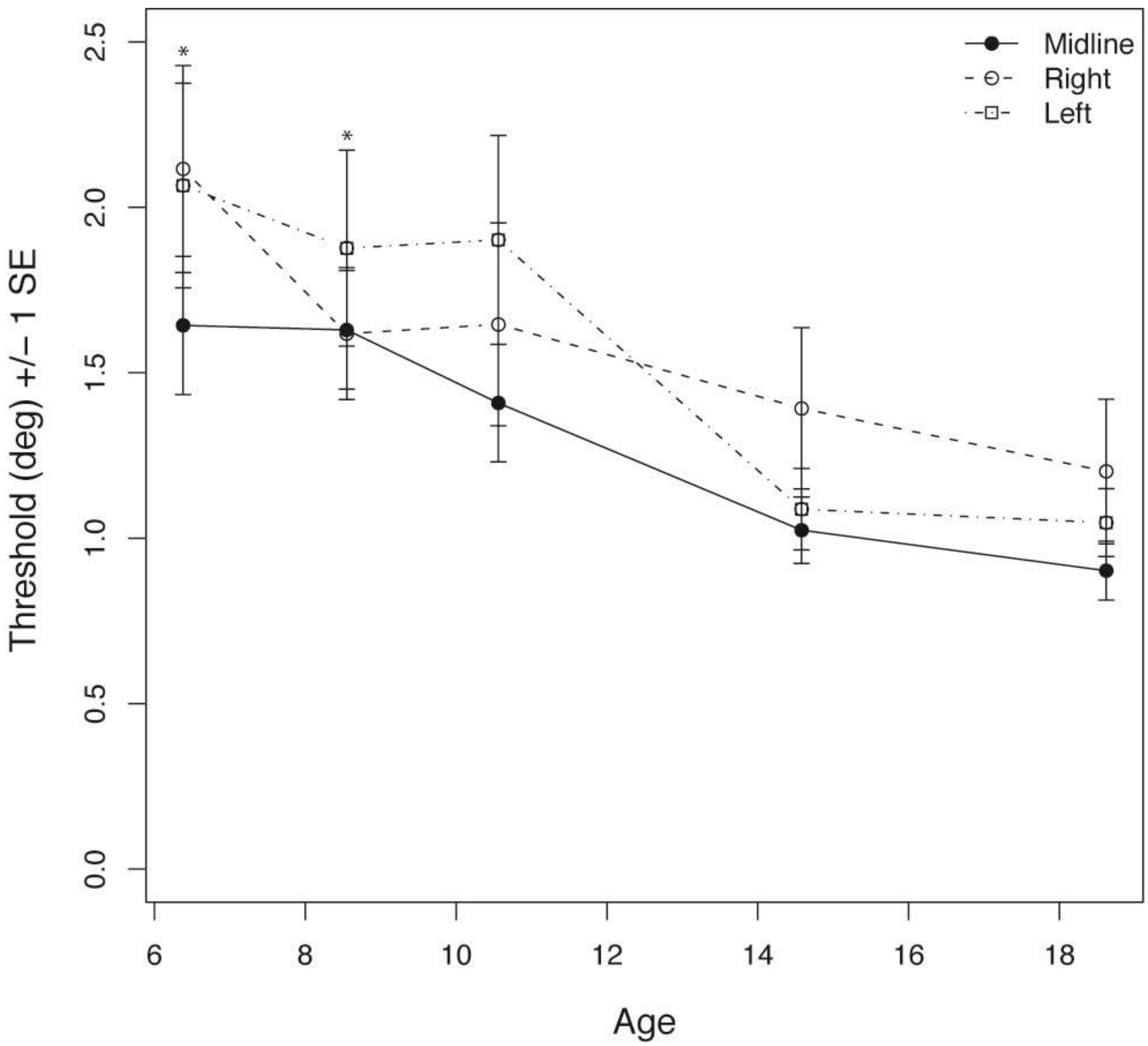


Figure 4. Mean threshold (± 1 *SE*) in degrees as a function of age. Higher values indicate lower sensitivity (Note *p < .05 compared to adults).

Figure 5

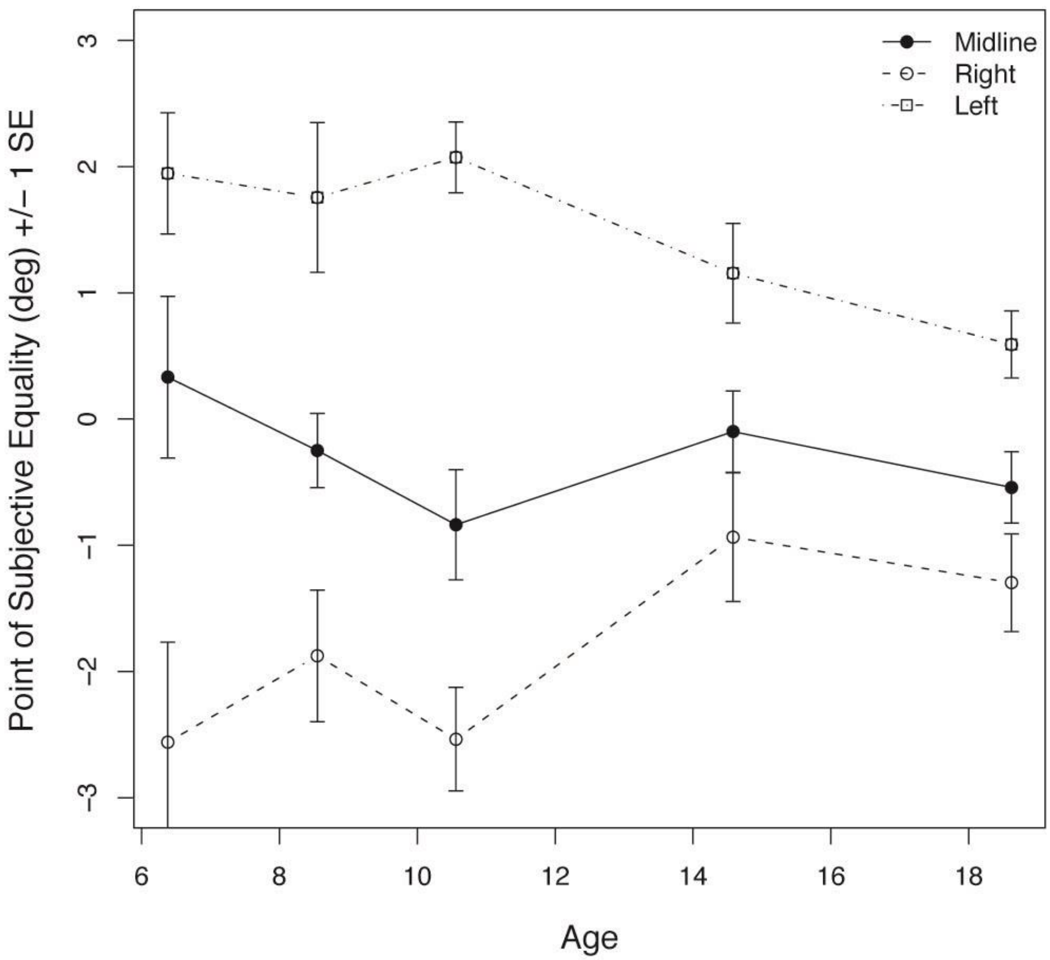


Figure 5. Mean point of subjective equality (± 1 *SE*) in degrees as a function of age. Zero corresponds to the actual position of the target. Positive values indicate fixation positions to the right of the target. Negative values indicate fixation positions to the left of the target.

Figure 6

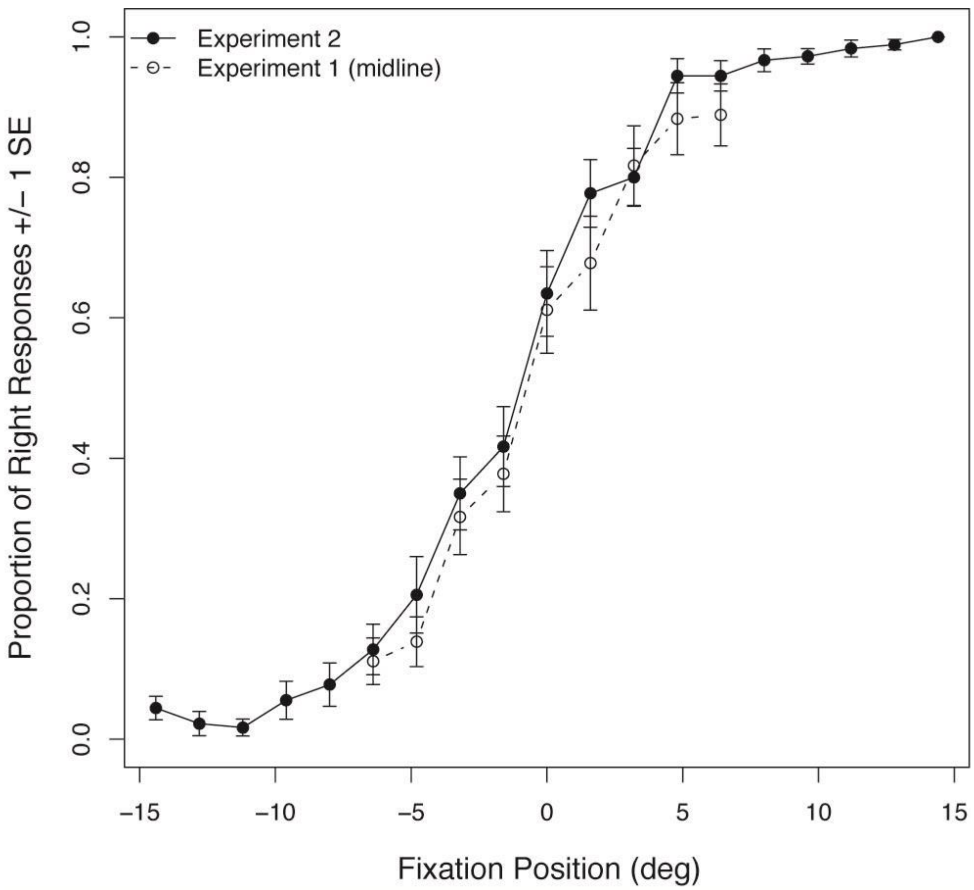


Figure 6. Mean proportion of trials on which (± 1 *SE*) of 6-year-olds indicated that the model appeared to look to the right of the target as a function of fixation position in Experiments 1 and 2. Positive values on the abscissa refer to fixation positions to the right of the target. Negative values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

Figure 7

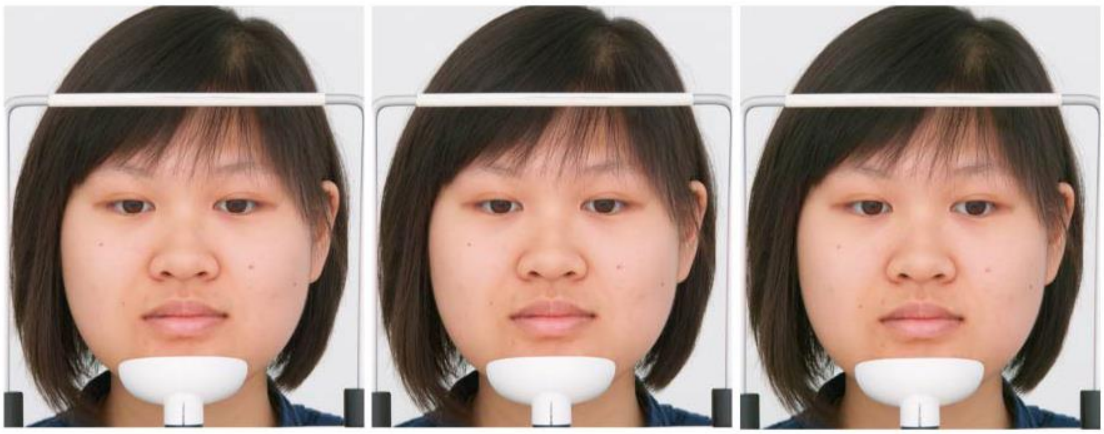


Figure 7. Example of the images displayed on a single trial in Experiment 3. The left and centre images show the model fixating a target at midline. The right image shows the model fixating a target 6.4° to the right of midline.

Figure 8

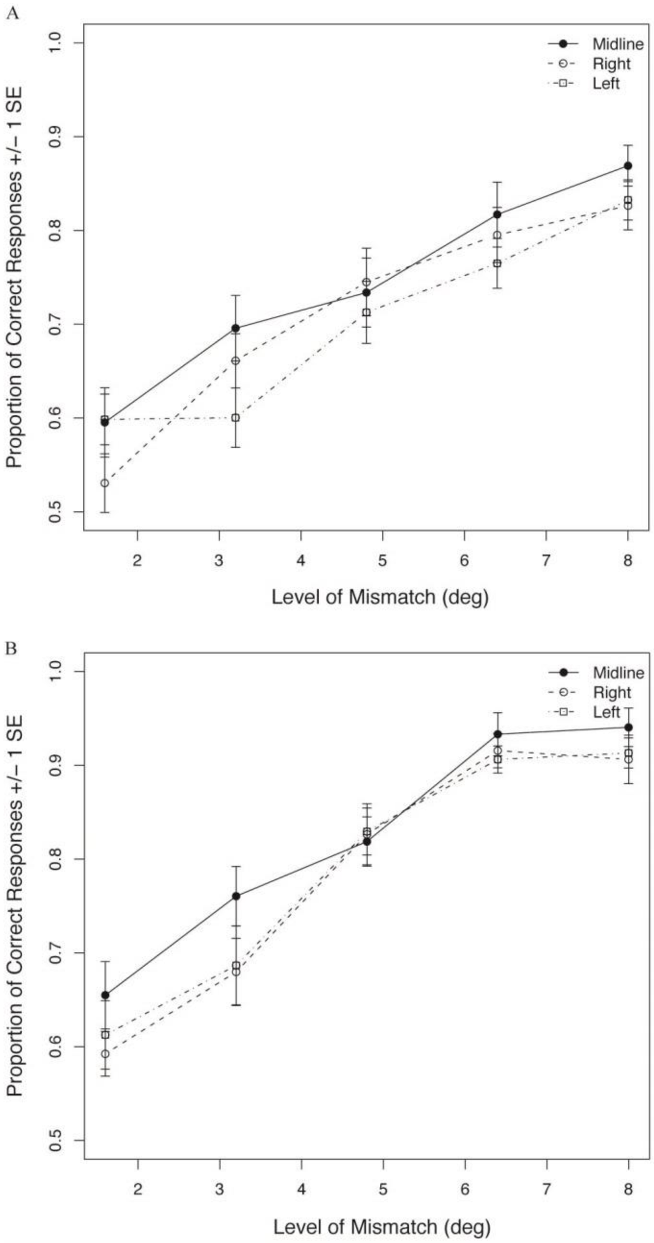


Figure 8. Panel A displays the mean proportion (±1 *SE*) of correct responses as a function of the level of mismatch in degrees for 8-year-olds for each of the three target positions. Panel B displays the corresponding data for adults.

Appendix A

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 75cm. 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 50-150 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 cm x 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

Curve fitting. 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[4]. 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 position 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, The Mathworks, Natick, MA), 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 0-0.2 and 0.8-1.0, respectively (Wichmann & Hill, 2001).

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 further from the fitted curve than expected (overdispersion).

[4] 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 > .5.

We calculated deviance (*D*), a measure of overdispersion defined as:

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

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 & Hill, 2001) for Matlab to generate 10,000 Monte Carlo simulated datasets. We then calculated the cumulative probability estimate for deviance (*CPE*(*D*)), defined as:

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

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 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:

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

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 (*rPD*) for each of 10,000 Monte Carlo simulated datasets. 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.

Chapter 3 - Study 2

Vida, M. D., & Maurer, D. (2012). The development of fine-grained sensitivity to eye contact after 6 years of age. *Journal of Experimental Child Psychology, 112*, 243-256.

Perceived differences between direct and averted gaze provide useful cues to the mental and emotional states of others. Direct gaze can signal the intent to communicate, threaten, or dominate, whereas deviations from eye contact can signal avoidance, deception, or attention toward a target in the environment (Argyle & Cook, 1976; Kendon, 1967). Hence, adults' ability to discriminate between direct and averted gaze is likely to affect their ability to make inferences about the mental and emotional states of others during real-world social interactions. Although adults can detect differences of approximately 1º in the direction of gaze toward objects in the environment (e.g., Symons et al., 2004), the range of directions of gaze over which adults perceive direct gaze (the cone of gaze) is relatively large, at approximately 5.5º in width (e.g., Gibson & Pick, 1963). Adults' relatively wide cone of gaze may reduce social costs associated with attributing averted gaze when gaze is actually direct (e.g., missing an opportunity to interact with a person who wishes to do so). Children first exceed chance in discriminating large differences between direct and averted gaze at age 2-3 (e.g., Doherty et al., 2009).

Previous studies have not examined the development of fine-grained sensitivity to direct and averted gaze during middle childhood, and have not used the same stimuli to compare sensitivity between children and adults. The purpose of Study 2 was to provide the first precise measurements of the horizontal and vertical cone of gaze from 6 years onward. In the current experiment, adults and children (6-, 8-, 10-, and 14-year-olds) viewed photographs of faces fixating the centre 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 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).

The results have implications for understanding social interactions involving children. Any immaturity in children's ability to discriminate differences between direct and averted gaze could 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. For example, a wider cone of gaze in younger children than in older children and adults could make younger children more likely to judge that a person's gaze is direct when it is actually averted, which could in turn lead younger children to be more likely to attempt to interact with a person who is not interested in doing so. The results also have implications for understanding mechanisms underlying developmental changes in sensitivity to direct and averted gaze. Specifically, a difference between developmental trajectories for judgments of direct and averted gaze and for triadic gaze (Study 1) (e.g., faster development of adult-like sensitivity to direct and averted gaze) could reflect a difference in underlying visual, cognitive, and/or neural mechanisms.

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/age) viewed photographs of a model fixating the centre 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.

Introduction

The direction of an individual's gaze can provide a useful cue to the target of his/her attention and can thereby allow inferences about his/her interests and intentions. Dyadic gaze indicates whether an individual is making eye contact and hence attending to the observer, whereas triadic gaze 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 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 et al., 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 et al., 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° 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 looker or virtual model is making eye contact with them even when gaze varies within a horizontal range 5-9° 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 gazer'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, as 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.

The 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, but 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, infants display a larger N240 ERP component when viewing a face with direct gaze than 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° to the left or right (Hains & Muir, 1996; Symons, Hains, & Muir, 1998). This effect was not observed for 5° vertical deviations (Symons et al., 1998), a failure that could reflect lower visual sensitivity to vertical than horizontal differences in gaze direction and/or a difference in infants' interpretations of horizontal versus vertical shifts of gaze. By 4-5 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- but not 2-year-olds children are able to indicate which face is making eye contact with them (Doherty, Anderson, & Howieson, 2009). At age 6, the horizontal cone of gaze appears to be quite wide. In the one previous study including 6-year-olds, children responded that gaze was direct across fixation positions 10-30 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 including older children, adults and children aged 7 and 11 years 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, bridge of nose) versus off-eye (mouth, ears, 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, children aged 8-15 years are faster at detecting faces presented with direct gaze than faces with averted gaze (Senju et al., 2008) and children aged 6-11 years 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 age 6 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 aged 6, 8, 10, and 14 years viewed photographs of faces fixating the center of the camera lens and a series of surrounding positions 1.6-8.0° 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 gaze 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, ±3 months, M = 6.54 years, 10 female), 8-year-olds (8 years, 6 months ±3 months, M = 8.54 years, 12 female), 10-year-olds (10 years, 6 months ±3 months, M = 10.54 years, 11 female), 14-year-olds (14 years, 6 months ±3 months, M = 14.47 years, 7 female), and adults (18-21 years, M = 19.35, 13 female) (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 the child'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. Six-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). Five additional children were tested but were replaced because they failed visual screening (three 8-year-olds, one 14-year-old) or because a crossover point could not be calculated for their data in one of the test blocks (one 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 1.6-8.0° to the left, right, above, and below the camera lens in steps of 1.6° (see Figure 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, 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 centre 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 B 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 21 inch monitor set to a resolution of 1152 x 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, the participant used the F key with a leftward-pointing arrow taped over 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 for description). In the vertical condition, the participant did not use the right and left buttons, but instead used the T key with an 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 subjects so that half of the participants in each age group completed the horizontal condition first and half completed vertical 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 centre of the camera lens (four trials) and the furthest points away from centre (four trials at 8.0° left/down and four trials at 8.0° up/right), presented in a pseudo-random order. During practice trials, participants received feedback indicating whether their response was correct or not (cartoon image of a happy face and 1000 Hz tone for correct responses and sad face with 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. Fourteen 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. Three 6-year-olds, four 8-year-olds, one 10-year-old, and one 14-year-old needed an additional attempt to reach criterion for the vertical block, and one 6-year-old needed an additional attempt 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 that would appear in the two target blocks. Before practice trials, the experimenter explained the task as follows (with an appropriate adjustment 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 (point to the left of participant), press this button (point to left button) to make the spaceship go in this direction. When Jenny is looking away from you in the other direction (point to the right of the participant), press this button (point 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 centre of a grey 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. Participants 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 minutes and completed the entire procedure in approximately 30 minutes.

Results.

Accuracy on catch trials. All participants responded correctly on every catch trial, with the exception of one 14-year-old and one 6-year-old, who each responded incorrectly to a single catch trial (out of the 16 presented across the two test blocks). Since 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 Figure 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) (MathWorks, Natick, MA, USA). 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 A 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/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, 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 value and one centered to the right/up would receive a positive score. Thus, any horizontal or vertical response bias will lead to a non-zero 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 the gaze cone. We carried out an age by axis mixed ANOVA with size of the gaze cone as the dependent variable (see Figure 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) 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, $p > .1$, $f^2 = .09$. Post-hoc Dunnett's tests for the horizontal and vertical conditions showed that horizontal cone width was significantly greater in 6-year-olds ($M = 8.48°$, $SD = 3.92$) than in adults ($M = 5.49°$, $SD = 1.69$), $p < .002$. There were no other significant differences, *p*s > .1. 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, Figure 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, and in horizontal cone size after age 8. The test for the vertical condition was significant, $t(85) = 2.51$, $p < .01$, $d = .60$, indicating that vertical cone size decreased linearly after age 6. The test for the horizontal condition was not significant, $p > .1$, indicating that horizontal cone size did not decrease linearly after age 8.

Centering of the gaze cone.

Maximum direct response. We carried out an age by axis mixed ANOVA with the maximum direct response as the dependent variable (Figure 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 ($M = 0.23$, $SD = 1.22$) and vertical ($M = -0.70$, $SD = 2.21$) conditions. However, there was no significant effect of age, $p > .9$, and no age by axis interaction, $p > .6$. We followed up the main effect of axis with two single-sample t-tests (one for each axis) comparing the maximum direct response to zero. In the vertical condition, the maximum direct response was significantly below zero (the participant's eye height), $t(89) = -3.02$, $p < .005$, $d = .32$. 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 (Figure 5). There was a marginally significant main effect of axis, $F(1, 85) = 3.24$, $p = .076$, $f^2 = .03$; the centering of the cone of gaze differed slightly between the horizontal (M = -0.12°, SD = 0.75) and vertical (M = -0.47°, SD = 1.66) conditions. However, there was no effect of age, $p > .6$, and no age by axis interaction, $p > .2$. In the vertical condition, the midpoint of the cone was significantly below zero (the participant's eye height), $t(89) = 2.70$, $p < .01$, $d = .28$. In the horizontal condition, the midpoint of the cone did not differ from zero (the bridge of the participant's nose), $p > .1$. 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° (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°) and Lord and Haith (1974) (fixation anywhere on the participant's eyes and bridge of nose, a region approximately 5° 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/herself, not surprisingly, they found a slightly wider range (approximately 7-9° 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° (18.2 cm), a value larger than the horizontal extent of 5.49° (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), positions that are 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 et al., 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 judgments. The vertical criterion may be relaxed because observers take into account the dimensions of their own face, which is typically taller than it is 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, & Miellet, 2010;

Dahl, Wallraven, Bülthoff, & 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 the observer's head or below the chin. That differential exposure may lead to greater perceptual sensitivity to horizontal than to vertical deviations from direct gaze.

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 the midpoint of the gaze cone. The current study is the first to measure the centering of adults' vertical cone, which was approximately 1° (approximately 2.5 cm) below the eye height of the participant, near the vertical midpoint of their 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 centre 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 than for downward deviations from direct gaze (see Figure 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 age 6 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° (22.2 cm) in 6-year-olds, which is over 50% larger than the cone width of 5.49° (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° 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 including 6-year-olds found that children at this age perceive eye contact over a much larger horizontal range of fixation positions (17.06° or 60 cm) (Thayer, 1977) than in the current study (8.47° or 22.2 cm). The live model in Thayer (1977) was farther away than the photographed models in the current study (200 versus 150cm), so one would expect a slightly larger cone of gaze. However, there was no adult reference group in Thayer (1977) to allow evaluation of this possibility. The one previous study including children older than 6 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 (e.g., the ears) or above/below (e.g., hairline, mouth) the eye region (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. Also, 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 age 6, while the extent of the horizontal cone shrank between 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 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° in gaze toward an object in the environment (Vida & Maurer, 2012), a smaller distance than the limit for adults' horizontal cone (2.74° 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 may 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 versus 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 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 age 8, children are as likely as adults to infer that a real-world partner is attending to them when the person is fixating any part of their face. Thus, from age 8 onward, immaturity in distinguishing direct from averted gaze will no longer limit children's interpretation of such social signals. Six-year-olds in the current experiment perceived eye contact over a wider horizontal range of positions than did older children and adults, and may thus 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, which 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 to 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 age 6 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 the participant could influence the participant 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. In summary, this investigation has provided the first evidence on fine-grained sensitivity to eye contact along the horizontal and vertical axes from age 6 to adulthood. The horizontal cone of gaze was over 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.

References

Adams, R. A., & Courage, M. L. (2002). Using a single test to measure human contrast sensitivity from early childhood to maturity. *Vision Research, 42,* 1205-1210.

Akechi, H., Senju, A., Kikuchi, Y., Tojo, Y., Osanai, H., & Hasegawa, T. (2009). Does gaze direction modulate facial expression processing in children with autism spectrum disorder? *Child Development, 80,* 1134-1146.

Ando, S. (2004). Perception of gaze direction based on luminance ratio. *Perception, 33,* 1173-1183.

Anstis, S. M., Mayhew, J. W., & Morley, T. (1969). The perception of where a face or television 'portrait' is looking. *The American Journal of Psychology, 82*, 474-489.

Argyle, M., & Cook, M. (1976). *Gaze and mutual gaze.* New York: Cambridge University Press.

Baron-Cohen, S. (1995). The eye direction detector (EDD) and the shared attention mechanism (SAM): Two cases for evolutionary psychology. In C. Moore & P. J. Dunham (Eds.), *Joint attention: Its origins and role in development* (pp. 41-59). Hillsdale, NJ: Erlbaum.

Baron-Cohen, S., Wheelwright, S., Hill, J., Raste, Y., & Plumb, I. (2001). The 'Reading the mind in the eyes' Test revised version: A study with normal adults, and adults with Asperger syndrome or high-functioning autism. *Journal of Child Psychology and Psychiatry, 42*, 241-251.

Bindemann, M. A., Burton, M., & Langton, S. R. H. (2007). How do eye gaze and expression interact? *Visual Cognition, 16*, 708-733.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.

Caldara, R., Zhou, X., & Miellet, S. (2010). Putting culture under the 'spotlight' reveals universal information use for face recognition. *Public Library of Science One, 5*, e9708.

Dahl, C. D., Wallraven, C. Bülthoff, H. H., & Logothetis, N. K. (2010). Humans and macaques employ similar face-processing strategies. *Current Biology, 19*, 509-513.

Dalgaard, P. (2008). *Introductory statistics with R.* New York: Springer.

Doherty, M. J., Anderson, J. R., & Howieson, L. (2009). The rapid development of gaze judgment ability at 3 years. *Journal of Experimental Child Psychology, 104*, 296-312.

Einav, S., & Hood, B. M. (2008). Tell-tale eyes: Children's attribution of gaze aversion as a lying cue. *Developmental Psychology, 44*, 1655-1667.

Emery, N. J. (2000). The eyes have it: the neuroethology, function and evolution of social gaze. *Neuroscience and Biobehavioral Reviews, 24*, 581-604.

Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research, 39*, 2325-2333.

Ewbank, M. P., Jennings, C., & Calder, A. (2009). Why are you angry with me? Facial expressions of threat influence perception of gaze direction. *Journal of Vision, 9*, 1-7.

Farroni, T., Csibra, G., Simion, F., & Johnson, M. H. (2002). Eye contact detection in humans from birth. *Proceedings of the National Academy of Sciences, 99*, 9602-9605.

Farroni, T., Mansfield, E. M., Lai, C., & Johnson, M. H. (2003). Infants perceiving and acting on the eyes: Tests of an evolutionary hypothesis. *Journal of Experimental Child Psychology, 85*, 199-212.

Farroni, T., Johnson, M. H., & Csibra, G. (2004). Mechanisms of eye gaze perception during infancy. *Journal of Cognitive Neuroscience*, *16*, 1320-1326.

Gamer, M., & Hecht, H. (2007). Are you looking at me? Measuring the cone of gaze. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 705-715.

Gibson, J. T., & Pick, A. D. (1963). Perception of another person's looking behavior. *The American Journal of Psychology, 76*, 386-394.

Hains, S. M. J., & Muir. D. W. (1996). Infant sensitivity to adult eye direction information. *Child Development, 67*, 1940-1951.

Hietanen, J.K., Leppänen, J. M., Peltola, M. J., Linna-aho, K., & Ruuhiala, H. J. (2008) Seeing direct and averted gaze activates the approach-avoidance motivational brain systems. *Neuropsychologia, 46*, 2423–2430.

Kendon, A. (1967). Some functions of gaze-direction in social interaction. *Acta Psychologica, 26,* 22-63.

Lawson, R. P., Clifford, C. W. G., & Calder, A. J. (2011). A real head-turner: Horizontal and vertical head directions are multichannel coded. *Journal of Vision, 11*, 1-17.

Lord, C. (1974). The perception of eye contact in children and adults. *Child Development, 45*, 1113–1117.

Lord, C., & Haith, M. M. (1974). The perception of eye contact. *Perception and Psychophysics, 16*, 413-416.

Macrae, C.N., Hood, B. M., Milne, A. B., Rowe, A. C., & Mason, M. F. (2002) Are you looking at me? Eye gaze and person perception. *Psychological Science, 13*, 460–464.

McCarthy, A., & Lee, K. (2009). Children's knowledge of deceptive gaze cues and its relation to their actual lying behavior. *Journal of Experimental Child Psychology, 103*, 117-134.

McCullagh, P., & Nelder, J. (1989). *Generalized Linear Models, Second Edition*. Boca Raton: Chapman and Hall/CRC.

Senju, A., Kikuchi, Y., Hasegawa, T., Tojo, Y., & Osanai, H. (2008). Is anyone looking at me? Direct gaze detection in children with and without autism. *Brain and Cognition, 67*, 127-139.

Senju, A., & Johnson, M. H. (2009). The eye contact effect: mechanisms and development. *Trends in Cognitive Sciences, 13*, 127-134.

Smith, A. D., Hood, B. M., & Hector, K. (2006). Eye remember you: Gaze direction modulates face recognition in a developmental study. *Developmental Science, 9*, 465-472.

Symons, L., Hains, S. M. J., & Muir, D. W. (1998). Look at me: Five-month-olds infants' sensitivity to very small deviations in eye-gaze during social interactions. *Infant Behavior & Development, 21*, 531-536.

Symons, L. A., Lee, K., Cedrone, C. C., & Nishimura, M. (2004). What are you looking at? Acuity for triadic eye gaze. *The Journal of General Psychology, 131*, 451-469.

Thayer, S. (1977). Children's detection of on-face and off-face gazes. *Developmental Psychology, 13*, 673-674.

Vida, M. D., & Maurer, D. (2012). Gradual improvement in fine-grained sensitivity to triadic gaze after 6 years of age. *Journal of Experimental Child Psychology, 11*, 299-318.

Zeifman, D., Delaney, S., & Blass, E. M. (1996). Sweet taste, looking and calm in 2- and 4-week-old infants: the eyes have it. *Developmental Psychology, 32*, 1090-1099.

Figures

Figure 1

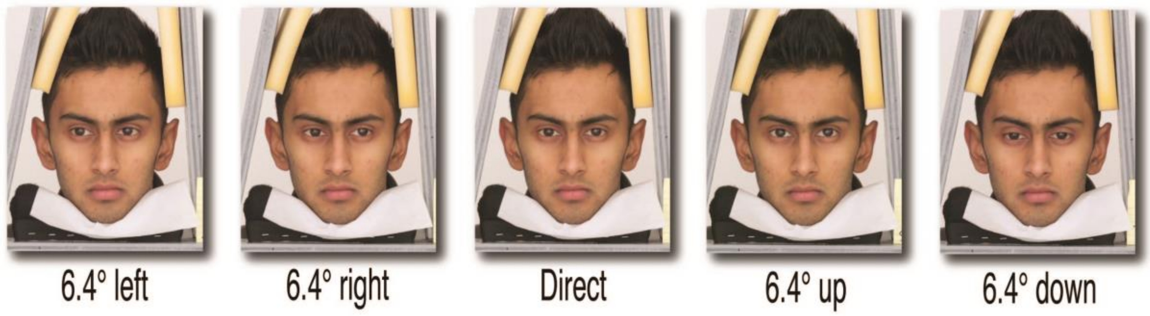
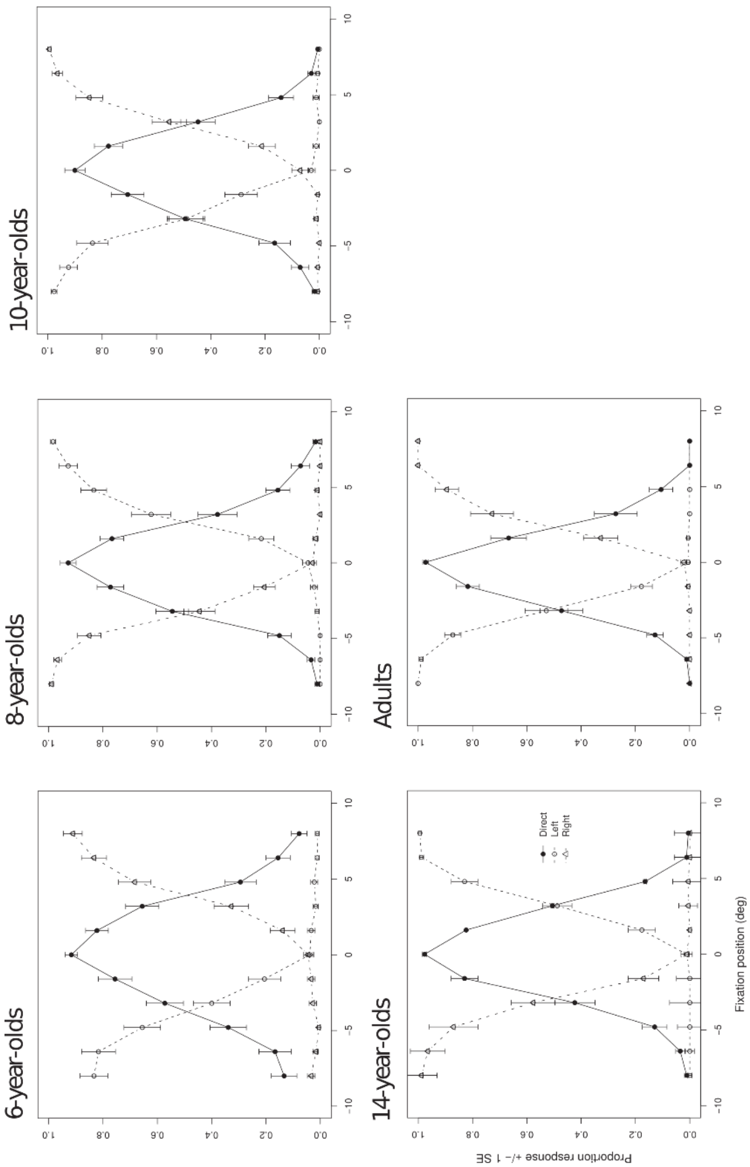


Figure 1. Examples of stimuli for one model.

Figure 2

A


6-year-olds
8-year-olds
10-year-olds
14-year-olds
Adults
Direct
Left
Right
Fixation position (deg)
Proportion response +/- 1 SE

B

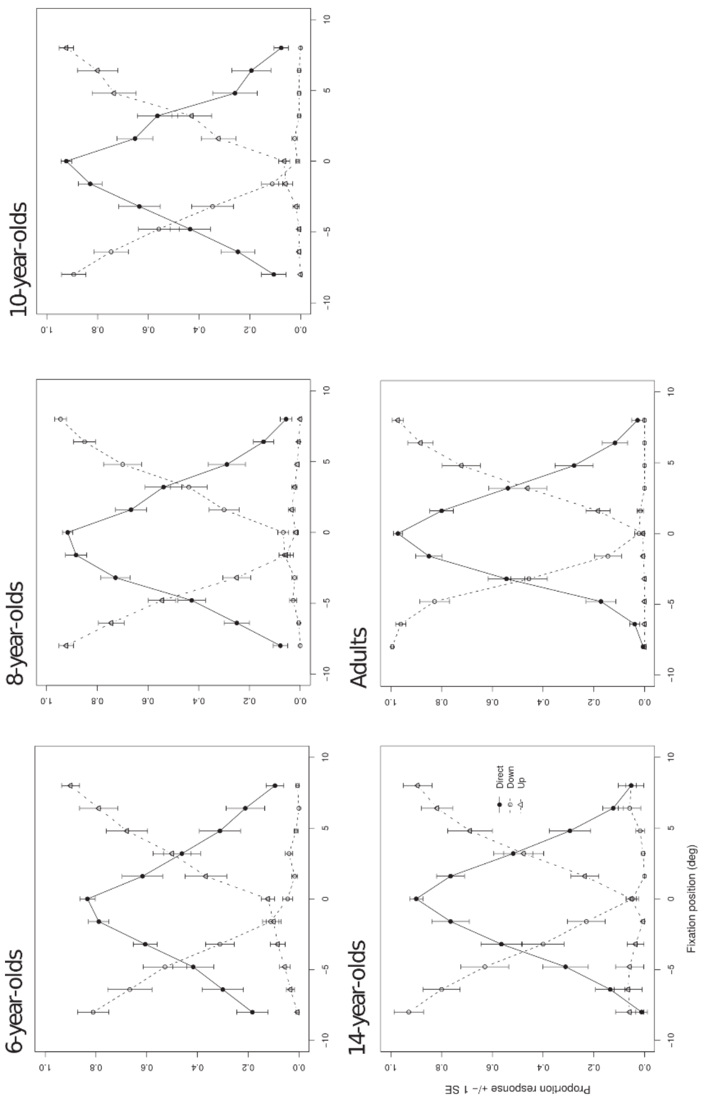


Figure 2. Panel A displays the proportion of each response type (± 1 *SE*) as a function of fixation position (negative values represent fixation positions to the left of the participant's nose, positive values represent fixation positions to the right) for the horizontal condition. Each plot displays the data for one age group. Panel B displays the corresponding data for the vertical condition (fixation positions with negative values represent fixation positions below the participant's eyes, positive values represent 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.

Figure 3

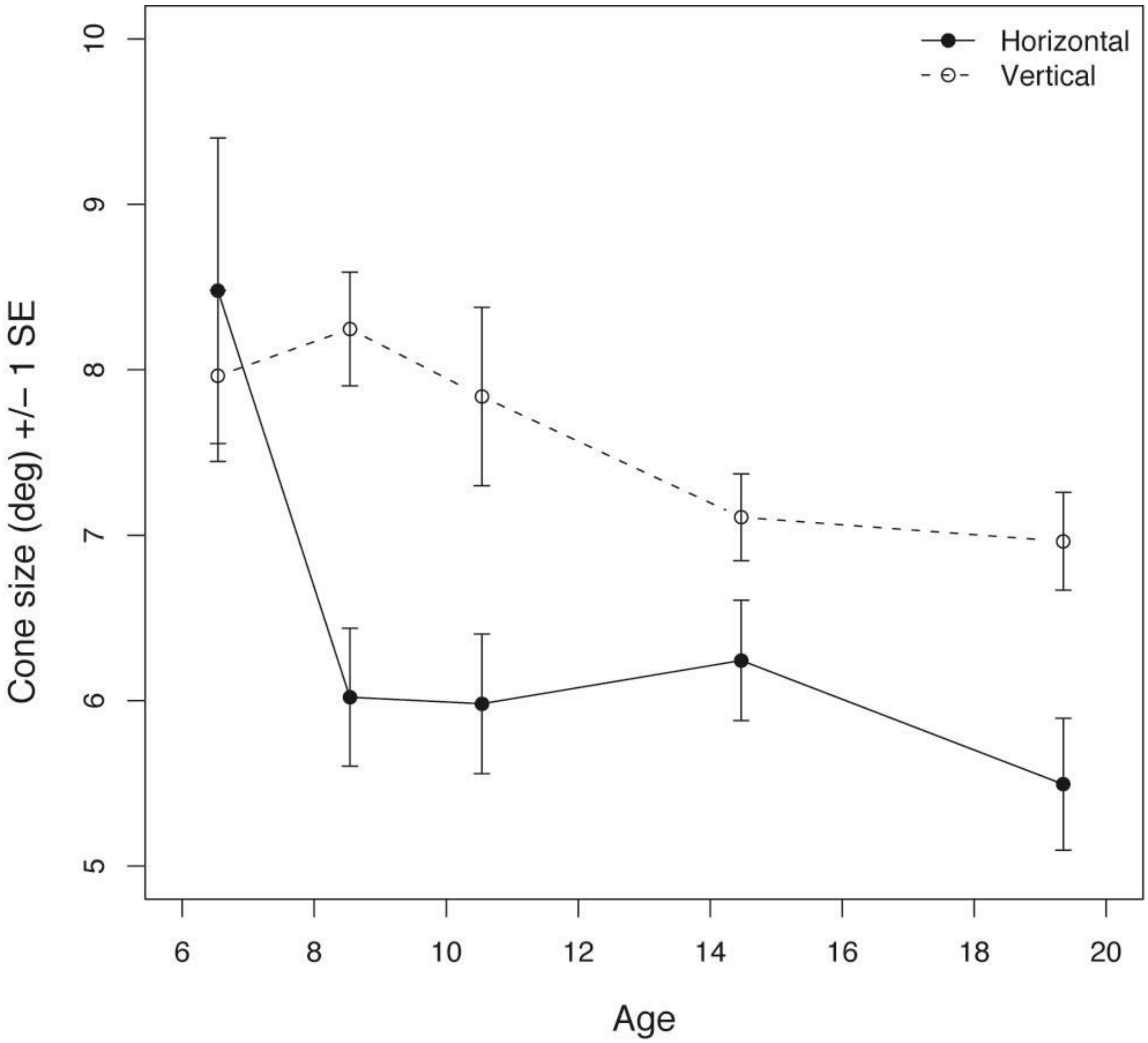


Figure 3. Size of the gaze cone (± 1 *SE*) in degrees as a function of age and axis. Higher values indicate a larger gaze cone.

Figure 4

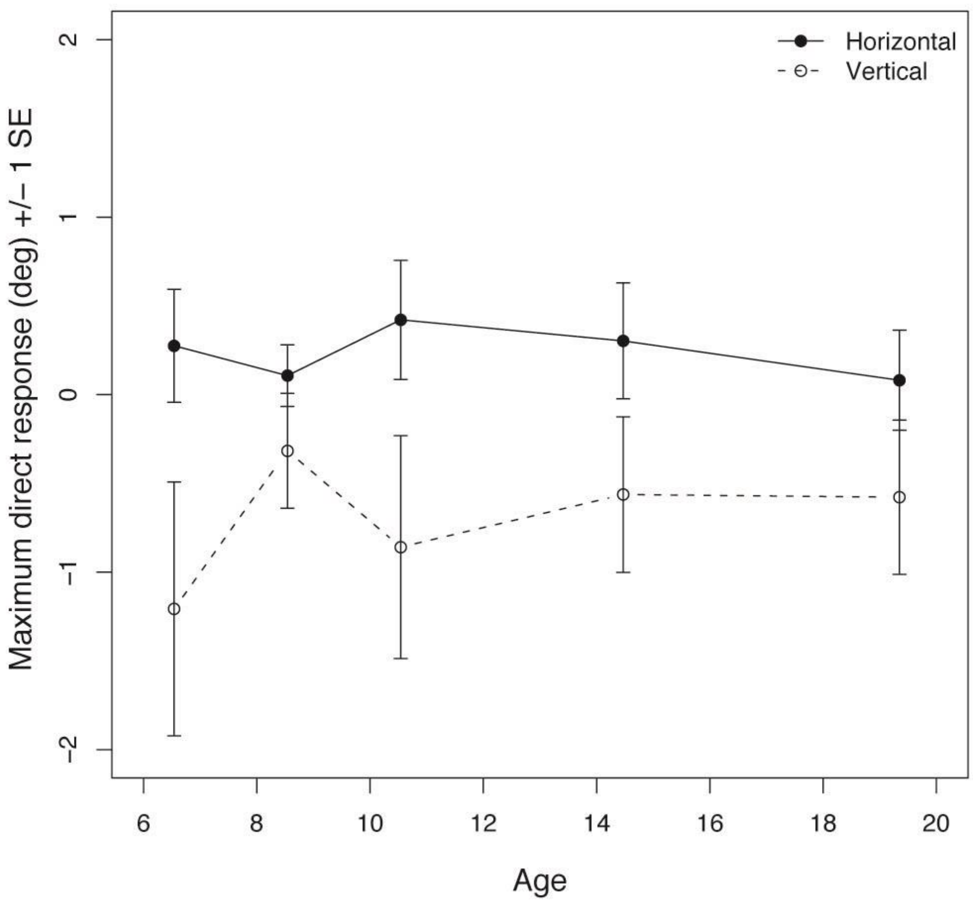


Figure 4. Maximum direct response (± 1 *SE*) in degrees as a function of age and axis. For horizontal judgments, positive values indicate fixation positions to the right of the participant's nose and negative values indicate fixation positions to the left of the participant's nose. For vertical judgments,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

Figure 5

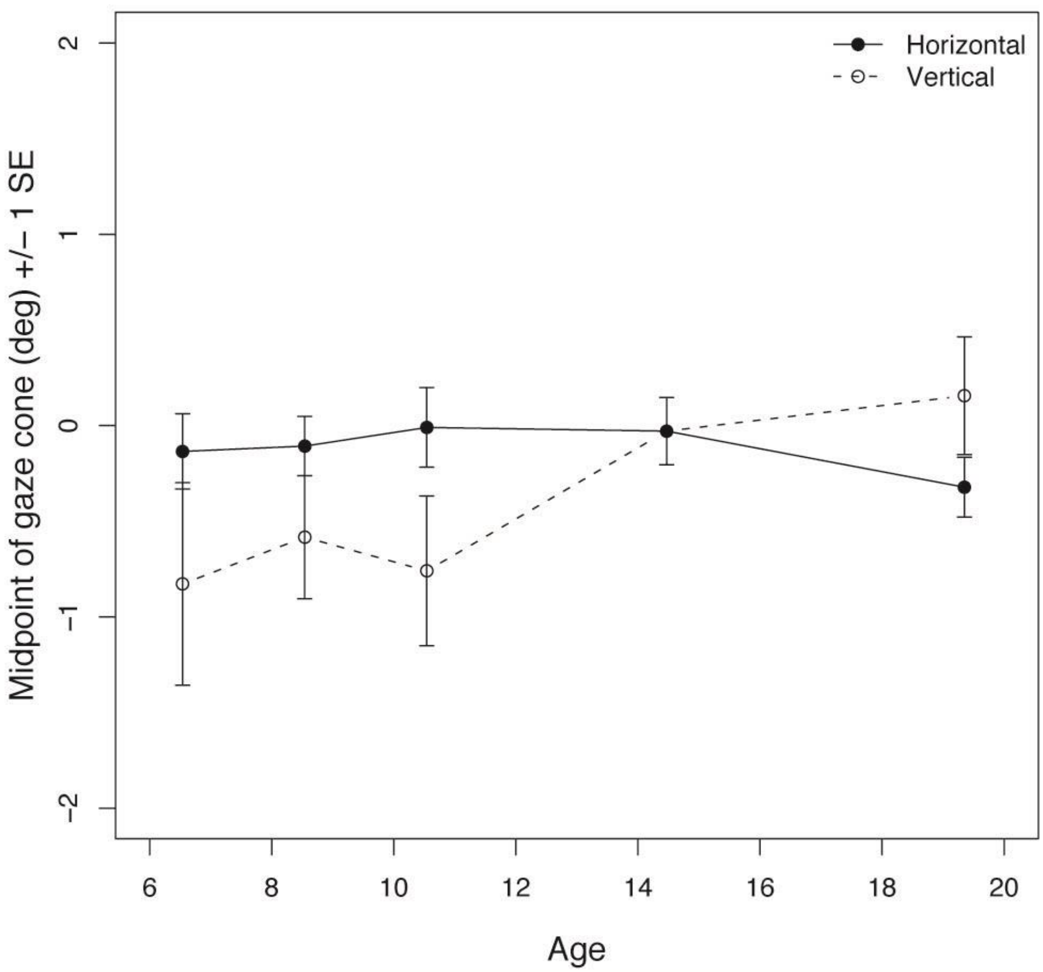


Figure 5. Midpoint of the gaze cone (± 1 *SE*) in degrees as a function of age and axis. Other details as in Figure 4.

Appendix A

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, 1978). 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 χ^2 distribution (Dalgaard, 2008). A χ^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 χ^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.

Appendix B

The lighting setup was 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 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 cm x 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.

Chapter 4 - Study 3

Vida, M. D., & Maurer, D. (2013). I see what you're saying: voice signals influence children's judgments of direct and averted gaze. *Journal of Experimental Child Psychology, 116*, 609-624.

Gaze and voice cues can provide complimentary information about the focus of a person's visual attention. For example, direct gaze and/or saying a person’s name can signal the intent to communicate, whereas averted gaze and/or an object-directed voice cue (e.g., ‘‘That looks nice!’’) can signal attention toward an object in the environment. The combination of information from voice and gaze cues may facilitate social judgments by allowing individuals to use information from voice cues to interpret ambiguous gaze cues.

In the only previous study investigating the influence of voice cues on judgments of gaze, adults' horizontal cone of gaze was wider when participants heard a voice saying the participant's own name than when the voice said a different person's name (Stoyanova et al., 2010). This pattern could indicate that hearing one's own name increases the width of the cone of gaze, and/or that hearing a different person's name decreases it. Study 2 indicates that, until 8 years of age, children’s horizontal cone of gaze is wider than that of adults.

The purpose of Study 3 was to investigate whether children combine information from gaze and voice cues when making judgments of gaze, and whether the combination allows young children to make more adult-like judgments of gaze. In Experiment 1, 6-year-olds, 8-year-olds, and adults made judgments of gaze while hearing an object-directed voice cue (e.g., ‘‘I see that.’’), a participant-directed voice cue (e.g., ‘‘I see you.’’), or no voice. By including a condition with no voice cues, I was able to assess, for the first time, whether object-directed voice cues, which can be interpreted as indicating that the model is looking at an object in the environment, can decrease the width of children’s cone of gaze, thereby allowing more adult-like judgments of gaze, and whether participant-directed voice cues, which can be interpreted as indicating that the model is looking at the participant, increase the width of the cone of gaze similarly in children and adults. In Experiment 2, I reduced the exposure time for the model’s face to see whether the added uncertainty would alter the effect of voice cues on adults’ judgments of gaze.

The results have implications for real-world social interactions involving children. The finding in Study 2 of a wider cone of gaze in 6-year-olds than in 8-year-olds and adults suggests that when the direction of gaze is the only available cue to the focus of a person’s attention, 6-year-olds will be more likely than older children and adults to infer that a person is paying attention to them when the person is actually attending to something else in the environment. However, a decrease in the width of 6-year-olds' cone of gaze in the presence of a particular voice cue would provide evidence that when relevant gaze and voice cues are present, 6-year-olds will be less likely to make these erroneous social judgments. The results may also provide information about the source of the narrowing of the horizontal cone of gaze between ages 6 and 8 in Study 2. If 6-year-olds' cone of gaze is wider than that of older children and adults solely because visual sensitivity to shifts of gaze is lower in younger children, one might expect that voice cues would not decrease the width of 6-year-olds' cone of gaze. However, if 6-year-olds' wider cone of gaze reflects a difference in interpretation of gaze cues (i.e., decisions about whether gaze is direct or averted when the direction of gaze is ambiguous), one might expect that voice cues could decrease the width of 6-year-olds' cone of gaze by influencing children's interpretation of gaze signals.

Abstract

Adults use gaze and voice signals as cues to the mental and emotional states of others. We examined the influence of voice cues on children's judgments of gaze. In Experiment 1, 6-year-olds, 8-year-olds, and adults viewed photographs of faces fixating the centre of the camera lens and a series of positions to the left and right and judged whether gaze was direct or averted. On each trial, participants heard the participant-directed voice cue (e.g., ‘‘I see you’’), an object-directed voice cue (e.g., ‘‘I see that’’), or no voice. In 6-year-olds, the range of directions of gaze leading to the perception of eye contact (the cone of gaze) was narrower for trials with object-directed voice cues than for trials with participant-directed voice cues or no voice. This effect was absent in 8-year-olds and adults, both of whom had a narrower cone of gaze than 6-yearolds. In Experiment 2, we investigated whether voice cues would influence adults' judgments of gaze when the task was made more difficult by limiting the duration of exposure to the face. Adults' cone of gaze was wider than in Experiment 1, and the effect of voice cues was similar to that observed in 6-year-olds in Experiment 1. Together, the results indicate that object-directed voice cues can decrease the width of the cone of gaze, allowing more adult-like judgments of gaze in young children, and that voice cues may be especially effective when the cone of gaze is wider because of immaturity (Experiment 1) or limited exposure (Experiment 2).

Introduction

The direction of people's gaze provides a cue to the focus of their attention, and thereby allows inferences about their intentions (Baron-Cohen, 1995; Baron-Cohen, Wheelwright, Hill, Raste, & Plumb, 2001; Senju & Johnson, 2009). Direct gaze can signal interest in the viewer, threat, or dominance, whereas averted gaze can signal attention directed toward an object in the environment, deception, or avoidance (Argyle & Cook, 1976; Einav & Hood, 2008; Kendon, 1967). Voice cues can also convey information about a person's attention and/or intention. For example, saying a person's name can signal the intent to communicate (Moray, 1959; Senju & Csibra, 2008), whereas an object-directed voice cue (e.g., "That looks nice!") can signal attention toward an object in the environment (e.g., Parise, Cleveland, Costabile, & Striano, 2007). The combination of information from voice and gaze cues may facilitate social judgments by allowing individuals to use information from voice cues to interpret ambiguous gaze cues. Previous research indicates that children's judgments of direct and averted gaze do not become adult-like until around 8 years of age (Vida & Maurer, 2012a). Here, we asked whether children combine information from gaze and voice cues when making judgments of direct and averted gaze, and whether the combination allows young children to make more adult-like judgments of gaze. We investigated these questions by having 6-, 8-year-olds, and adults judge the direction of gaze in photographs of faces while hearing voice cues implying that the model was looking at the participant (e.g., "I see you."), or at an object in the environment (e.g., "I see that.").

Adults' judgments of direct and averted gaze. Adults can detect horizontal and vertical differences of approximately 1° in the direction of someone else's gaze toward objects in the environment (e.g., Symons, Lee, Cedrone, & Nishimura, 2004; Vida & Maurer, 2012b; 2012c). However, the range of directions of gaze over which adults perceive eye contact (the cone of gaze) is much larger, at approximately 5.5° in width (Gibson & Pick, 1963; Lord & Haith, 1974; Vida & Maurer, 2012a) and 7° in height (Vida & Maurer, 2012a). These values indicate that adults tend to perceive eye contact over a range of directions of gaze corresponding with the width and height of their own face (Vida & Maurer, 2012a). Adults' tendency to perceive eye contact over a relatively large range of directions of someone else's gaze may minimize social costs associated with missing an invitation to interact with someone who is looking toward them.

In the only previous study of the effect of voice cues on judgments of direct and averted gaze, adults viewed faces which had direct gaze or gaze averted in a series of directions to the left and right (Stoyanova, Ewbank, & Calder, 2010). Each face was accompanied by a voice calling the participant's own first name or another person's first name. The cone of gaze was wider when participants heard their own name than when they heard another person's name. Hearing one's own name could signal that someone is directing attention toward oneself, whereas hearing another person's name could signal that someone is attending to another person in the environment. Hence, the effect of voice cues in Stoyanova et al. (2010) could indicate that the cone of gaze becomes wider when participants hear their own name, becomes narrower when participants hear another person's name, or both.

The development of sensitivity to direct and averted gaze. From birth, infants respond preferentially to eye contact, at least when shown faces with direct gaze and gaze averted far to the side. When shown such a pairing, newborns look longer at the face that makes eye contact (Farroni et al., 2002). By 4 months of age, infants not only look but also smile longer at faces with direct gaze (Hains & Muir, 1996; Symons, Hains, & Muir, 1998) and the N240 ERP (event-related potential) is larger for such faces compared to faces with averted gaze (Farroni, Johnson, & Csibra, 2004). The ERP difference may reflect greater cortical processing of faces with direct gaze. By 4-5 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). Together, these results suggest that from early in the first year of life, infants detect and respond selectively to eye contact.

By 3 years of age, children can make explicit judgments about direct and averted gaze when differences in the direction of gaze are large. When shown pairs of faces in which gaze is direct in one face and averted 25° in the other, 3-year-olds, but not 2-year-olds, are able to report which face is making eye contact (Doherty, Anderson, & Howieson, 2009). By 6 years of age, children are sensitive to much smaller differences between direct and averted gaze. In one study, 6-, 8-, 10-, 14-year-olds, and adults viewed photographs of models fixating the centre of a camera lens and a series of positions to the left/right or up/down. The width of the horizontal cone of gaze was over 50% larger in 6-year-olds (8.47°) than in adults (5.49°), and decreased to an adult-like width by 8 years of age (Vida & Maurer, 2012a). The vertical cone of gaze was statistically adult-like by age 6. Thus, 6-year-olds attribute eye contact to a face that is in fact looking within approximately 4.25° to either side of straight ahead (approximately 2° beyond the edge of the child's own face), whereas older children and adults attribute eye contact to a face looking within approximately 2.75° to either side of straight ahead, a range corresponding roughly with the width of the participant's own face. The narrowing of the horizontal cone of gaze between ages 6 and 8 could reduce social costs associated with attributing eye contact when a person's gaze is actually averted (e.g., perceiving others as attempting to establish a social interaction when they are actually looking at another target in the environment). Together, these results suggest that sensitivity to direct and averted gaze is present from birth, but that judgments do not become adult-like until approximately 8 years of age.

Voices influence children’s responses to gaze cues as early as infancy. Voice cues implying that an adult's attention is directed toward the infant versus toward an object influence infants' responses to shifts in the adult’s gaze. For example, at 6 months of age (youngest age tested), infants are more likely to orient in the direction of an adult's averted gaze when hearing infant-directed speech than when hearing adult-directed speech (Senju & Csibra, 2008). At 10-13 months (youngest age tested), infants' response to a novel toy depends on whether or not the adult seen during familiarization looked at, and spoke about, the toy with which the infant was familiarized (Parise, Cleveland, Costabile, & Striano, 2007). At 16-17 months (youngest tested), infants asked to point to the referent of a novel noun choose the object an adult was looking at when they first heard the noun (Baldwin, 1991). Together, these results suggest that sensitivity to combinations of gaze and voice cues is, at least to some degree, present before 2 years of age.

In sum, previous studies indicate that voice cues influence adults' judgments of direct and averted gaze (e.g., Stoyanova et al., 2010), and influence infants' behavioural responses to gaze cues (e.g., Parise et al., 2007). Previous research also indicates that children's sensitivity to direct and averted gaze does not become adult-like until around 8 years of age (Vida & Maurer, 2012a). The purpose of the current study was to investigate whether voice cues modulate children's judgments of direct and averted gaze. In Experiment 1, 6-year-olds, 8-year-olds, and adults made judgments of gaze while hearing an object-directed voice cue (e.g., "I see that."), a participant-directed voice cue (e.g., "I see you."), or no voice. By including a no voice condition, we were able to assess, for the first time, whether object-directed voice cues, which can be interpreted as indicating that the model is looking at an object in the environment, can decrease the width of children's cone of gaze, thereby allowing more adult-like judgments of gaze, and whether participant-directed voice cues, which can be interpreted as indicating that the model is looking at the participant, increase the width of the cone of gaze similarly in children and adults. In Experiment 2, we reduced the exposure time for the model's face to see if the added uncertainty would alter the effect of voice cues on adults' judgments of gaze.

Experiment 1

In Experiment 1, we investigated whether voice cues modulate children's judgments of direct and averted gaze in the age period when the cone of gaze is decreasing to an adult size (between ages 6 and 8) (Vida & Maurer, 2012a). Specifically, 6-year-olds, 8-year-olds, and adults viewed photographs of faces fixating the centre of the camera lens and a series of positions to the left and right, and pressed a button to indicate whether the model's gaze was direct or averted toward one of two identical toy jewels placed to the left and right of the model's face. As each face was presented, participants heard an object-directed voice, participant-directed voice, or no voice. We compared the width of the cone of gaze among the three voice conditions to see if it was smaller for the object-directed condition and/or larger for the participant-directed condition.

Method.

Participants. Participants were English-speaking 6-year-olds (6 years, 6 months ± 3 months, *M* = 6.52 years, 11 female), 8-year-olds (8 years, 6 months ± 3 months, *M* =

8.51 years, 15 female), and adults (18-24 years, *M* = 20.30 years, 17 female) (*n* = 24/group). 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 child's birth. All participants were visually screened and had normal or corrected-to-normal vision. Adults and 8-year-olds were required to have at least 20/20 letter acuity on the Lighthouse eye chart and normal stereoacuity as measured by the Randot test. The 6-year-olds met the same stereoacuity criterion, but the acuity criterion was relaxed to 20/25 because acuity is still improving in this age range (Adams & Courage, 2002; Ellemberg, Lewis, Liu, & Maurer, 1999). An additional two children were tested, but were replaced because they failed visual screening (one 8-year-old), or because their response curves were so broad that we were unable to estimate the width of the cone of gaze in at least one voice condition (one 6-year-old) (see Results for description of this measure).

Stimuli.

Faces. All face stimuli came from the stimulus set used in Vida and Maurer (2012a). Stimuli were full-colour digital photographs of adults with a neutral expression fixating the middle of the camera lens and a series of positions ranging from 1.6° to 8.0° to the left and right, in increments of 1.6° (see Figure 1). The stimulus set included three male and three female models (all Caucasian). All facial images were displayed at life size and at an eye height of 113 cm on a Dell P1130 Trinitron 21 inch monitor set to a resolution of 1152 x 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 computer.

Voices. Voice stimuli were digital audio recordings of four native English-speaking adults (2 male, 2 female) saying phrases implying that they were either looking at the participant (participant-directed voice set) or looking at an object in the environment (object-directed voice set). All voices were recorded with an AT-812 (Audio-Technica, Stow, OH, USA) dynamic microphone and a Duet (Apogee Electronics, Santa Monica, CA, USA) audio interface controlled by an Apple computer running Reaper software (Cockos, San Francisco, CA, USA). Each voice clip was normalized in MATLAB to achieve consistent loudness across clips. Any periods of silence at the beginning and/or end of each voice clip were removed in MATLAB.

Speakers were instructed to use an enthusiastic, positive-sounding tone of voice for all phrases. There were six phrases in each set. The following phrases were included in the participant-directed voice set: “Hello.”, “Hi there.”, “You’re good.”, “You’re nice.”, “You’re super.”, and “I see you.”. The following phrases were included in the object-directed voice set: “That’s nice.”, “That’s good.”, “That’s cool.", “What’s that?”, “That’s shiny.”, and “I see that.”. In each set, four phrases had two syllables and two phrases had three syllables. An independent-samples t-test indicated that there was no difference in duration between the participant-directed (M = 1039.02 ms, SD = 268.24) and object-directed (M = 1063.46 ms, SD = 156.60) stimuli, $p > .7$. Voices were presented at a typical conversational level (approximately 60 dB) through a pair of Reveal Digital Series 80-watt desktop speakers placed 30 cm to the left and right of the computer monitor.

Apparatus. Participants were positioned 150 cm in front of the computer monitor and speakers. Participants used a chin rest to maintain a consistent head position and an eye height of 113 cm (the eye height of the model) above the floor. Two identical plastic toy jewels, 3 cm in diameter, were mounted on narrow wooden boards and were positioned 58 cm from the participant (92 cm from the monitor), at a height of 113 cm (the eye height of the model and participant). The jewels were placed 4.5 cm to either side of midline (9 cm apart). From the participant's position, the jewels appeared to the left and right of the model's face.

Participants entered responses on a computer keyboard placed on a table directly in front of them. 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 a red circle taped over the top to respond to catch trials (see Design section for description). The experimenter used an additional computer keyboard to advance the experiment.

Design. Each participant completed a test block in which he or she judged the direction of gaze in the face of a single model. 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 four times in test trials and four times in practice trials across the participants in a given age group.

The practice block consisted of 12 trials, with the model fixating the centre of the camera lens (4 trials) and the points farthest away from centre (four trials at 8.0° left and four trials at 8.0° right), presented in a 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 three attempts to reach a criterion of 75% accuracy. All 8-year-olds and adults, and 22 6-year-olds, reached criterion on the first attempt. Two 6-year-olds required a second attempt to reach criterion. No voices were presented during the practice block.

In the test block, for each voice condition, participants viewed the face of one of six models fixating the camera lens and a series of 11 positions covering a range from 8.0° left to 8.0° right, in steps of 1.6°. Each participant completed eight trials at each fixation position, for a total of 88 trials per voice condition. In the no voice condition, no sound was presented. In the object-directed and participant-directed voice conditions, on each trial, participants heard the voice of a person matching the sex of the face. For each participant, the identity of the speaker was randomly selected from among two speakers of the appropriate sex. Each participant saw the same model's face and heard the same model's voice on each trial. On each trial, the voice clip to be presented was randomly selected from among six voice clips in the appropriate set. Trials from the three voice conditions were intermixed and presented in a random order, with the constraint that the same voice cue was not presented on consecutive trials. Participants received breaks after 88 and 164 trials. To assess attentiveness, we included five catch trials that appeared at random positions within each set of 88 trials, with the constraint that catch trials were never fewer than five trials apart. In each catch trial, a cartoon image of rocks appeared on the screen. Participants were instructed to press a button to sound an alarm when they saw this image. During the test block, participants received general encouragement but no trial-specific feedback.

Procedure. After the procedure was explained, written consent was obtained from a parent of each child participant, and verbal assent was also obtained from 8-year-olds. After positioning each participant appropriately in the apparatus, the experimenter displayed a photograph of the model that would appear in the practice block. The experimenter explained the task as follows (with appropriate adjustments if the model was male):

This is Jenny. She is an explorer who loves to search for buried treasure!

After pressing a key to present a cartoon image of the inside of a cave, the experimenter continued:

Jenny has been searching for treasure deep in this cave, and now she is lost! To find her way out of the cave, she has to look at you and follow you. The problem is that there are some treasures in the cave, like these jewels. Jenny loves jewels, and she always wants to stop and look at them when she notices them. If Jenny is looking at the jewels instead of looking at you, she could get lost. Your job will be to help Jenny stay on course by watching her face carefully and deciding if she is looking at you or away from you toward one of the jewels. If you think Jenny is looking at you, press this button [experimenter points to blue button]. *If she is looking away from you, toward this jewel* [points to left jewel]*, press this button* [points to left arrow]. *If she is looking away from you, toward this jewel* [points to right jewel]*, press this button* [points to right arrow].

The experimenter then initiated practice trials. Once the participant reached criterion, the experimenter introduced the model to be presented in the test block, then delivered the following instruction:

This is James. Like Jenny, he is an explorer who is lost in the cave. We're going to help James find his way out the cave, just like we did with Jenny.

The experimenter then pressed a button to display a photograph of rocks, and delivered the following instruction:

James is lost in a part of a cave that has lots of rocks. If you see rocks like these, you can sound an alarm to warn James so that he doesn't trip on the rocks. To sound the alarm, press this button [experimenter points to red button]. *Also, James loves to talk, so you'll hear him saying lots of different things. Try to ignore what he says, and just pay attention to where he is looking.*

At the start of each test trial, a black fixation cross appeared at the centre of the screen. When the participant appeared to fixate the cross, the experimenter, who could see the participant but not the monitor with the face stimuli, pressed a key to present a photograph of the model's face accompanied, if applicable, by a clip of the speaker's voice. The face remained on the screen until the voice clip had finished playing and the participant had entered an appropriate response. Participants typically completed the entire procedure in approximately 30 minutes.

Results.

Accuracy on catch trials. Accuracy on catch trials was very high in each group (6-year-olds: $M = .99$, $SD = .02$; 8-year-olds: $M = .99$, $SD = .03$; adults: $M = .99$, $SD = .01$). Since the group means were identical and near ceiling, we did not carry out statistical analyses to evaluate group differences for these data. The high accuracy in each age group suggests that participants in all age groups were attentive throughout the procedure.

Curve fitting. For each participant, we calculated the proportion of the eight trials at each fixation position on which the model was judged to be looking directly toward the participant, left, or right (see Figure 2). To quantify sensitivity to direct and averted gaze, as in Vida and Maurer (2012a), we fit logistic functions relating each participant's proportions of left and right responses to the fixation positions. All fits were carried out using the glmfit routines from the Statistics Toolbox in MATLAB. The sum of the left and right 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 Vida and Maurer (2012a) for all fits. Following Vida and Maurer (2012a), we calculated the width of the cone of gaze as the difference (in degrees) between the points of intersection between the fitted direct function and the fitted left and 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 width of the cone of gaze.

Width of the cone of gaze. We carried out an age (six, eight, adult) by voice condition (no voice, participant-directed voice, object-directed voice) mixed ANOVA with the width of the cone of gaze as the dependent variable (see Figure 3). There were main effects of age, $F(2, 69) = 10.40$, $p < .001$, $\eta_p^2 = .23$, and voice condition, $F(2, 138) = 6.52$, $p < .005$, $\eta_p^2 = .09$. There was also a significant interaction between age and voice condition, $F(4, 138) = 3.49$, $p < .02$, $\eta_p^2 = .09$.

We followed up the age by voice condition interaction with repeated-measures ANOVAs evaluating the simple main effect of voice condition in each age group. There was a simple effect of voice condition in 6-year-olds, $F(2, 46) = 8.41$, $p < .002$, $\eta_p^2 = .27$, but not in 8-year-olds, $p > .5$, or adults, $p > .9$. We followed up the simple main effect of voice condition in 6-year-olds with Holm-Bonferroni-corrected (Holm, 1979) paired-samples t-tests comparing the width of 6-year-olds' cone of gaze between each possible pair of voice conditions. Six-year-olds' cone of gaze was significantly narrower in the object-directed voice condition ($M = 7.64°$, $SD = 2.53$) than in the participant-directed voice condition ($M = 8.69°$, $SD = 2.40$), $t(23) = 4.71$, $p < .001$, $\alpha = .017$, $d = .43$, and the no voice condition ($M = 8.57°$, $SD = 2.98$), $t(23) = 3.26$, $p < .005$, $\alpha = .025$, $d = .34$. However, 6-year-olds' cone of gaze did not differ between the no voice condition and the participant-directed voice condition, $p > .7$. In light of previous research indicating that 6-year-olds' cone of gaze is wider than that of adults, but reaches an adult-like width by age 8 (Vida & Maurer, 2012a), we also investigated whether there was an effect of age on the width of the cone of gaze in each voice condition. We carried out one-way ANOVAs evaluating the simple main effect of age for each voice condition. For each voice condition, there was an effect of age, ps $< .01$, η_p^2s $> .1$. In each voice condition, a Dunnett's post-hoc comparing the width of cone of gaze of 6- and 8-year-olds to that of adults indicated that the cone of gaze was significantly narrower in adults than in 6-year-olds, *p*s < .005, with no differences between adults and 8-year-olds, *p*s > .2.

Effect of voice cues on the proportions of 'direct' and 'averted' responses in 6-year-olds. Our finding that 6-year-olds' cone of gaze was narrower in the object-directed voice condition than in the other voice conditions could reflect a general tendency to avoid attributing eye contact when hearing an object-directed voice cue, regardless of the direction of the model's gaze, that is, for unambiguous direct gaze, and for shifts of gaze to the sides, regardless of size. We conducted three analyses to evaluate this possibility. The first analysis arises from the prediction that any such general tendency to avoid reporting eye contact would lead to a lower frequency of 'direct' responses for faces with straight gaze (i.e., images in which the model was fixating the centre of the camera lens) in the object-directed voice condition than in the other voice conditions. To evaluate this prediction, we calculated the proportion of each 6-year-old participant's 'direct' responses for straight gaze in each voice condition. We then carried out a repeated-measures ANOVA with voice condition as the independent variable and the proportion of direct gaze responses for straight gaze as the dependent variable. There was no effect of voice condition, $p > .75$, a result suggesting that the observed effect of voice condition on 6-year-olds' cone of gaze does not reflect a general tendency to avoid attributing eye contact when hearing object-directed voice cues.

Two additional analyses arose from the prediction that a general tendency to avoid attributing eye contact when hearing an object-directed voice cue could lead participants to enter more 'averted' responses, in both the unexpected (e.g., responding 'left' when gaze is directed to the right) directions, and expected (e.g., responding 'right' when the model's gaze is directed to the right) directions, and to do so regardless of the deviation of gaze. To evaluate this possibility, we calculated the proportions of 6-year-olds' 'averted' responses in the unexpected and expected directions for each deviation of gaze from direct and each voice condition. We carried out a repeated-measures ANOVA with deviation of gaze from direct (1.6°, 3.2°, 4.8°, 6.4°, 8.0°) and voice condition as independent variables, and the proportion of responses in the unexpected direction as the dependent variable. There was a significant effect of deviation of gaze, $F(4, 92) = 3.96$, $p < .006$, $\eta_p^2 = .15$, which indicates that the proportion of responses in the unexpected direction decreased with increasing deviations of gaze from direct, but there was no effect of voice condition and no interaction, ps > .2. This result indicates that 6-year-olds were sensitive to the deviations in eye gaze. However, the sensitivity of this analysis may have been limited because the proportion of responses in the unexpected direction was at or near zero for larger deviations of gaze from direct. Inspection of Figure 2 confirms that there was no clear trend toward a difference between voice conditions in the proportion of responses in the unexpected direction. We carried out a similar ANOVA with the proportion of responses in the expected direction as the dependent variable. There was an effect of deviation of gaze, $F(4, 92) = 225.55$, $p < .001$, $\eta_p^2 = .91$, which indicates that the proportion of responses in the expected direction increased with the deviation of gaze from direct (see Figure 2), as would be expected if the responses reflect processing of the eye gaze cue, not just the voice. There was also an effect of voice condition, $F(2, 46) = 6.76$, $p < .004$, $\eta_p^2 = .23$. There was no interaction, $p > .35$. We followed up the effect of voice condition with Holm-Bonferroni-corrected paired-samples t-tests comparing the proportion of responses in the expected direction between each pair of voice conditions. There was no difference between the no voice condition ($M = .55$, $SD = .15$) and the participant-directed voice condition ($M = .55$, $SD = .12$), $p > .80$. However, the proportion of responses in the expected direction was higher in the object-directed voice condition ($M = .59$, $SD = .13$) than in the no voice condition, $t(23) = 3.43$, $p < .003$, $\alpha = .017$, $d = .28$, and the self-directed voice condition, $t(23) = 3.35$, $p < .004$, $\alpha = .02$, $d = .32$. Our finding that object-directed voice cues lead to more attributions of averted gaze in the expected direction when gaze was in fact averted to the side (e.g., responding 'right' when gaze was in fact averted to the right), with no effect on attributions of averted gaze in the unexpected direction (e.g., responding 'left' when gaze is in fact averted to the right), is consistent with our finding in the main analysis of a narrower cone of gaze in the object-directed voice condition. In conjunction with our finding of no effect of voice cues on the proportion of 'direct' responses to straight gaze, this pattern suggests that the narrower cone of gaze in the object-directed voice condition does not reflect a general tendency to avoid attributing eye contact, regardless of the direction of gaze. Rather, it appears to reflect an increased tendency to perceive averted gaze in the expected direction, when gaze is actually averted.

Slope of response curves. An additional question is whether voice cues and age influence the steepness of the transition between 'direct' and 'averted' responses. To investigate this question, we examined the slope parameter of the logistic functions fit to 'averted' responses. A larger slope parameter indicates a steeper transition between 'direct' and 'averted' responses.

We carried out a mixed ANOVA with voice condition and age as independent variables and slope as the dependent variable. There was a significant effect of age, $F(2, 69) = 21.58$, $p < .0001$, $\eta_p^2 = .38$, with no effect of voice condition and no interaction, *p*s > .35. A Dunnett's post-hoc indicated that the slope was shallower in both 6-year-olds ($M = 1.88$, $SD = 1.95$) and 8-year-olds ($M = 2.52$, $SD = 2.33$) than in adults ($M = 7.57$, $SD = 4.81$), *p*s < .001. Hence, voice cues did not influence the steepness of the transition between 'direct' and 'averted' responses, but the transition became steeper after age 8.

Discussion. The current results provide the first information on the influence of voice cues on children’s sensitivity to directed and averted gaze. Voice cues affected judgments of gaze in 6-year-olds, but not in 8-year-olds or adults. Six-year-olds’ cone of gaze was narrower when they heard a voice cue implying that the model was looking at an object in the environment (e.g., “I see that”) (7.64°) than when they heard a voice cue implying that the model was looking at the participant (8.69°), or when no voice was presented (8.57°), with no difference between the latter two. Follow up analyses indicated that the narrower cone of gaze in the object-directed voice condition does not reflect a general tendency to avoid attributing eye contact or a change in the slope of the fitted curves, but instead reflects an increased tendency to perceive averted gaze in the expected direction when gaze is actually averted. Although 6-year-olds' cone of gaze was narrower in the object-directed voice condition than in the other voice conditions, their cone of gaze was nevertheless wider than that of 8-year-olds and adults in every voice condition.

Our finding that object-directed voice cues lead to a narrower cone of gaze in 6-year-olds suggests that 6-year-olds combine information from gaze and voice cues when making judgments of eye gaze. Importantly, our results also suggest that combining information from gaze and voice cues can allow 6-year-olds, in whom judgments of direct and averted gaze are not yet adult-like (Vida & Maurer, 2012a), to make more adult-like judgments of gaze. Without a voice cue, 6-year-olds judged that the model was looking directly at them when gaze was in fact within approximately 4.25° to either side of straight ahead (approximately 2° beyond the edge of the participant's face). This pattern was not observed in 8-year-olds and adults, who attributed eye contact within a range corresponding roughly with the width of the participant's own face. With the object-directed voice cues, 6-year-olds perceived eye contact within approximately 3.8° to either side of straight ahead (approximately 1.5° beyond the edge of the participant's face).

We were surprised that voice cues had no effect on the cone of gaze in the two older groups, despite previous evidence that hearing one's own name rather than a different name increases the width of adults' cone of gaze (Stoyanova et al., 2010). It is possible that object-directed voice cues exert a stronger effect in young children because, unlike adults, children tend to weight auditory cues more strongly than visual cues when both are present (e.g., Sloutsky & Napolitano, 2003). However, it is also possible that the effect is not limited to young children, but is instead linked to the amount of uncertainty in participants' judgments of gaze. In cross-modal tasks, signals in an irrelevant modality exert a stronger influence when signals in the target modality are degraded or ambiguous (e.g., Collignon et al., 2008; de Gelder & Vroomen, 2000). Although the boundaries of the cone of gaze are, by definition, located at the position where the participant is most uncertain about whether gaze is direct or averted, the distance of the boundaries from straight gaze may reflect general differences in participants' certainty about the direction of gaze. Reducing adults' ability to discriminate between direct and averted gaze by decreasing the brightness of the stimulus leads to a stronger bias to perceive direct gaze when gaze is actually averted (e.g., Martin & Rovira, 1981). Similarly, adults are less accurate in discriminating between leftward and rightward gaze for inverted faces than for upright faces (e.g., Jenkins & Langton, 2003; Schwaninger, Lobmaier, & Fischer, 2005), and their cone of gaze is wider for inverted faces (Vida et al., 2013). Hence, the wider cone of gaze in 6-year-olds than in 8-year-olds and adults in the current experiment, and in previous research (Vida & Maurer, 2012a), may reflect greater uncertainty about the direction of gaze in 6-year-olds. Voice cues may have influenced judgments of gaze in 6-year-olds, but not in older children and adults, because 6-year-olds were more uncertain about the direction of gaze.

Another possible contributor to age differences in the effect of voice cues is the spatial relation between the boundaries of the cone of gaze and the edges of the participant's face. By age 8, the width and height of the cone of gaze correspond roughly to the width and height of the participant's own face, a pattern suggesting that the boundaries of the cone of gaze may be calibrated to match the dimensions of the participant's own face (Vida & Maurer, 2012a). This calibration may set a lower limit for the size of the cone of gaze, so that, under typical viewing conditions, the cone of gaze is unlikely to be narrower than the participant's face. Hence, object-directed voice cues may not have decreased the width of the cone of gaze in 8-year-olds and adults because the width of their cone of gaze was at the minimum value in the absence of voice cues. Since 6-year-olds' cone of gaze was much wider than their own face and that of 8-year-olds and adults, there may have been more room for 6-year-olds' judgments to be influenced by an informative voice cue.

Experiment 2

In Experiment 2, we attempted to increase adults' uncertainty, and consequently, the width of their cone of gaze, by having the face disappear after 600 ms rather than having it remain until the participant responded, as it did in Experiment 1. We expected that increasing adults' uncertainty and/or the width of their cone of gaze would lead to greater influence of voice cues on judgments of gaze.

Method.

Participants. Participants were 24 adults (18-27 years, *M* = 21.14 years, 17 female) not tested in Experiment 1, who met the same visual screening criteria as adults in Experiment 1. One additional participant was tested, but was excluded and replaced because the participant was obviously inattentive during the procedure.

Design and procedure. The design and procedure were the same as in Experiment 1, except that each face was replaced by a blank screen 600 ms after onset instead of remaining visible until the participant entered a response.

Results.

Accuracy on catch trials. Accuracy on catch trials was very high (*M* = .98, *SD* = .06), a result suggesting that participants were attentive throughout the procedure.

Width of the cone of gaze. For each participant, we used the method described in Experiment 1 to estimate the width of the cone of gaze in each voice condition (see Figure 4 and Figure 5). To examine the effect of limiting the duration of exposure on adults' sensitivity to direct and averted gaze, we carried out a planned one-tailed independent-samples t-test evaluating the specific hypothesis that adults' cone of gaze was wider in the no voice condition of Experiment 2 than in the no voice condition in

Experiment 1. The cone of gaze was marginally significantly wider in Experiment 2 (*M* = 6.44°, *SD* = 1.97) than in Experiment 1 (*M* = 5.71°, *SD* = 1.38), $t(46) = 1.48$, $p = .07$, $d = .42$. This pattern is consistent with previous findings that when uncertainty about the difference between direct and averted gaze is higher, adults show a stronger bias to perceive eye contact when gaze is actually averted (Martin & Rovira, 1981; Vida et al., 2013).

We carried out a repeated-measures ANOVA with voice condition as the independent variable and the width of the cone of gaze as the dependent variable. There was a significant effect of voice condition, $F(2, 46) = 5.40$, $p < .01$, $\eta_p^2 = .19$. We followed up this effect with Holm-Bonferroni-corrected (Holm, 1979) paired-samples t-tests evaluating all pair-wise differences among voice conditions. In the object-directed voice condition, the cone of gaze was significantly narrower (*M* = 5.81°, SD = 1.94) than in the no voice condition (*M* = 6.44°, *SD* = 1.97), $t(23) = 3.21$, $p < .004$, $\alpha = .017$, $d = .33$, and was marginally significantly narrower than in the participant-directed condition (*M* = 6.15°, *SD* = 1.92), $t(23) = 2.11$, $p = .04$, $\alpha = .025$, $d = .18$. There was no difference in the width of the cone of gaze between the no voice and participant-directed voice conditions, $p > .2$. Hence, the effect of voice condition was qualitatively similar to that observed in 6-year-olds in Experiment 1.

Effect of voice cues on the proportions of 'direct' and 'averted' responses. We used the methods described in Experiment 1 to investigate whether the narrower cone of gaze in the object-directed voice condition could reflect a general tendency to avoid attributing eye contact when hearing those voice cues, regardless of the direction of gaze. We first asked whether voice condition affected the proportion of 'direct' responses for unambiguous straight gaze. There was no effect of voice condition, $p > .55$. We also asked whether voice condition affected the proportions of 'averted' responses in the unexpected and expected directions for each deviation of gaze from direct. We carried out a repeated-measures ANOVA with deviation of gaze and voice condition as independent variables and the proportion of 'averted' responses in the unexpected direction as the dependent variable. There were no effects of gaze or voice condition, and there was no interaction, *p*s > .3. The proportion of responses in the unexpected direction was at or near zero for most deviations of gaze from direct, a pattern that may have limited the sensitivity of our analyses. Inspection of Figure 4 confirms that there was no clear trend toward a difference between voice conditions in the proportion of responses in the unexpected direction. We carried out an additional ANOVA with the proportion of 'averted' responses in the expected direction as the dependent variable. There were effects of deviation of gaze, $F(4, 92) = 191.97$, $p < .001$, $\eta_p^2 = .89$, and voice condition, $F(2, 46) = 5.17$, $p < .01$, $\eta_p^2 = .69$, but no interaction, $p > .1$. We followed up the effect of voice condition with Holm-Bonferroni-corrected paired-samples t-tests comparing the proportion of averted responses in the expected direction between each pair of voice conditions. There was no difference between the no voice ($M = .70$, $SD = .12$) and participant-directed ($M = .71$, SD

= .13) conditions, $p > .6$. However, the proportion of responses in the expected direction was higher in the object-directed voice condition ($M = .74$, $SD = .12$) than in the no voice condition, $t(23) = 3.13$, $p < .006$, $\alpha = .017$, $d = .33$, and the participant-directed voice condition, $t(23) = 2.56$, $p < .02$, $\alpha = .02$, $d = .32$. Together, these results suggest that, as in 6-year-olds in Experiment 1, the effect of object-directed voice cues in the current experiment does not reflect a general tendency to avoid attributing eye contact.

Slope of response curves. We used the methods described in Experiment 1 to investigate whether voice cues influenced the steepness of the transition between 'direct' and 'averted' responses. We carried out a repeated-measures ANOVA with voice condition as the independent variable and slope as the dependent variable. There was no effect of voice condition, $p > .8$. Hence, as in Experiment 1, voice cues did not influence the steepness of the transition between 'direct' and 'averted' responses.

Discussion. Adults' cone of gaze in the no voice condition in the current experiment (6.44°) was slightly wider than that of adults in the no voice condition in Experiment 1 (5.71°), a result suggesting that limiting the duration of exposure to faces increased adults uncertainty about the direction of gaze. Unlike adults in Experiment 1, adults' cone of gaze in the current experiment was narrower in the object-directed voice condition (5.81°) than in the no voice (6.44°) and participant-directed voice conditions (6.15°), with no difference between the latter two. Follow up analyses indicated that the effect of object-directed voice cues does not reflect a general tendency to avoid attributing direct gaze, but instead reflects an increased tendency to perceive averted gaze in the expected direction when gaze is actually averted. Follow up analyses also indicated that voice cues did not influence the steepness of the transition between 'direct' and 'averted' responses. This pattern is identical to that found in 6-year-olds in Experiment 1 with unlimited exposure time.

General Discussion

The current study provides the first information on the influence of voice cues on children's judgments of direct and averted gaze. In Experiment 1, voice cues affected the width of the cone of gaze in 6-year-olds, but not in 8-year-olds or adults. Six-year-olds' cone of gaze was narrower when they heard an object-directed voice cue (e.g., "I see that.") than when they heard a participant-directed voice cue (e.g., "I see you."), or no voice, with no difference between the latter two. In Experiment 2, adults' judgments of gaze were made more difficult by limiting the duration of exposure to the face. Adults' cone of gaze tended to be wider than in Experiment 1, and the effect of voice cues on adults' judgments of gaze was the same as in 6-year-olds in Experiment 1.

In the current study, object-directed voice cues affected judgments of eye gaze in 6-year-olds, but not in older participants, when the task was relatively easy (Experiment 1), and affected adults' judgments when the task was more difficult (Experiment 2). This pattern suggests that the effect of object-directed voice cues may be related to participants' uncertainty about the difference between direct and averted gaze, so that the effect will tend to be larger when uncertainty is higher, whether the uncertainty is caused by immaturity or limited exposure. This interpretation is consistent with previous findings from adults that a cue in an irrelevant modality has a larger influence when the target stimulus is degraded or ambiguous (e.g., Collignon et al., 2008). The current results are also consistent with the possibility that the minimum width of the cone of gaze is limited by the size of the participant's own face (see Vida & Maurer, 2012a), so that voice cues are likely to decrease the width of the cone of gaze only when it is wider than the participant's face in the absence of voice cues, as in 6-year-olds in Experiment 1, and adults in Experiment 2. Together, the results of Experiments 1 and 2 suggest that both adults and children as young as 6 combine information from gaze and object-directed voice cues when making judgments of eye gaze, and that this ability can lead to a narrowing of the cone of gaze, thereby allowing more adult-like judgments of gaze in young children.

Children's ability to combine information from gaze and voice cues has implications for understanding the development of real-world social cognition. The finding in the current study and in previous research (Vida & Maurer, 2012a) of a wider cone of gaze in 6-year-olds than in 8-year-olds and adults suggests that when the direction of gaze is the only available cue to the focus of a person's attention, 6-year-olds will be more likely than older children and adults to make errors in social judgments.

Specifically, 6-year-olds may be more likely to infer that a person is paying attention to the child when the person is actually attending to something else in the environment. However, the current results suggest that when both gaze and object-directed voice cues are present, 6-year-olds will be less likely to make these erroneous social judgments.

The observed influence of voice cues on children's judgments of eye gaze could also play a role in developmental changes in judgments of gaze. The cone of gaze narrows considerably between 6 and 8 years (Vida & Maurer, 2012a), a change that may reflect the accumulation of experience with the social and visual properties of gaze cues. Our results suggest that voice cues could facilitate this development by allowing the child to make more adult-like judgments and/or providing feedback about whether the child made the appropriate interpretation. Individual differences in exposure to such cues might also lead to individual differences in the speed of acquiring adult-like sensitivity to direct and averted gaze.

One remaining question is why the participant-directed voice cues (e.g., “I see you.”) did not lead to a wider cone of gaze than observed in the no voice condition at any age. This is especially surprising because a previous study reported that adults' cone of gaze is larger when they hear their own, rather than someone else’s name (Stoyanova et al., 2010). However, the absence of a no voice condition in that study makes it impossible to distinguish a widening of the cone of gaze when hearing one’s own name from a narrowing of the cone of gaze when hearing another person’s name. One possibility is that participant-directed voice cues are effective only if they are personalized (e.g., the participant’s first name). Future research could investigate this possibility by having participants make judgments of gaze while hearing someone calling the participant's own name, another name, or no name at all.

The current results leave several additional questions open for future research. For example, since voice cues affected judgments of eye gaze in 6-year-olds, the youngest age group able to complete the current procedure, the current results do not indicate when in development the effect of voice cues emerges. Future studies could investigate this question by testing children younger than 6 years with a modified version of our procedure. In addition, it is possible that we would have observed a different effect of voice condition if we had used a baseline condition including voice cues that provide no information about the focus of a person's attention (e.g., nonsense speech or speech in a language foreign to the participant). The mere presence of a voice could influence judgments of gaze by alerting or distracting participants. Future studies could investigate these possibilities by replicating the current study with a baseline condition including a voice cue that provides no information about the focus of a person's attention. Finally, since all speakers in the current study used a positive-sounding tone of voice, the current results do not indicate whether variations in the affective properties of voices could influence judgments of gaze. Previous research indicates that the cone of gaze of both adults (Ewbank, Jennings, & Calder, 2009) and 8-year-olds (Rhodes, Addison, Jeffery, Ewbank & Calder, 2012), is wider for angry faces than for fearful or neutral faces, with no difference between the latter two. Future studies could investigate whether the emotional prosody of a voice exerts a similar influence on children's and adults' judgments of gaze.

Conclusions. The current investigation has provided the first information on the influence of voice cues on children’s judgments of the direction of gaze. Our results suggest that both children and adults combine information from gaze and voice cues when making judgments of eye gaze, and that voice cues may be especially effective when the cone of gaze is wider because of immaturity or limited exposure to the face stimulus. Importantly, our results also suggest that the ability to combine information from gaze and voice cues may allow young children to make more adult-like judgments about others' attention and intention than they are able to make in the absence of relevant voice cues.

References

Adams, R. A., & Courage, M. L. (2002). Using a single test to measure human contrast sensitivity from early childhood to maturity. *Vision Research, 42*, 1205-1210.

Argyle, M., & Cook, M. (1976). *Gaze and mutual gaze*. New York: Cambridge University Press.

Baldwin, D. A. (1991). Infants' contribution to the achievement of joint reference. *Child Development, 63*, 875-890.

Baron-Cohen, S. (1995). *The eye direction detector (EDD) and the shared attention mechanism (SAM): Two cases for evolutionary psychology*. In C. Moore & P. J. Dunham (Eds.), Joint attention: Its origins and role in development (pp. 41-59). Hillsdale, NJ: Lawrence Erlbaum.

Baron-Cohen, S., Wheelwright, S., Hill, J., Raste, Y., & Plumb, I. (2001). The reading the mind in the eyes test revised version: A study with normal adults, and adults with Asperger syndrome or high-functioning autism. *Journal of Child Psychology and Psychiatry, 42*, 241-251.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.

Collignon, O., Girard, S., Gosselin, F., Roy, S., Saint-Amour, D., Lassonde, M., & Lepore, F. (2008). Audio-visual integration of emotion expression. *Brain Research, 1242*, 126-135.

de Gelder, B., & Vroomen, J. (2000). The perception of emotions by ear and by eye.

Cognition & Emotion, 14, 289-311.

Doherty, M. J., Anderson, J. R., & Howieson, L. (2009). The rapid development of gaze judgment ability at 3 years. *Journal of Experimental Child Psychology, 104*, 296-312.

Einav, S., & Hood, B. M. (2008). Tell-tale eyes: Children's attribution of gaze aversion as a lying cue. *Developmental Psychology, 44*, 1655-1667.

Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research, 39*, 2325-2333.

Ewbank, M. P., Jennings, C., & Calder, A. (2009). Why are you angry with me? Facial expressions of threat influence perception of gaze direction. *Journal of Vision, 9*, 1-7.

Farroni, T., Csibra, G., Simion, F., & Johnson, M. H. (2002). Eye contact detection in humans from birth. *Proceedings of the National Academy of Sciences, 99*, 9602-9605.

Farroni, T., Mansfield, E. M., Lai, C., & Johnson, M. H. (2003). Infants perceiving and acting on the eyes: Tests of an evolutionary hypothesis. *Journal of Experimental Child Psychology, 85*, 199-212.

Farroni, T., Johnson, M. H., & Csibra, G. (2004). Mechanisms of eye gaze perception during infancy. *Journal of Cognitive Neuroscience, 16*, 1320-1326.

Gibson, J. T., & Pick, A. D. (1963). Perception of another person's looking behavior.

American Journal of Psychology, 76, 386-394.

Hains, S. M. J., & Muir, D. W. (1996). Infant sensitivity to adult eye direction information. *Child Development*, *67*, 1940-1951.

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, *6*, 65-70.

Jenkins, J., & Langton, R. H. (2003). Configural processing in the perception of eye-gaze direction. *Perception*, *32*, 1181-1188.

Kendon, A. (1967). Some functions of gaze-direction in social interaction. *Acta Psychologica*, *26*, 22-63.

Lord, C., & Haith, M. M. (1974). The perception of eye contact. *Perception and Psychophysics*, *16*, 413-416.

Martin, W. W., & Rovira, M. L. (1981). *Journal of Nonverbal Behavior, 5*, 155-163.

Maxwell, S. E., & Delaney, H. D. (2004). *Designing experiments and analyzing data: a model comparison perspective.* Lawrence Erlbaum Associates, Mahwah, N.J., 2nd edition.

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology*, *11*, 56-60.

Parise, E., Cleveland, A., Costabile, A., & Striano, T. (2007). Influence of voice cues on learning about objects in joint attention contexts. *Infant Behavior & Development*, *30*, 380-384.

Rhodes, G., Addison, B., Jeffery, L., Ewbank, M., & Calder, A. J. (2012). Facial expressions of threat influence perceived gaze direction in 8-year-olds. *Public Library of Science One, 7,* e49317.

Schwaninger, A., Lobmaier, J. S., & Fischer, M. H. (2005). The inversion effect on gaze perception reflects processing of component information. *Experimental Brain Research, 167*, 49-55.

Senju, A. & Csibra, G. (2008). Gaze following in humans depends on communicative signals. *Current Biology, 18*, 668-671.

Senju, A., & Johnson, M. H. (2009). The eye contact effect: mechanisms and development. *Trends in Cognitive Sciences, 13*, 127-134.

Sloutsky, V. M., & Napolitano, A. C. (2003). Is a picture worth a thousand words? Preference for auditory modality in young children. *Child Development, 74*, 822-833.

Stoyanova, R. S., Ewbank, M. P., Calder, A. J. (2010). "You talkin' to me?": Self-relevant auditory signals influence perception of gaze direction. *Psychological Science, 21*, 1765-1769.

Symons, L., Hains, S. M. J., & Muir, D. W. (1998). Look at me: Five-month-old infants' sensitivity to very small deviations in eye gaze during social interactions. *Infant Behavior and Development, 21*, 531-536.

Symons, L. A., Lee, K., Cedrone, C. C., & Nishimura, M. (2004). What are you looking at? Acuity for triadic eye gaze. *Journal of General Psychology, 131*, 451-469.

Vida, M. D., & Maurer, D. (2012a). The development of fine-grained sensitivity to eye contact after 6 years of age. *Journal of Experimental Child Psychology, 112*, 243-256.

Vida, M. D., & Maurer, D. (2012b). Gradual improvement in fine-grained sensitivity to triadic gaze after 6 years of age. *Journal of Experimental Child Psychology, 111*, 299-318.

Vida, M. D., & Maurer, D. (2012c). Sensitivity to vertical differences in triadic gaze is slow to develop. *Journal of Vision, 12*, 634.

Vida, M. D., Maurer, D., Calder, A. J., Rhodes, G., Walsh, J. A., Pachai, M. V., & Rutherford, M. D. (2013). The influences of face inversion and facial expression on sensitivity to eye contact in high-functioning adults with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 43*, 2536-2548.

Figures

Figure 1

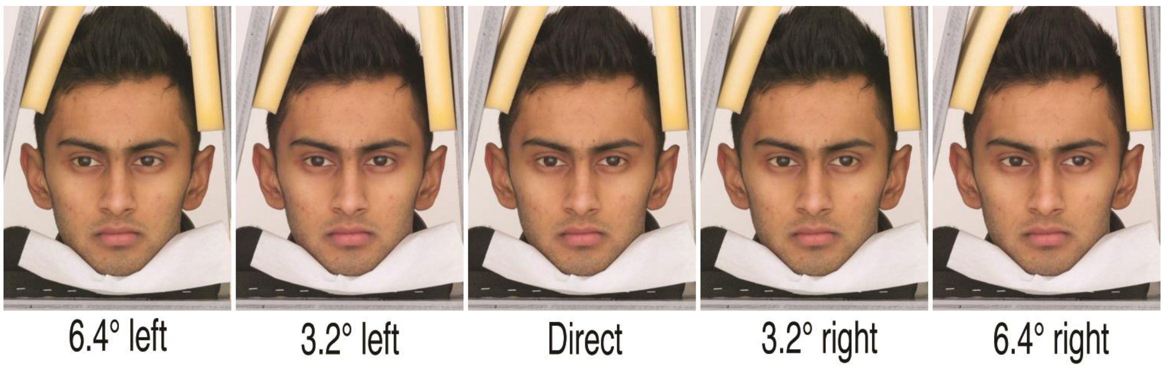


Figure 1. Examples of face stimuli for one of the six models presented in the current study.

Figure 2

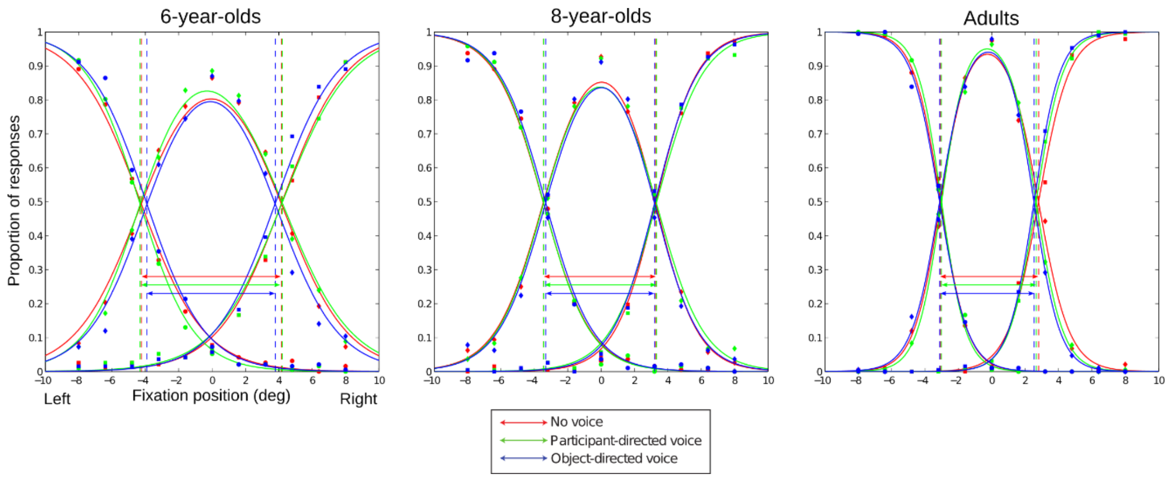


Figure 2. Logistic functions fit to the mean proportion of each response type in Experiment 1 for the no voice (red), participant-directed voice (green), and object-directed voice (blue) conditions. Each plot displays the data for one age group, as a function of the direction of gaze (deg). The axis labels given for 6-year-olds apply to the other age groups. In each plot, each data point represents the mean proportion of a given response type across all participants of that age, for a given voice condition and fixation position (deg). Data points marked with a circle represent 'averted left' responses, whereas diamonds represent 'direct' responses, and squares represent 'averted right' responses. The curves to the left in each plot fit 'averted left' responses, the curves in the centre fit 'direct' responses, and the curves to the right fit 'averted right' responses. The dashed vertical lines show the crossover points between the 'direct' curve and the 'left' and 'right' curves. The horizontal arrows represent the width of the cone of gaze. Curves, data points, dashed lines, and arrows are coloured by voice condition, according to the colours shown in the legend.

Figure 3

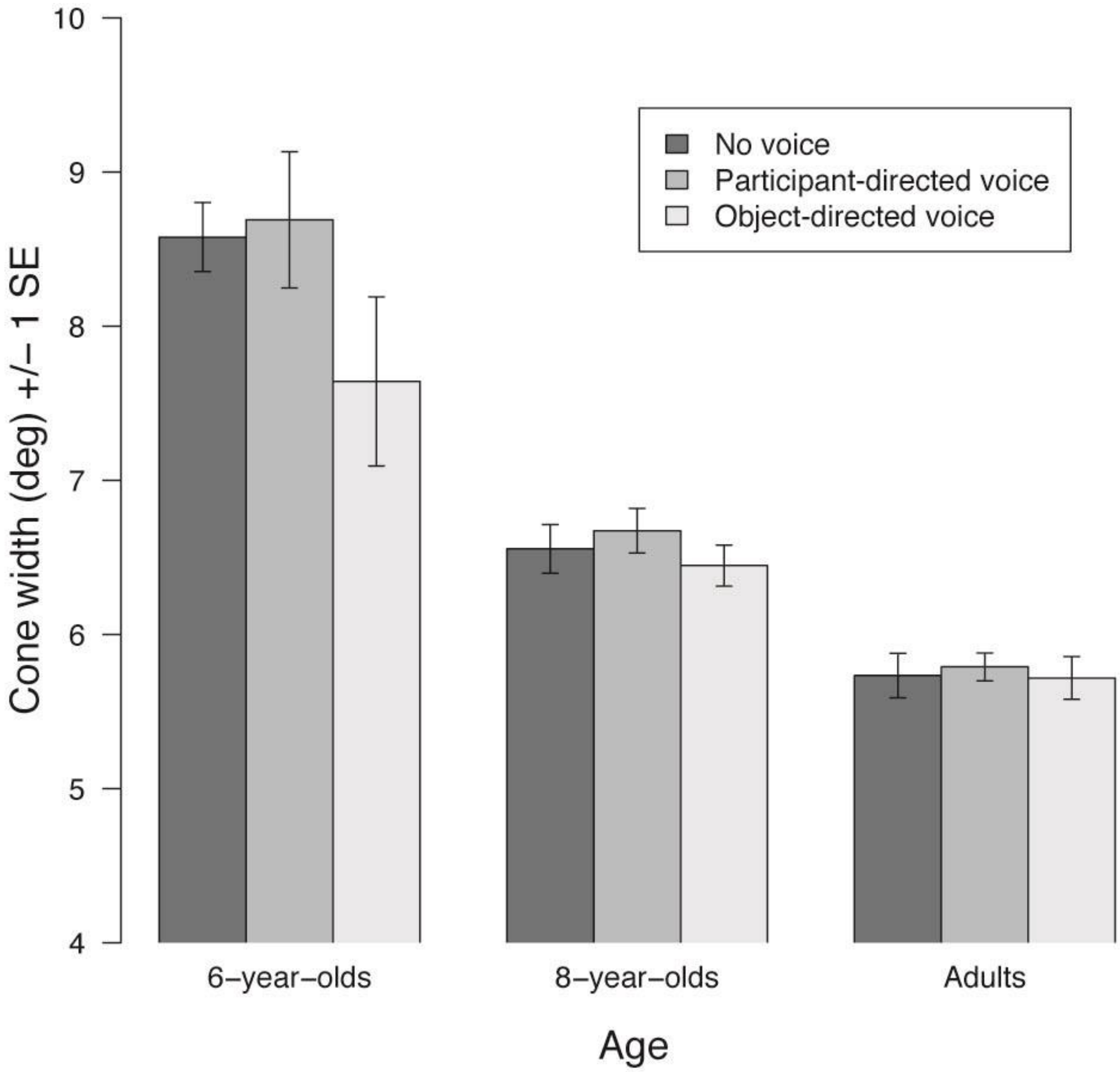


Figure 3. Mean width of the cone of gaze (in degrees) ± 1 *SE* as a function of age and voice condition in Experiment 1.

Figure 4

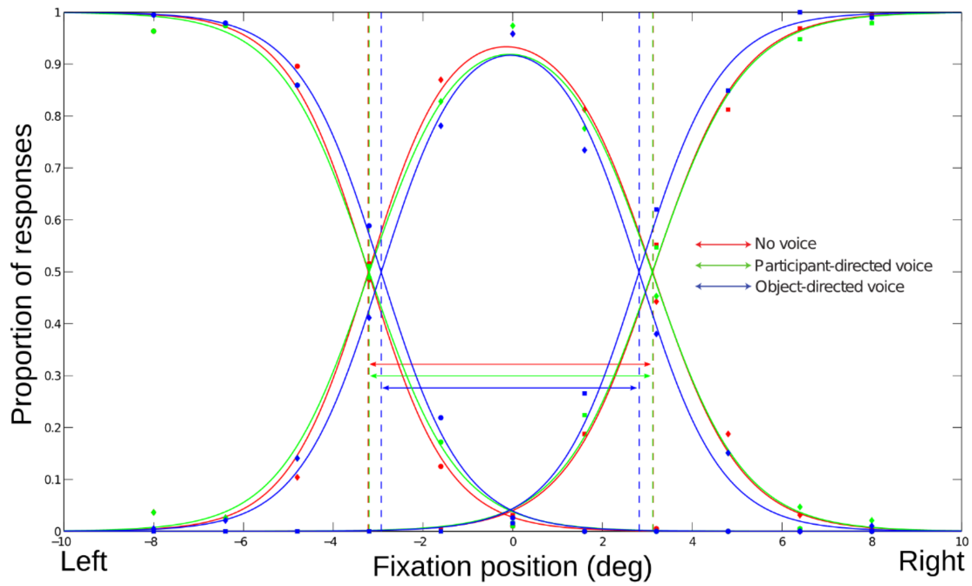


Figure 4. Logistic functions fit to the mean proportions of each response type for adults in Experiment 2, as a function of fixation position (deg) and voice condition. All other details as in Figure 2.

Figure 5

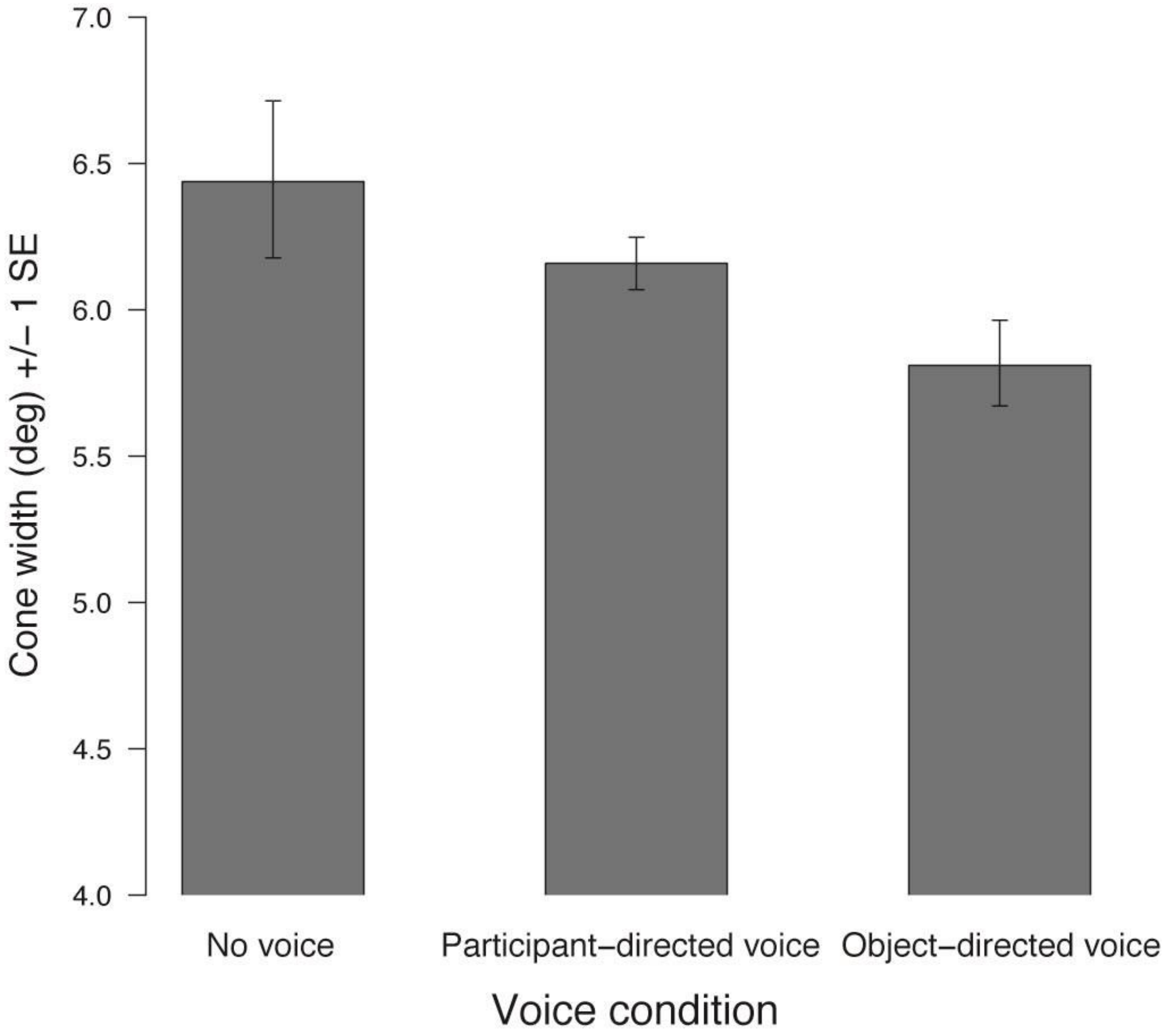


Figure 5. Mean width of the cone of gaze (in degrees) ± 1 *SE* as a function of voice condition in Experiment 2.

Chapter 5 - Study 4

Vida, M. D., Maurer, D., Calder, A. J., Rhodes, G., Walsh, J. A., Pachai, M. V., & Rutherford, M. D. (2013). The influences of face inversion and facial expression on sensitivity to eye contact in high-functioning adults with autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *43*, 2536-2548.

In typical adults, judgments of gaze are impaired by face inversion (Jenkins & Langton 2003; Schwaninger et al. 2005), a result suggesting that sensitivity to the direction of gaze could be tuned by experience to be specialized for upright faces. In addition, facial expression modulates typical adults' judgments of eye contact (Ewbank et al. 2009), a result suggesting that typical adults integrate information from expression and gaze cues when making judgments of eye contact, and that adults may possess a bias to interpret threatening signals as being self-directed.

Adults with autism spectrum disorders (ASD) show abnormal eye contact during face-to-face interactions (American Psychiatric Association, 2013), abnormal fixation of the eye region when viewing faces (e.g., Dalton et al. 2005; Jones et al. 2008; Klin et al. 2002; Pelphrey et al. 2002; Spezio et al. 2007, but also see Falck-Ytter & von Hofsten 2011), and abnormal physiological responses to perceived eye contact (Kaartinen et al. 2012; Kyläiinen & Hietanen, 2006, but also see Joseph et al. 2008), all of which could reflect and/or contribute to abnormal experience with gaze cues. Under at least some circumstances, individuals with ASD are less accurate than typical individuals in discriminating differences between direct and averted gaze (e.g., Campbell et al., 2006; Dratsch et al., 2013; Gepner et al., 1996; Howard et al., 2000; Wallace et al., 2006; Webster & Potter 2008; 2011). There is also evidence that the effect of gaze on judgments of expression is abnormal in children with ASD (Akechi et al., 2010; 2011), and that performance on a visual search task involving judgments of eye gaze is distorted by face inversion in typically developing children, but not in children with ASD (Senju et al., 2008).

Previous studies have not measured the width of the cone of gaze in high-functioning adults with ASD, and have not investigated the influences of face inversion and facial expression on judgments of direct and averted gaze in this population. That was the purpose of Study 4. Specifically, I examined the influences of face inversion and facial expression on sensitivity to eye contact in high-functioning adults with ASD. In addition, I measured for the first time the precise width of the cone of gaze in this population. Participants with and without ASD viewed photographs of angry, fearful, and neutral faces. Gaze was either direct or averted, varying in a series of small steps to the left and right. In separate blocks of trials, participants viewed each face in an upright and inverted orientation. For each face, participants pressed one of three buttons to indicate whether the model's gaze was direct or averted to the left or right. For each participant, we estimated the width of the cone of gaze for each expression and orientation.

The results have implications for understanding social interactions involving high-functioning adults with ASD. A difference in the size of the cone of gaze between adults with and without ASD, or atypical modulation of the cone of gaze by facial expression in adults with ASD, could lead to atypical social judgments. For example, if individuals with ASD do not show the widening of the cone of gaze observed for angry expressions in typical adults (Ewbank et al., 2009), they may fail to interpret a person's hostility as being self-directed when it is appropriate to do so, and may therefore fail to take appropriate actions to avoid a potential threat. The results also have implications for understanding mechanisms underlying developmental changes in sensitivity to the direction of gaze. For example, the finding in previous research that typical adults' sensitivity to the direction of gaze is higher for upright faces than for inverted faces (Jenkins & Langton, 2003; Schweinberger et al., 2005) could reflect tuning of mechanisms for discriminating the direction of gaze (e.g., responses in STS, see Carlin & Calder, 2012) by experience with upright faces. The absent effect of face inversion on gaze processing observed in children with ASD (Senju et al., 2008) could reflect a developmental delay in this tuning. An abnormal effect of inversion on judgments of gaze in adults with ASD could indicate that this abnormal tuning persists into adulthood.

Abstract

We examined the influences of face inversion and facial expression on sensitivity to eye contact in high-functioning adults with and without an autism spectrum disorder (ASD). Participants judged the direction of gaze of angry, fearful, and neutral faces. In the typical group only, the range of directions of gaze leading to the perception of eye contact (the cone of gaze) was narrower for upright than inverted faces. In both groups, the cone of gaze was wider for angry faces than for fearful or neutral faces. These results suggest that in high-functioning adults with ASD, the perception of eye contact is not tuned to be finer for upright than inverted faces, but that information is nevertheless integrated across expression and gaze direction.

Introduction

Eye contact is central to human social interaction. The direction of people's gaze provides a cue to the focus of their attention, which can in turn support inferences about their interests and intentions (Argyle & Cook, 1976; Kendon, 1967). In typical adults, judgments of gaze are impaired by face inversion (Jenkins & Langton, 2003; Schwaninger, Lobmaier, & Fischer, 2005), a result suggesting that sensitivity to the direction of gaze could be tuned by experience to be specialized for upright faces. In addition, facial expression modulates typical adults' judgments of eye contact (Ewbank, Jennings, & Calder, 2009; Rhodes, Addison, Jeffery, Ewbank, & Calder, 2012), a result suggesting that typical adults may integrate information from expression and gaze cues when making judgments of eye contact.

Adults with autism spectrum disorders (ASD) show deficits in some aspects of gaze processing, including understanding of the social meaning of gaze (e.g., Baron-Cohen et al., 2001), and discriminating small differences between direct and averted gaze in upright faces (e.g., Dratsch et al., 2013). Here, we investigated whether the influences of face inversion and facial expression on sensitivity to eye contact are typical in adults with ASD by having high-functioning adults with and without ASD judge whether gaze was direct or averted to the left or right in photographed faces that varied in facial expression and orientation.

Sensitivity to eye contact in typical adults. Typical adults can detect differences of 1-2° in the direction of gaze toward objects in the environment (Bock, Dicke, & Thier, 2008; Symons, Lee, Cedrone, & Nishimura, 2004; Vida & Maurer, 2012a). However, the range of directions of gaze over which adults judge that an observer is looking directly at them (called the "cone of gaze") is much larger, at approximately 5.5° in width (Gibson & Pick, 1963; Lord & Haith, 1974; Vida & Maurer, 2012b) and 7° in height (Vida & Maurer, 2012b). Failure to perceive eye contact when a person's gaze is directed toward oneself could result in social costs (e.g., missed opportunities to interact with others). Typical adults' tendency to perceive eye contact over a relatively large range of directions of gaze could serve to minimize these costs.

In typical adults, face inversion impairs sensitivity to the direction of gaze, as indicated by higher thresholds for discriminating between leftward and rightward gaze for inverted faces than for upright faces (Jenkins & Langton, 2003; Schwaninger et al., 2005). This effect appears to be driven primarily by the inversion of the eyes. When the orientation of the eye region (including eyebrows, eyelids, and part of the bridge of the nose) and that of the outer face context are manipulated independently, inversion of the eye region impairs sensitivity to the direction of gaze to a similar extent whether the face context is upright or inverted (Jenkins & Langton, 2003). Also, typical adults' ability to discriminate small differences in the direction of gaze is equal for full faces and for eyes isolated by occluding all but the visible surface of the eyeball (the palpebral fissure) and the lower eyelid, and is equally impaired when these stimuli are inverted (Schwaninger et al., 2005). These results suggest the importance of visual cues in and around the palpebral fissure, as viewed in an upright orientation.

In typical adults, the perception of eye contact interacts reciprocally with that of facial expression. Several studies have demonstrated that the direction of gaze affects processing of facial expression (see Graham & LaBar, 2012, for review). Some of these studies indicate that eye contact facilitates the perception of facial expressions associated with approach (e.g., anger) and that it impairs the perception of those associated with avoidance (e.g., fear) (e.g., Adams & Kleck, 2003; Milders, Hietanen, Leppänen, & Braun, 2011). However, others report that eye contact generally facilitates expression perception (e.g., Bindemann, Burton, & Langton, 2008). There is also evidence that facial expression affects the perception of eye contact. The cone of gaze is wider for angry than for fearful or neutral faces, with no difference between the latter two (Ewbank et al., 2009; Rhodes et al., 2012). As suggested in Ewbank et al. (2009), the observed effect of facial expression on judgments of eye contact may indicate that typical adults possess an adaptive bias to interpret hostile signals as self-directed. Taken together, these results suggest that typical adults combine information from gaze and expression when judging either gaze or facial expression. This ability may be adaptive, as it may allow individuals to respond selectively to combinations of expression and gaze cues that are important for survival. For example, an angry face with direct gaze may be interpreted as a stronger signal of threat than an angry face with averted gaze (e.g., Adams & Kleck, 2005), because the former indicates that the threat is directed toward the viewer.

Sensitivity to eye contact in autism. Abnormal eye contact during face-to-face social interactions is a characteristic of autism (American Psychiatric Association, 2000). Individuals with autism are known to have impairments in their ability to perceive mental state information from the direction of gaze (Baron-Cohen, Baldwin, & Crowson, 1997; Baron-Cohen et al., 1995; Baron-Cohen & Goodheart, 1994; Baron-Cohen et al., 2001), show autonomic hyper-arousal to eye contact (Kaartinen et al., 2012; Kyläiinen & Hietanen, 2006, but also see Joseph, Ehrman, McNally, & Keehn, 2008), and, at least under some circumstances, spend less time than controls fixating the eye region when viewing faces (e.g., Dalton et al., 2005; Jones, Carr, & Klin, 2008; Klin, Jones, Schultz, Volkmar, & Cohen, 2002; Pelphrey et al., 2002; Spezio, Adolphs, Hurley, & Piven, 2007, but also see Falck-Ytter & von Hofsten, 2011).

Given sufficient differences between direct and averted gaze and a long duration of exposure to the stimulus, individuals with ASD can make accurate judgments of eye contact (Ashwin, Ricciardelli, & Baron-Cohen, 2009; Senju, Kikuchi, Hasegawa, Tojo, & Osanai, 2008). For example, high-functioning adults with ASD are as accurate as typical adults in discriminating between direct gaze and gaze averted 30° to the left or right (Ashwin et al., 2009). However, both children and adults with ASD are less accurate than controls in discriminating small differences between direct and averted gaze (Campbell et al., 2006; Dratsch et al., 2013; Gepner, de Gelder, & de Schonen, 1996; Howard et al., 2000; Webster & Potter, 2008; Webster & Potter, 2011). Even when differences between direct and averted gaze are large, high-functioning adults with ASD are less accurate and slower than controls when the duration of exposure is short (Wallace, Coleman, Pascalis, & Bailey, 2006). These results suggest that the ability to discriminate between direct and averted gaze is impaired in individuals with ASD compared to that in typical individuals.

One previous study suggests that the effects of face inversion on gaze processing are atypical in children with ASD (Senju et al., 2008). In this study, 9- to 15-year-old children with and without ASD viewed arrays of five or nine faces and judged whether a face with a particular direction of gaze (direct, averted left or averted right) was present in the array. When faces were presented in an upright orientation, typically developing children showed more efficient visual search (i.e., a smaller difference in response time between smaller and larger arrays) for detection of direct gaze than for averted gaze. This effect was not present for inverted faces. In contrast, children with ASD showed more efficient search for direct gaze in both orientations (Senju et al., 2008). This result suggests that the perceptual mechanism underlying sensitivity to eye contact may not be specialized for upright faces in ASD.

Previous research suggests that the effects of the direction of gaze on processing of facial expression may be atypical in children with ASD. In one study, typically developing 9- to 14-year-old children were faster to recognize fearful and angry faces when they were paired with a motivationally congruent direction of gaze (e.g., anger with direct gaze, fear with averted gaze) than when gaze and expression were incongruent. This effect was absent in children with ASD (Akechi et al., 2009). In a second study, typically developing 9- to 14-year-old children showed greater amplitude in the N170 ERP component for congruent combinations of expression and gaze than for incongruent combinations. This result may reflect more extensive cortical processing of expressions presented with a congruent direction of gaze. This effect was also absent in children with ASD (Akechi et al., 2010). In sum, children with ASD do not show evidence of typical interactions between perceptions of expression and gaze, when measured by either behavioural or neural indices.

In sum, previous research indicates that the influence of face inversion on gaze processing (Senju et al., 2008), and the influence of the direction of gaze on the perception of facial expression (e.g., Akechi et al., 2009; 2010), are atypical in children with ASD. Previous studies have not examined the influences of face inversion or facial expression on sensitivity to eye contact in adults with ASD, and have not provided precise estimates of the width of the cone of gaze in this population. That was the purpose of the current study. Specifically, we examined the influences of face inversion and facial expression on sensitivity to eye contact in high-functioning adults with ASD. In addition, we measured for the first time the precise width of the cone of gaze in this population. Participants with and without ASD viewed photographs of angry, fearful, and neutral faces. Gaze was either direct or averted, varying in a series of small steps to the left and right. In separate blocks of trials, participants viewed each face in an upright and inverted orientation. For each face, participants pressed one of three buttons to indicate whether the model's gaze was direct or averted to the left or right. For each participant, we estimated the width of the cone of gaze for each expression and orientation. The results of this investigation provide the first information on whether individuals with ASD combine information from expression and gaze cues when making judgments of eye contact. The results also provide the first information on whether the atypical interactions between perceptions of expression and gaze (Akechi et al., 2009; 2010) and the atypical effect of inversion on gaze processing (Senju et al., 2008) observed in children with ASD persist into adulthood, or whether these aspects of sensitivity normalize by adulthood, an outcome that could reflect a developmental delay.

Method.

Participants. The ASD group consisted of 17 adults (12 male, *M* age = 27.6 years, age range = 18-42 years) with autism spectrum disorders, and an age- and IQ- (Wechsler Adult Intelligence Scale, Version 3) matched control group consisted of 17 adults (14 male, *M* age = 26.3 years, age range = 20-44 years) without any developmental disorders (see Table 1 for demographic information). Before entering the study, all participants in the ASD group had previously received clinical diagnoses of autism, Asperger syndrome, or pervasive developmental disorder not otherwise specified. One of the authors (MDR) confirmed their diagnoses with the Autism Diagnostic Observation Schedule (ADOS-G)

Module 4 (Lord et al., 2000, see Table 2 for diagnostic information). All participants had normal or corrected-to-normal letter acuity. Four additional participants with ASD were replaced because they failed to meet our criterion for performance on practice trials (see Procedure section for details) (n = 1), or because their response curves were too broad to allow confident estimation of the width of the cone of gaze (see Curve Fitting section for description of this measure) from their data for at least one expression and orientation (n = 3).

Stimuli. The stimuli came from the set used in Ewbank et al. (2009), which was comprised of images from the NimStim Face Stimulus Set (Tottenham et al., 2009) and the Karolinska Directed Emotional Faces image set (Lundqvist & Litton, 1998). The stimuli consisted of grayscale digital photographs of four adult males posing angry, fearful, and neutral expressions. As in the only previous study of the influence of facial expression on sensitivity to eye contact (Ewbank et al., 2009), we confined our stimuli to male faces because male and female faces have been shown to differentially influence recognition of angry expressions (Becker, Kenrick, Neuberg, Blackwell, & Smith, 2007). Hence, the current results do not allow the assessment of whether the effects of expression on sensitivity to eye contact differ between male and female faces. The direction of gaze was either direct or digitally manipulated in small steps (2, 3, 4, 5, 7, or 9 pixels to the left and right) (see Figure 1 for examples). We added the nine pixel images to the original stimuli because the seven pixel images were not sufficient to define the boundaries of the cone of gaze for several participants in Ewbank et al. (2009). The method of manipulating the direction of gaze used for the current stimuli does not allow direct comparisons between our results and those of previous studies in which sensitivity to eye contact was measured in degrees of eye rotation (e.g., Dratsch et al., 2013; Gamer & Hecht, 2007; Gamer, Hecht, Seipp, & Hiller, 2011; Vida & Maurer, 2012b). However, this method nevertheless provides a realistic and fine-grained manipulation of the direction of gaze, and therefore allows the assessment of relative differences in sensitivity to eye contact (e.g., differences between adults with and without ASD). Face images subtended a visual angle of approximately 12° x 8° from a distance of 50 cm. The images were displayed on a Sony SDM-M81 18-inch LCD monitor set to a resolution of 1152 x 870 and a refresh rate of 75 Hz. The experiment was run in Matlab 7.6.0 (R2008a) (MathWorks, Natick, MA, USA) with the Psychophysics Toolbox extensions (Brainard, 1997) on an Apple Mac mini computer.

Apparatus. Participants were positioned 50 cm in front of the computer monitor. Participants entered responses on a computer keyboard placed on a table directly in front of them. The experiment used four keys on the keyboard. 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, and the G key with a blue circle taped over the top to indicate direct responses. Participants pressed the spacebar to begin each trial.

Design. Each participant completed two blocks of test trials, one including only upright faces and the other including only inverted faces. The order of blocks was counterbalanced across participants. Before the test blocks, each participant received a practice block.

The practice block consisted of 12 trials in which each of the four models was presented with a neutral expression. On each trial, gaze was either direct or averted to the farthest positions (nine pixels) to the left or right. 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. Sixteen participants in the ASD group and 15 participants in the typical group met this criterion on the first attempt, for both the upright and inverted blocks. Two participants in the typical group required a second attempt to reach criterion in the inverted block. One participant in the ASD group was replaced for failure to reach this criterion within three attempts.

In each of the two test blocks (upright and inverted), the participant viewed each of the three expressions, four models and 13 directions of gaze twice, for a total of 312 trials per block. Trials were presented in a pseudo-randomized order, with the constraint that the same direction of gaze and expression were presented on no more than two consecutive trials. During test trials, participants received general encouragement but no trial-specific feedback.

Procedure. Written consent was obtained after explaining the procedure. The experimenter introduced the task by explaining that the participant would see a series of faces on the screen, and that the participant's task would be to press one of the three buttons on the keyboard to indicate whether the model appeared to be looking at the participant, or away from the participant to the left or right. The participant then initiated practice trials. At the start of each trial, the words, "Press spacebar to continue." appeared at the centre of the screen. When the participant pressed the spacebar, an image of one of the faces appeared. After 500 ms, the image disappeared and was replaced by the words, "Where was that person looking?", which remained on the screen until the participant pressed one of the three response keys[6]. When the participant met the 75% accuracy criterion on the practice block, 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 minutes and completed the entire

[6] In the previous study using a similar method, each face was presented for 200 ms (Ewbank et al., 2009). We were concerned that some lower-functioning participants would find it too difficult to perform the task with this duration. We extended the exposure time to 500 ms to make the task easier.

procedure in approximately 30 minutes.

Results.

Curve fitting. For each participant, we calculated the proportion of the eight trials at each direction of gaze on which the model was judged to be looking directly toward the participant, to the left, and to the right (see Figure 2). To quantify sensitivity to eye contact, we fit logistic functions relating each participant's proportion of left and right responses to the directions of gaze. All fits were carried out using the glmfit routines from the Statistics Toolbox in Matlab (R2008a). The sum of the left and right 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 Vida & Maurer (2012b) for all fits (see Appendix A for details). Following Ewbank et al. (2009) and Vida and Maurer (2012b), we calculated the width of the cone of gaze as the difference (in pixels) between the points of intersection between the fitted ‘‘direct’’ function and the left and right functions. These points of intersection correspond to the directions of gaze where the participant was equally likely to judge that the model was making eye contact or looking away. The distance between the right and left points of intersection provides a measure of the width of the horizontal cone of gaze. Three individuals in the ASD group were replaced because their response curves were too broad to allow confident estimation of the width of the cone of gaze in at least one condition.

Width of the cone of gaze. We carried out a mixed ANOVA with orientation (upright, inverted) and expression (anger, fear, neutral) as within-subject factors, group (ASD, typical) as a between-subject factor and the width of the cone of gaze as the dependent variable (see Figure 3). There were significant main effects of orientation, $F(1, 32) = 13.13$, $p < .002$, $\eta_p^2 = .29$, expression, $F(2, 64) = 4.89$, $p < .02$, $\eta_p^2 = .13$, and group, $F(1, 32) = 4.55$, $p < .05$, $\eta_p^2 = .12$. There were also interactions between orientation and group, $F(1, 32) = 6.18$, $p < .02$, $\eta_p^2 = .16$, and between orientation and expression, $F(2, 64) = 10.55$, $p < .001$, $\eta_p^2 = .25$. There was no interaction between expression and group, or between orientation, expression, and group, *p*s > .45.

To follow up the interaction between orientation and group, we first asked whether face inversion affected the width of the cone of gaze in each group (see Figure 4). We carried out paired-samples t-tests (one for each group, Bonferroni-corrected $\alpha = .025$) evaluating the null hypothesis that there was no difference in the width of the cone of gaze between upright and inverted faces. For the typical group, the cone of gaze was narrower in the upright condition ($M = 7.3$, $SD = 1.5$) than in the inverted condition ($M = 8.8$, $SD = 1.8$), $t(16) = 5.75$, $p < .001$, $d = .89$. For the ASD group, the width of the cone of gaze did not differ between the upright ($M = 6.6$, $SD = 2.0$) and inverted ($M = 6.9$, $SD = 2.1$) conditions, $p > .5$. In light of previous evidence that children with ASD make normal judgments of eye contact for upright faces, but do not show the distortion of judgments for inverted faces observed in typical children (Senju et al., 2008), we also investigated whether there was a group difference in the width of the cone of gaze for each face orientation. To examine this question, we carried out independent-samples t-tests (one for each orientation, Bonferroni-corrected $\alpha = .025$) evaluating the null hypothesis of no group difference in the width of the cone of gaze. For upright faces, there was no significant difference in the width of the cone of gaze between the ASD ($M = 6.6$, $SD = 2.0$) and typical ($M = 7.3$, $SD = 1.5$) groups, $p > .25$. For inverted faces, the cone of gaze was narrower in the ASD group ($M = 6.9$, $SD = 2.1$) than in the typical group ($M = 8.8$, $SD = 1.8$), $t(32) = 2.78$, $p < .01$, $d = .95$.

We followed up the expression by orientation interaction with repeated-measures ANOVAs (one for each orientation) evaluating the null hypothesis of no difference among the expression categories (see Figure 5). For upright faces, there was a simple effect of expression, $F(2, 66) = 14.16$, $p < .001$, $\eta_p^2 = .30$. We followed up this effect with three paired-samples t-tests (Bonferroni-corrected $\alpha = .017$) comparing the width of the cone of gaze for upright faces between each possible pair of expressions. The cone of gaze was wider for anger ($M = 8.0$, $SD = 2.3$) than for fear ($M = 6.6$, $SD = 2.4$), $t(33) = 3.57$, $p < .002$, $d = .70$, and for neutral ($M = 6.3$, $SD = 1.6$), $t(33) = 6.32$, $p < .001$, $d = .80$. There was no difference between fear and neutral, $p > .5$. For inverted faces, there was a simple main effect of expression, $F(2, 66) = 3.95$, $p < .03$, $\eta_p^2 = .11$. We followed up this effect with paired-samples t-tests (Bonferroni-corrected $\alpha = .017$). There were no significant differences in the width of the cone of gaze between anger (M = 7.8, SD = 2.7) and fear (M = 8.7, SD = 3.4), or between anger and neutral (M = 7.1, SD = 2.4), ps > .1. There was a trend in the direction of a wider cone of gaze for fear than neutral, but this did not reach the corrected statistical threshold, $t(33) = 2.46$, $p = .02$. Thus, although there was a significant simple main effect of expression for inverted faces, none of the pair-wise differences among expression categories were significant after correcting for multiple comparisons.

Individual differences in the effect of face inversion. Unlike typical adults in the current study and in previous studies (e.g., Jenkins & Langton, 2003; Schwaninger et al., 2005), the ASD group in the current study displayed no effect of inversion on judgments of eye contact. However, it is possible that factors such as symptom severity or IQ modulated the magnitude of the effect of inversion within the ASD group. To investigate this possibility, we first calculated the size of the effect of inversion for each participant in the ASD group by subtracting the mean width of the cone of gaze for upright faces from that for inverted faces. We then carried out three Pearson correlations testing the association between measures of symptom severity (social, communication, repetitive) and the effect of inversion in the ASD group. There were no significant correlations, rs = -.09-.03, ps > .45. We also carried out three Pearson correlations testing the association between measures of IQ (verbal, performance, full-scale) and the effect of inversion within the ASD group. There were no significant correlations, rs = .27-.35, *p*s > .15. Hence, in the current sample of 17 high-functioning adults with ASD, we found no evidence that symptom severity or IQ modulated the magnitude of the effect of inversion.

Ideal observer analysis. As shown in Figure 1, the eyelids tend to be more closed in angry faces than in fearful or neutral faces. Hence, the wider cone of gaze observed for angry faces in the current study could reflect lower visibility of parts of the palpebral fissure (e.g., the iris and sclera) that provide cues to the direction of gaze. To investigate this possibility, we carried out an ideal observer analysis. An ideal observer is a theoretical model that uses the optimal strategy for a given task (see Geisler, 1989; Tjan et al., 1995, for details). The performance of our ideal observer was determined by the amount of variation in pixel luminance between images that was informative for discriminating the direction of gaze (see Appendix A for further details). In our task, shifts of gaze were generated by digitally manipulating the position of the iris within the palpebral fissure. Therefore, all low-level information available to perform the task was contained exclusively in the palpebral fissure. The dependent measure of our ideal observer analysis was the 75% root mean square (RMS) contrast threshold, which represents the minimum stimulus visibility at which the ideal observer was able to achieve 75% accuracy in discriminating between leftward and rightward gaze. A lower contrast threshold indicates that there is more information available for discriminating the direction of gaze.

We allowed the ideal observer only two choices (left or right) instead of the three choices (direct, left, or right) provided to human observers. This allowed us to specify the correct response for each trial, which in turn allowed us to vary the visibility of the stimulus according to the ideal observer's responses (see Appendix A for further details). The availability of low-level visual information will constrain human observers' sensitivity to the direction of gaze (e.g., Watt, Craven, & Quinn, 2007), whether two or three response alternatives are allowed. Hence, the current analysis allows inferences about the role of low-level visual information in the effects of facial expression on judgments of eye contact.

Inspection of Figure 6 indicates that thresholds were lower for directions of gaze that diverged more from straight ahead. This result indicates that for larger shifts of gaze, there was more information available to discriminate between leftward and rightward gaze. This result is expected because, as shown in Figure 1, a larger shift of gaze in a particular direction causes the eyes to appear less similar to eyes in which gaze is shifted in the opposite direction. Critically, Figure 6 also indicates that angry and neutral faces produced identical thresholds, whereas fearful faces produced lower thresholds. Note that this will be true whether the stimulus is upright or inverted. This result suggests that there is more information available to perform the task in fearful faces than in angry or neutral faces, with no difference between the latter two. This pattern is different from our finding that in both the typical and ASD groups, the cone of gaze was wider for angry faces than for fearful or neutral faces, with no difference between the latter two, and that the effect of expression was limited to upright faces. Hence, our ideal observer analysis suggests that the wider cone of gaze for upright angry faces does not arise from a lack of low-level visual information available for discriminating the direction of gaze.

Discussion

The current study provides the first information on the influences of face inversion and facial expression on sensitivity to eye contact in high-functioning adults with ASD, and provides the first precise estimates of the width of the cone of gaze in this population. The effect of inversion on the width of the cone of gaze differed between the groups. In the typical group, the cone of gaze was narrower for upright than inverted faces, a pattern suggesting that sensitivity to eye contact is specialized for upright faces. In the ASD group, the width of the cone of gaze was the same for upright and inverted faces. The cone of gaze for inverted faces was wider in the typical group than in the ASD group (i.e., for inverted faces, participants in the ASD group performed better than participants in the typical group), but there was no group difference in the width of the cone of gaze for upright faces. Although the effect of inversion on the width of the cone of gaze was atypical in the ASD group, the effects of expression on the cone of gaze were the same in each group. For upright faces, the cone of gaze was wider for angry faces than for fearful or neutral faces, with no difference between the latter two, a result suggesting that facial expression influences gaze perception similarly in the two groups. For inverted faces, there was no systematic effect of expression on the width of the cone of gaze in either group.

Sensitivity to eye contact in upright and inverted faces. In the current study, the cone of gaze of typical adults was narrower for upright than inverted faces. This finding is consistent with previous evidence that typical adults are more accurate in judging the direction of gaze for upright faces than for inverted faces (e.g., Jenkins & Langton, 2003; Schwaninger et al., 2005). These results suggest that the system for detecting eye contact could be tuned by experience with upright faces. This experience could also contribute to developmental changes in children's ability to discriminate small differences between direct and averted gaze (Vida & Maurer, 2012b) and could influence tuning of cortical mechanisms for coding the direction of gaze (e.g., Calder, Jenkins, Cassel, & Clifford, 2008).

When viewing upright faces, the ASD group made judgments of eye contact comparable to those of the control group, but did not show the widening of the cone of gaze for inverted faces observed in the typical group. This pattern is consistent with the results of a previous study that found differences when children with and without ASD viewed arrays of five or nine faces and judged whether a face with a particular direction of gaze (direct, averted left, or averted right) was present in the array. For upright faces, typically developing children showed more efficient visual search (i.e., a smaller difference in response time between smaller and larger arrays) for detection of direct gaze than for averted gaze. This effect was absent for inverted faces. In contrast, children with ASD showed more efficient search for direct gaze in both orientations (Senju et al., 2008). Our results indicate that the atypical effects of face inversion on judgments of eye contact observed in children with ASD (Senju et al., 2008) persist into adulthood. Together, our results and those of Senju et al. (2008) suggest that sensitivity to eye contact is not specialized for upright faces in children or adults with ASD.

The observed group difference in the influence of face inversion on sensitivity to eye contact could be a result of those with ASD having spent less time fixating the eye region of faces during early development (e.g., Jones et al., 2008). Differences in experience with the eye region could lead to differences in expertise in processing visual information within the eye region, which could contribute to differences in perceptual strategies. For example, normal expertise in processing information within the eye region could enable typical adults to base their estimates of the direction of gaze on relatively complex visual cues, at least some of which are likely to vary in appearance between upright and inverted faces (e.g., the appearance of the iris and sclera). This strategy could lead to lower sensitivity for inverted than upright faces. In contrast, lower expertise in processing information within the eye region could lead adults with ASD to adopt a perceptual strategy based on relatively simple visual cues, which may not vary significantly in appearance between upright and inverted faces (e.g., bilateral symmetry).

This strategy could allow normal or near-normal sensitivity for upright faces, with no impairment for inverted faces.

An additional variable that could modulate sensitivity to eye contact in ASD is motion. The one previous study of the ability of adults with ASD to discriminate small differences between direct and averted gaze in a single face reported lower sensitivity in high-functioning adults with ASD than in typical adults (Dratsch et al., 2013). This result differs from our finding of no group difference in the width of the cone of gaze for upright faces. One key difference between our study and that of Dratsch et al. (2013) is that stimuli in the previous study were dynamic videos, whereas stimuli in the current study were static photographs. Since individuals with ASD show deficits in perception of complex non-biological and biological motion (e.g., Blake, Turner, Smoski, Pozdol, & Stone, 2003; Freitag et al., 2008), it is possible that a general impairment in processing of complex motion could contribute to abnormally low sensitivity to eye contact in ASD (Dratsch et al., 2013).

Although adults with ASD in the current study were able to make normal judgments of eye contact for upright faces, it should be noted that we replaced four participants with ASD because they did not reach criterion on practice trials (*n* = 1) or because their response curves were so broad that we were unable to confidently estimate the width of the cone of gaze (*n* = 3). Three of these participants scored well below the mean for the ASD group on at least one measure of IQ, and scored above the group mean on measures of the severity of social and communication symptoms, whereas one scored near the group mean on these measures. Hence, it is possible that sensitivity to eye contact is abnormally low in adults with ASD who are lower functioning and/or have more severe symptoms than the ASD group in the current study.

Effects of facial expression on sensitivity to eye contact. Despite the fact that judgments of eye contact were not modulated by inversion in the ASD group, judgments were nevertheless modulated by expression. In both groups, the cone of gaze for upright faces was wider for angry faces than for fearful or neutral faces, with no difference between the latter two, and there was no systematic effect of expression for inverted faces. To our knowledge, this is the first evidence that facial expression influences judgments of eye contact in individuals with ASD. Our finding that inversion eliminated the effect of facial expression on the cone of gaze is consistent with previous research indicating that inversion disrupts recognition of facial expression in adults with and without ASD (see Weigelt, Koldewyn, & Kanwisher, 2012, for review). Our results suggest that although sensitivity to eye contact may not be tuned normally to upright faces in adults with ASD, sensitivity to facial expression is nevertheless tuned to be finer for upright than inverted faces.

As suggested in Ewbank et al. (2009), the wider cone of gaze for upright angry faces may reflect an adaptive bias to interpret hostile signals as self-directed. Our results suggest that this bias may be intact in adults with ASD. The current results are consistent with previous studies indicating that behavioural markers of threat detection are, to at least some degree, intact in individuals with ASD. Like typical adults, high-functioning adults with ASD are faster to detect angry faces than happy faces (Ashwin, Wheelwright, & Baron-Cohen, 2006; Krysko & Rutherford, 2009). Also, when viewing pairs of faces in which one face is that of a convicted murderer and the other is a layperson, high-functioning adults with ASD are as accurate as typical adults in choosing the more dangerous-looking face (Miyahara, Ruffman, Fujita, & Tsujii, 2010). The current results provide further evidence that behavioural markers of threat detection are intact in ASD.

Previous studies have not examined the effects of expression on judgments of eye gaze in children or adults with ASD. However, previous research suggests that the opposite influence, of gaze direction on behavioural and neural indices of expression processing, is atypical in children with ASD (Akechi et al., 2009; 2010). Together, our results and those of previous studies could indicate that interactions between expression and gaze are developmentally delayed in ASD, such that these interactions are atypical in childhood, but normalize by adulthood. Alternatively, the results could indicate that interactions between gaze and expression are unidirectional in ASD, such that the influence of expression on the perception of gaze is normal, but the opposite influence is atypical. Future studies investigating the effect of expression on judgments of eye contact in children with ASD, and the effect of gaze on judgments of expression in adults with ASD, would allow evaluation of these possibilities.

Although the effects of expression in both the typical and ASD groups in the current study could reflect differences in the affective content of the facial expressions, they could instead reflect differences in lower-level visual information (e.g., the visibility of cues to the direction of gaze within the palpebral fissure). Two findings in the current study provide evidence against the latter possibility. First, as in Ewbank et al. (2009), face inversion eliminated the effects of expression on the cone of gaze. Since eye cues to the direction of gaze are equally visible in upright and inverted faces, it seems unlikely that the effects of expression in the current study were driven by differences in the visibility of these cues. Second, our ideal observer analysis revealed no differences between neutral and angry faces in the amount of low-level visual information available for discriminating the direction of gaze. Together, these results suggest that the wider cone of gaze for upright angry faces does not reflect differences in low-level visual cues.

Our results and those of previous studies (Ashwin et al., 2006; Krysko & Rutherford, 2009; Miyahara et al., 2010) suggest that behavioural markers of threat detection are normal in adults with ASD. However, it is possible that these responses are mediated by an abnormal mechanism in ASD. It has been reported that when viewing facial expressions, individuals with ASD display both abnormally low (Ashwin, Baron-Cohen, Wheelwright, O'Riordan, & Bullmore, 2007; Baron-Cohen et al., 1999; Critchley et al., 2000) and high (e.g., Dalton et al., 2005; Kleinhans et al, 2009; Monk et al., 2010) activation in the amygdala, a brain region thought to be involved in alerting other brain areas involved in social perception and cognition to the emotional salience of stimuli (see Schultz, 2005, for review), and in driving physiological responses to this emotional salience (see Dedovic, Duchesne, Andrews, Engert, & Pruessner, 2009, for review). Hence, although the influence of facial expression on judgments of eye contact was normal in the ASD group, this effect could be associated with abnormally high or low neural and/or physiological responses to the emotional salience of the facial expressions. Future studies could evaluate these possibilities by measuring the neural and physiological correlates of the effects of facial expression on judgments of eye contact in ASD.

Limitations. A potential limitation in the current study is that response times were not recorded, and so the current results do not allow the assessment of group differences in response times. In the one previous study of the ability of high-functioning adults with ASD to discriminate small differences between direct and averted gaze in a single face, there was no difference in response times between adults with and without ASD (Dratsch et al., 2013). Hence, it seems unlikely that a group difference would have been present in the current study.

Conclusions. This investigation has provided the first information on the influences of face inversion and facial expression on sensitivity to eye contact in high-functioning adults with ASD, and has provided the first precise estimates of the width of the cone of gaze in this population. The current results suggest that, like typical adults and children, high-functioning adults with ASD possess an adaptive bias to interpret hostile signals as self-directed. However, the lack of an inversion effect among adults with ASD suggests that that their perception of eye contact may not rely on the same type of visual processing as in typical individuals.

References

Adams, R. B., Jr., & Kleck, R. E. (2003). Perceived gaze direction and the processing of facial displays of emotion. *Psychological Science, 14*, 644-647.

Adams, R. B., Jr., & Kleck, R. E. (2005). Effects of direct and averted gaze on facially communicated emotion. *Emotion, 5*, 3-11.

Akechi, H., Senju, A., Kikuchi, Y., Tojo, Y., Osanai, H., & Hasagawa, T. (2009). Does gaze direction modulate facial expression processing in children with autism spectrum disorder? *Child Development, 80*, 1134-1146.

Akechi, H., Senju, A., Kikuchi, Y., Tojo, Y., Osanai, H., & Hasegawa, T. (2010). The effect of gaze direction on the processing of facial expressions in children with autism spectrum disorder: An ERP study. *Neuropsychologia, 48*, 2841-2851.

American Psychiatric Association (2000). Diagnostic and Statistical Manual of Mental Disorders (DSM-IV-TR) (4th edn), American Psychiatric Publishing, Inc.

Argyle, M., & Cook, M. (1976). *Gaze and mutual gaze*. New York: Cambridge University Press.

Ashwin, C., Baron-Cohen, S., Wheelwright, S., O'Riordan, M., & Bullmore, E. T. (2007). Differential activation of the amygdala and the 'social brain' during fearful face processing in Asperger Syndrome. *Neuropsychologia, 45*, 2-14.

Ashwin, C., Wheelwright, S., & Baron-Cohen, S. (2006). Finding a face in the crowd: Testing the anger superiority effect in autism. *Brain and Cognition, 61*, 78-95.

Ashwin, C., Ricciardelli, P., & Baron-Cohen, S. (2009). Positive and negative gaze perception in autism spectrum disorders. *Social Neuroscience, 4*, 153-164.

Baron-Cohen, S. (1995). *The eye direction detector (EDD) and the shared attention mechanism (SAM): Two cases for evolutionary psychology*. In C. Moore & P. J. Dunham (Eds.), Joint attention: Its origins and role in development (pp. 41-59). Hillsdale, NJ: Lawrence Erlbaum.

Baron-Cohen, S., Baldwin, D., & Crowson, M. (1997). Do children with autism use the Speaker's Direction of Gaze (SDG) strategy to crack the code of language? *Child Development, 68*, 48-57.

Baron-Cohen, S., Campbell, R., Karmiloff-Smith, A., Grant, J., & Walker, J. (1995). Are children with autism blind to the mentalistic significance of the eyes? *British Journal of Developmental Psychology, 13*, 379-398.

Baron-Cohen, S., & Goodhart, F. (1994). The "seeing leads to knowing" deficit in autism: the Pratt and Bryant probe. *British Journal of Developmental Psychology, 12*, 397-402.

Baron-Cohen, S., Ring, H., Wheelwright, S., Bullmore, E., Brammer, M., Simmons, A., & Williams, S. (1999). Social intelligence in the normal and autistic brain: an fMRI study. *European Journal of Neuroscience, 11*, 1891-1898.

Baron-Cohen, S., Wheelwright, S., Hill, J., Raste, Y., & Plumb, I. (2001). The reading the mind in the eyes test revised version: A study with normal adults, and adults with

Asperger syndrome or high-functioning autism. *Journal of Child Psychology and Psychiatry, 42*, 241-251.

Becker, D. V., Kenrick, D. T., Nueberg, S. L., Blackwell, K. C., & Smith, D. M. (2007). The confounded nature of angry men and happy women. *Journal of Personality and Social Psychology, 92*, 179-190.

Bindemann, M. A., Burton, M., & Langton, S. R. H. (2007). How do eye gaze and expression interact? *Visual Cognition, 16*, 708-733.

Blake, R., Turner, L. M., Smoski, M. J., Pozdol, S. L., & Stone, W. L. (2003). Visual recognition of biological motion is impaired in children with autism. *Psychological Science, 14*, 151-157.

Bock, S. W., Dicke, P., & Thier, P. (2008). How precise is gaze following in humans? *Vision Research, 48*, 946-957.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.

Calder, A. J., Jenkins, R., Cassel, A., & Clifford, C. W. G. (2008). Visual representation of eye gaze is coded by a non-opponent multichannel system. *Journal of Experimental Psychology: General, 137*, 244-261.

Campbell, R., Lawrence, K., Mandy, W., Mitra, C., Jeyakuma, L., & Skuse, D. (2006). Meanings in motion and faces: Developmental associations between the processing of intention from geometrical animations and gaze detection accuracy. *Development and Psychopathology, 18,* 99-118.

Critchley, H. D., Daly, E. M., Bullmore, E. T., Williams, S. C., Van Amelsvoort, T., Robertson, D. M., Rowe, A., Phillips, M., McAlonan, G., Howlin, P., & Murphy, D. G. (2000). The functional neuroanatomy of social behaviour: changes in cerebral blood flow when people with autistic disorder process facial expressions. *Brain, 123,* 2203-2212.

Dalgaard, P. (2008). Introductory statistics with R. New York: Springer.

Dalton, K. M., Nacewicz, B. M., Johnstone, T., Schaefer, H. S., Gernsbacher, M. A., Goldsmith, H. H., Alexander, A. L., Davidson, R. J. (2005). Gaze fixation and the neural circuitry of face processing in autism. Nature Neuroscience, 8, 519-526.

Dedovic, K., Duchesne, A., Andrews, J., Engert, V., & Pruessner, J. C. (2009). The brain and the stress axis: the neural correlates of cortisol regulation in response to stress. *Neuroimage*, *47*, 864–871.

Dratsch, T., Schwartz, C., Yanev, K., Schilbach, L., Vogeley, K., & Bente, G. (2013). Getting a grip on social gaze: Control over others' gaze helps gaze detection in high-functioning autism. *Journal of Autism and Developmental Disorders, 43*, 286-300.

Ewbank, M. P., Jennings, C., & Calder, A. (2009). Why are you angry with me? Facial expressions of threat influence perception of gaze direction. *Journal of Vision, 9,* 1-7.

Falck-Ytter, T., & von Hofsten, C. (2011). How special is social looking in ASD: A review. In O. Braddick, J. Atkinson & G. Innocenti (Eds.), *Progress in brain research, Vol. 189* (p. 225-238). Burlington: Academic Press.

Freitag, C. M., Konrad, C., Häberlen, M., Kleser, C., von Gontard, A., Reith, W., Troje, N. F., & Krick, C. (2008). Perception of biological motion in autism spectrum disorders. *Neuropsychologia, 46*, 1480-1494.

Gamer, M., & Hecht, H. (2007). Are you looking at me? Measuring the cone of gaze. *Journal of Experimental Psychology*. *Human Perception and Performance, 33,* 705-715.

Gamer, M., Hecht, H., Seipp, N., & Hiller, W. (2011). Who is looking at me? The cone of gaze widens in social phobia. *Cognition and Emotion*, *25*, 756-764.

Geisler, W. S. (1989). Sequential ideal-observer analysis of visual discriminations. *Psychological Review, 96,* 267-314.

Gepner, B., de Gelder, B., & de Schonen, S. (1996). Face processing in autistics: Evidence for a generalised deficit? *Child Neuropsychology, 2*, 123-139.

Gibson, J. T., & Pick, A. D. (1963). Perception of another person's looking behavior. *American Journal of Psychology, 76*, 386-394

Graham, R., & LaBar, K. S. (2007). The Garner selective attention paradigm reveals dependencies between emotional expression and gaze direction in face perception. *Emotion, 7*, 296-313.

Graham, R., & LaBar, K. S. (2012). Neurocognitive mechanisms of gaze-expression interactions in face processing and social attention. *Neuropsychologia, 50*, 553-566.

Howard, M. A., Cowell, P. E., Boucher, J., Broks, P., Mayes, A., Farrant, A., & Roberts, N. (2000). Convergent neuroanatomical and behavioural evidence of an amygdala hypothesis of autism. *Neuroreport, 11*, 2931-2935.

Jenkins, R., & Langton, S. R. H. (2003). Configural processing in the perception of eye-gaze direction. *Perception, 32*, 1181-1188.

Jones, W. B. A., Carr, K. B. A., & Klin, A. (2008). Absence of preferentially looking to the eyes of approaching adults predicts level of social disability in 2-year-old toddlers with Autism Spectrum Disorder. *Archives of General Psychiatry, 65*, 946-954.

Joseph, R. M., Ehrman, K., McNally, R., & Keehn, B. (2008). Affective response to eye contact and face recognition ability in children with ASD. *Journal of the International Neuropsychological Society, 14*, 947-955.

Kaartinen, M., Puura, K., Mäkelä, T., Rannisto, M., Lemponen, R., Helminen, M., Salmenin, R., Himanen, S., & Hietanen, J. K. (2012). Autonomic arousal to direct gaze correlates with social impairments among children with ASD. *Journal of Autism and Developmental Disorders, 42*, 1917-1927.

Kendon, A. (1967). Some functions of gaze-direction in social interaction. *Acta Psychologica, 26*, 22-63.

Kleinhans, N. M., Johnson, L. C., Richards, T., Mahurin, R., Greenson, J., Dawson, G., & Aylward, E. (2009). Reduced neural habituation in the amygdala and social impairments in autism spectrum disorders. *American Journal of Psychiatry, 166*, 467-475.

Klin, A., Jones, W., Schultz, R., Volkmar, F., & Cohen, D. (2002). Visual fixation patterns during viewing of naturalistic social situations as predictors of social competence in individuals with autism. *Archives of General Psychiatry, 59,* 809-816.

Krysko, K. M., & Rutherford, M. D. (2009). A threat-detection advantage in those with autism spectrum disorders. *Brain and Cognition*, *69,* 472-480.

Kyläiinen, A., & Hietanen, J. K. (2006). Skin conductance responses to another person's gaze in children with autism. *Journal of Autism and Developmental Disorders, 36*, 517-525.

Leekam, S., Baron-Cohen, S., Perrett, D., Milders, M., & Brown, S. (1997). Eye-direction detection: A dissociation between geometric and joint attention skills in autism. *British Journal of Developmental Psychology, 15*, 77-95.

Lord, C., & Haith, M. M. (1974). The perception of eye contact. *Perception and Psychophysics, 16*, 413-416.

Lord, C., Risi, S., Lambrecht, L., Cook, E. H., Leventhal, B. L., Dilavore, P. C., Pickles, A., & Rutter, M. (2000). The autism diagnostic observation schedule-generic: a standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders, 30*, 205-223.

Lundqvist, D., & Litton, J. E. (1998). The Averaged Karolinska Directed Emotional Faces--AKDEF. AKDEF CD ROM. Psychology section, Karolinska Institutet, Stockholm.

McCullagh, P., & Nelder, J. (1989). *Generalized linear models* (2nd ed.). Boca Raton, FL: Chapman & Hall/CRC.

Milders, M., Hietanen, J. K., Leppänen, J. M., & Braun, M. (2011). Detection of emotional faces is modulated by the direction of eye gaze. *Emotion*, *11*, 1456-1461.

Miyahara, M, Ruffman, T., Fujita, C. & Tsujii, M. (2010). How well can young people with Asperger's disorder recognize threat and learn about affect in faces?: A pilot study. *Research in Autism Spectrum Disorders, 4*, 242-248.

Monk, C. S., Weng, S., Wiggins, J. L., Kurapati, N., Louro, H. M. C., Carrasco, M., Maslowsky, J., Risi, S., & Lord, C. (2010). Neural circuit of emotional face processing in autism spectrum disorders. *Journal of Psychiatry and Neuroscience, 35*, 105-114.

Peli, E. (1991). Contrast sensitivity function and image discrimination. *Journal of the Optical Society of America A, 18*, 283-293.

Pelphrey, K. A., Morris, J. P., & McCarthy, G. (2005). Neural basis of eye gaze processing deficits in autism. *Brain, 128*, 1038-1048.

Pelphrey, K. A., Sasson, N. J., Reznick, J. S., Paul, G., Goldman, B. D., & Piven, J. (2002). Visual scanning of faces in autism. *Journal of Autism and Developmental Disorders, 32*, 249-261.

Pinkham, A. E., Hopfinger, J. B., Pelphrey, K. A., Piven, J., & Penn, D. L. (2008). Neural bases for impaired social cognition in schizophrenia and autism spectrum disorders. *Schizophrenia Research*, *99*, 164-175.

Rhodes, G., Addison, B., Jeffery, L., Ewbank, M., & Calder, A. J. (2012). Facial expressions of threat influence perceived gaze direction in 8-year-olds. *Public Library of Science One, 7,* e49317.

Schwaninger, A., Lobmaier, J. S., & Fischer, M. H. (2005). The inversion effect on gaze perception reflects processing of component information. *Experimental Brain Research*, *167*, 49-55.

Schultz, R. T. (2005). Developmental deficits in social perception in autism: the role of the amygdala and fusiform face area. *International Journal of Developmental Neuroscience*, *23*, 125-141.

Senju, A., Kikuchi, Y., Hasegawa, T., Tojo, Y., & Osanai, H. (2008). Is anyone looking at me? Direct gaze detection in children with and without autism. *Brain and Cognition*, *67*, 127-139.

Spezio, M. L., Adolphs, R., Hurley, R. S. E., & Piven, J. (2007). Analysis of face gaze in autism with "Bubbles". *Neuropsychologia, 45*, 144-151.

Symons, L. A., Lee, K., Cedrone, C. C., & Nishimura, M. (2004). What are you looking at? Acuity for triadic eye gaze. *Journal of General Psychology, 131*, 451-469.

Tjan, B. S., Braje, W. L., Legge, G. E., & Kersten, D. (1995). Human efficiency for recognizing 3-D objects in luminance noise. *Vision Research, 35*, 3053-3069.

Tottenham, N., Tanaka, J. W., Leon, A. C., McCarry, T., Nurse, M., & Hare, T. A., Marcus, D. J., Westerlund, A., Casey, B. J., & Nelson, C. (2009). The NimStim set of facial expressions: Judgments from untrained research participants. *Psychiatry Research, 168*, 242-249.

Vida, M. D., & Maurer, D. (2012a). Gradual improvement in fine-grained sensitivity to triadic gaze after 6 years of age. *Journal of Experimental Child Psychology, 111*, 299-318.

Vida, M. D., & Maurer, D. (2012b). The development of fine-grained sensitivity to eye contact after 6 years of age. *Journal of Experimental Child Psychology, 112*, 243-256.

Wallace, S., Coleman, M., Pascalis, O., & Bailey, A. (2006). A study of impaired judgment of eye-gaze direction and related face processing deficits in autism spectrum disorders. *Perception, 35*, 1651-1664.

Watson, A. B., & Pelli, D. G. (1983). QUEST: a Bayesian adaptive psychometric method. *Perception and Psychophysics, 33*, 113-120.

Watt, R., Craven, B., & Quinn, S. (2007). A role for the eyebrows in regulating the visibility of eye gaze direction. *The Quarterly Journal of Experimental Psychology, 60*, 1169-1177.

Webster, S., & Potter, D. D. (2008). Brief report: Eye direction detection improves with development in autism. *Journal of Autism and Developmental Disorders, 38,* 1184-1186.

Webster, S., & Potter, D. D. (2011). Gaze perception develops atypically in children with autism. *Child Development Research*, Article ID 462389, 1-9.

Weigelt, S., Koldewyn, K., & Kanwisher, N. (2012). Face identity recognition in autism spectrum disorders: A review of behavioural studies. *Neuroscience and Biobehavioral Reviews, 36*, 1060-1084.

Tables

Table 1

Age and IQ scores of participants; standard deviations are shown in parentheses

Group	*Age (years)*	*Verbal IQ*	*Performance IQ*	*Full-scale IQ*
ASD	27.6 (6.5)	97.6 (14.7)	101.9 (14.8)	99.5 (12.6)
Control	26.3 (6.4)	97.8 (12.3)	100.6 (13.7)	99.5 (12.8)
	$t(32) = .56$, $p > .55$	$t(32) = .05$, $p > .95$	$t(32) = .25$, $p > .80$	$t(32) = .01$, $p > .95$

Table 2

ADOS scores for the ASD group: Mean, standard deviation in parentheses, and range

Communication	*Social*	*Repetitive*
4.2 (2.5)	8.5 (3.2)	.3 (.6)
2-9	3-16	0-2

Figures

Figure 1

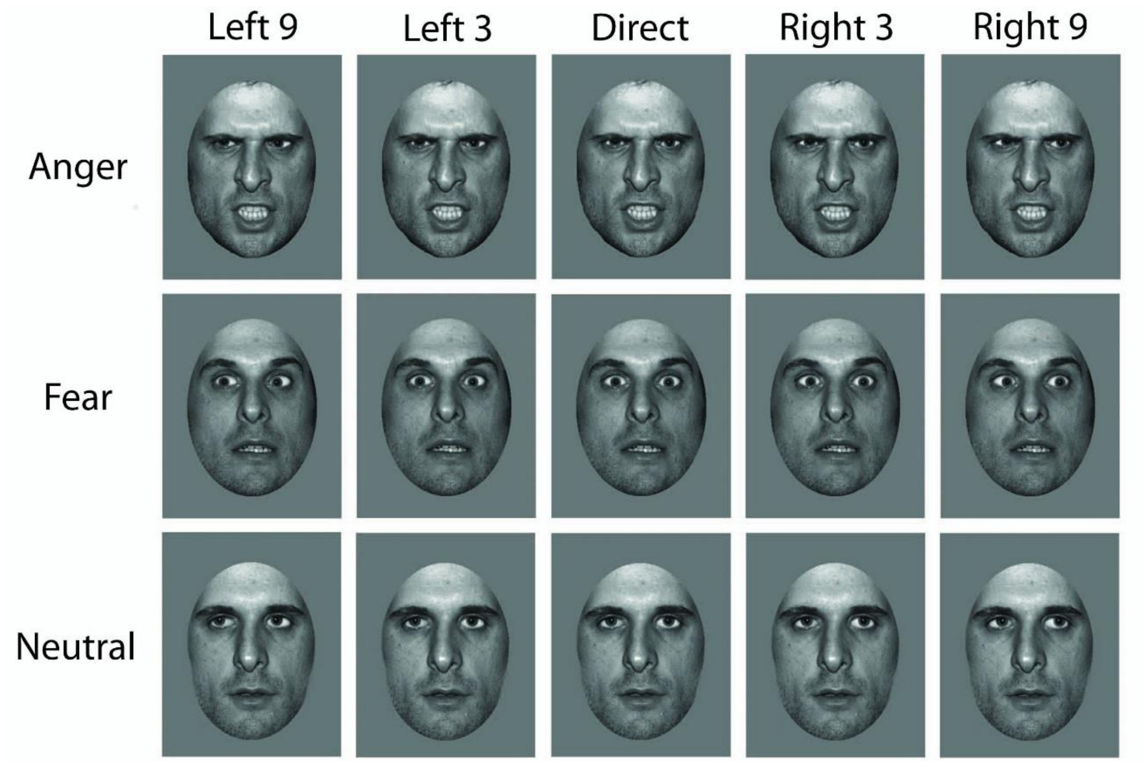
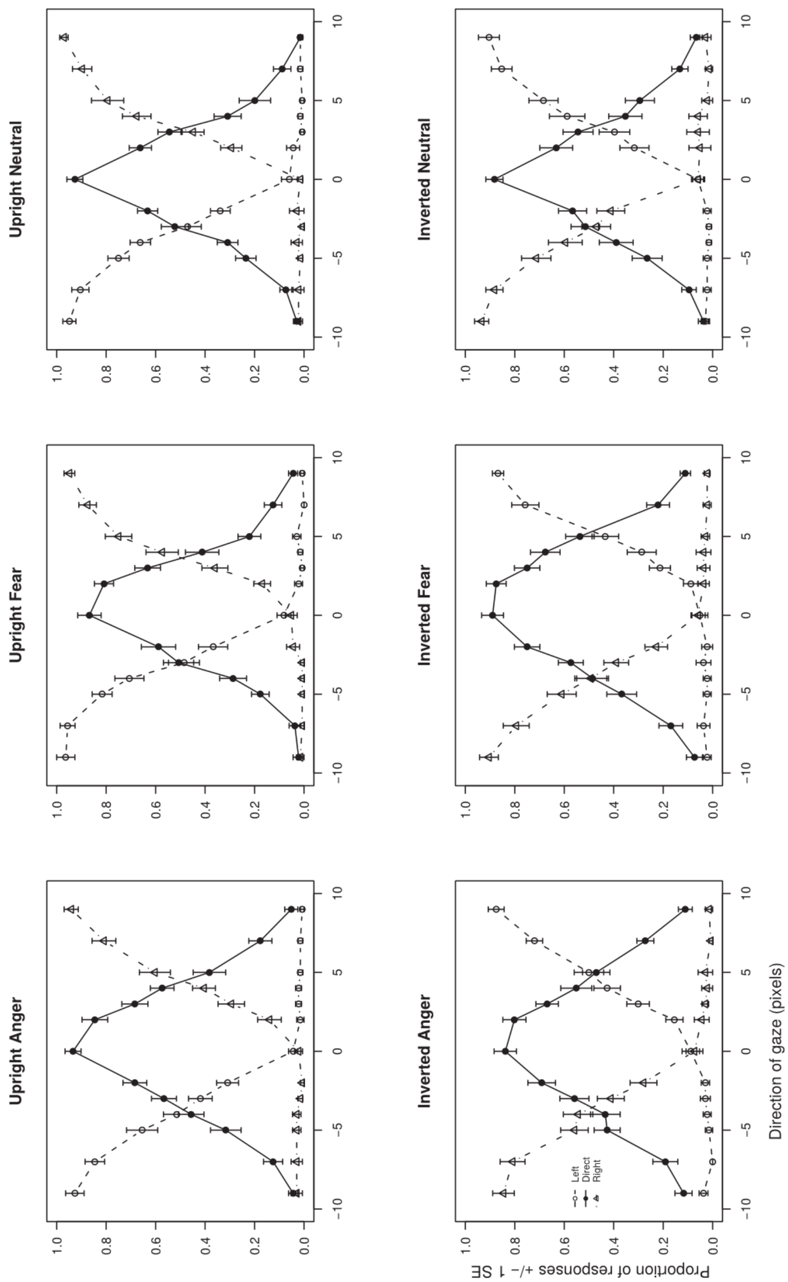


Figure 1. Examples of stimuli. Each model displayed angry, fearful and neutral expressions. One model posing each of the three expressions is shown for five of the directions of gaze used in the current experiment: 9 pixels left, 3 pixels left, direct gaze, 3 pixels right, and 9 pixels right.

Figure 2

A


Upright Neutral
Upright Fear
Upright Anger
Inverted Neutral
Inverted Fear
Inverted Anger
Left
Direct
Right
Direction of gaze (pixels)
Proportion of responses +/− 1 SE

B

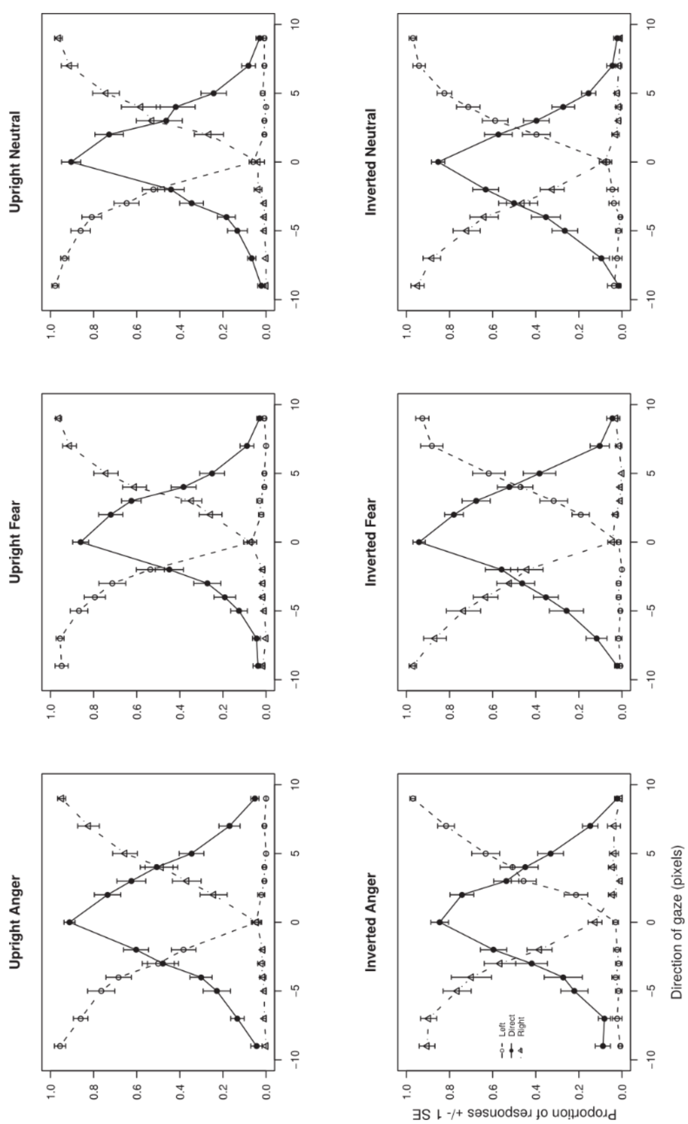


Figure 2. (A) Mean proportion of each response type ± 1 *SE* for typical participants, as a function of direction of gaze. Each plot displays the data for one expression and orientation. For the upright condition, negative values on the x axes represent gaze directed to the participant's left, and positive values represent gaze directed to the participant's right. For the inverted condition, negative values on the x axes represent gaze directed to the participant's right, and positive values represent gaze directed to the participant's left. The legend and axis labels supplied for the bottom left plot apply to all other plots in this panel. (B) Corresponding data for participants in the ASD group.

Figure 3

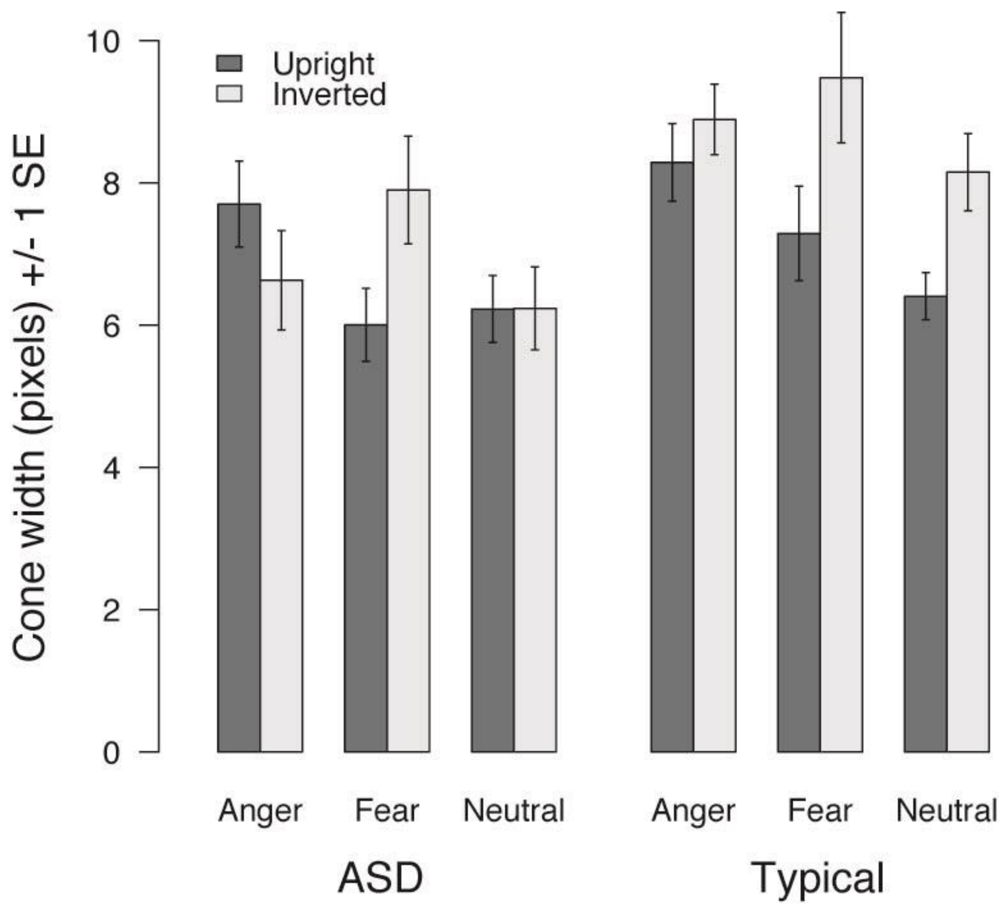


Figure 3. Mean width of the cone of gaze (pixels) ± 1 *SE* as a function of expression, orientation, and group.

Figure 4

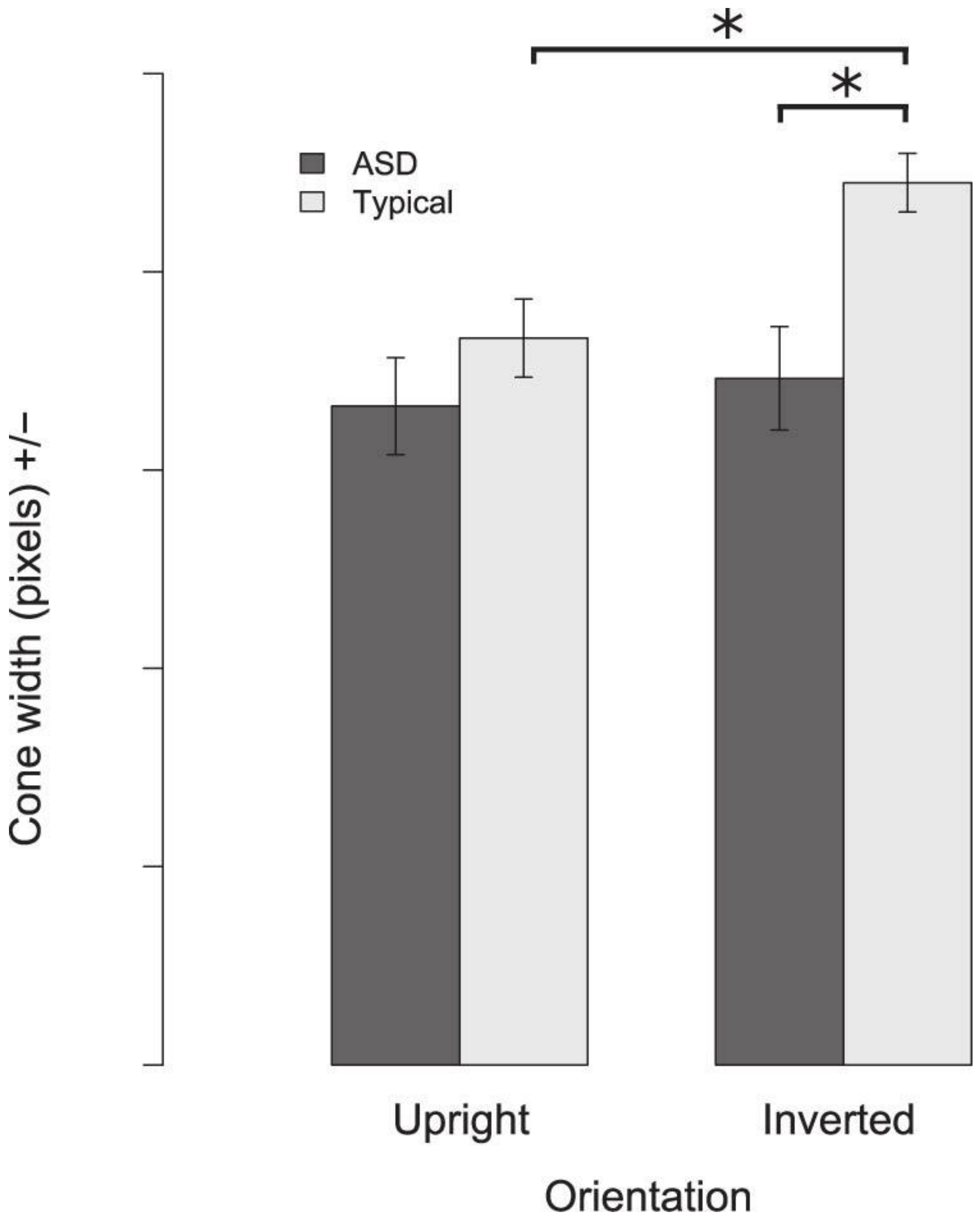


Figure 4. Mean width of the cone of gaze (pixels) ± 1 *SE* as a function of orientation and group.* indicates a significant difference, $p < .01$.

Figure 5

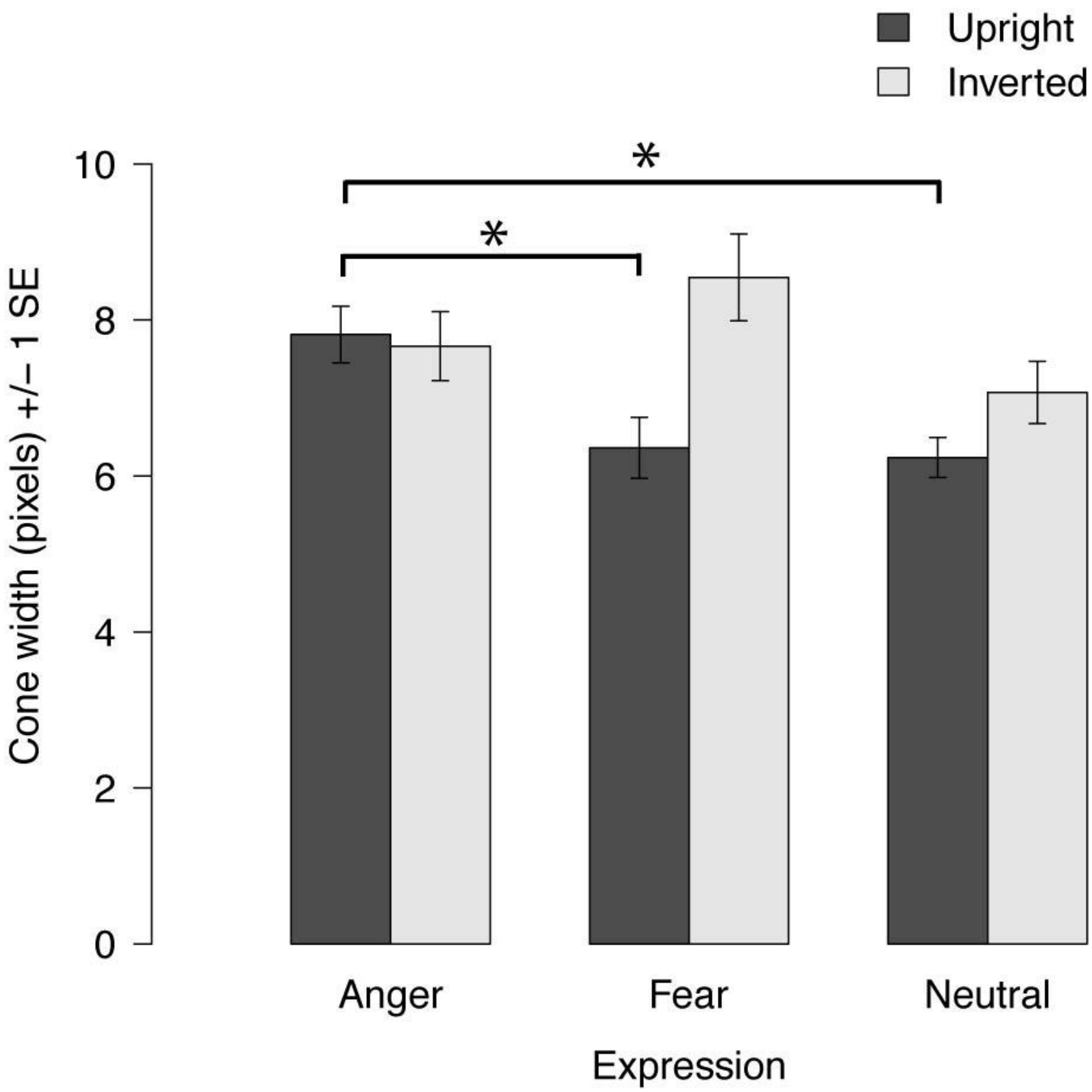


Figure 5. Mean width of the cone of gaze (pixels) ± 1 *SE* as a function of expression and orientation. * indicates a significant difference, $p < .01$.

Figure 6

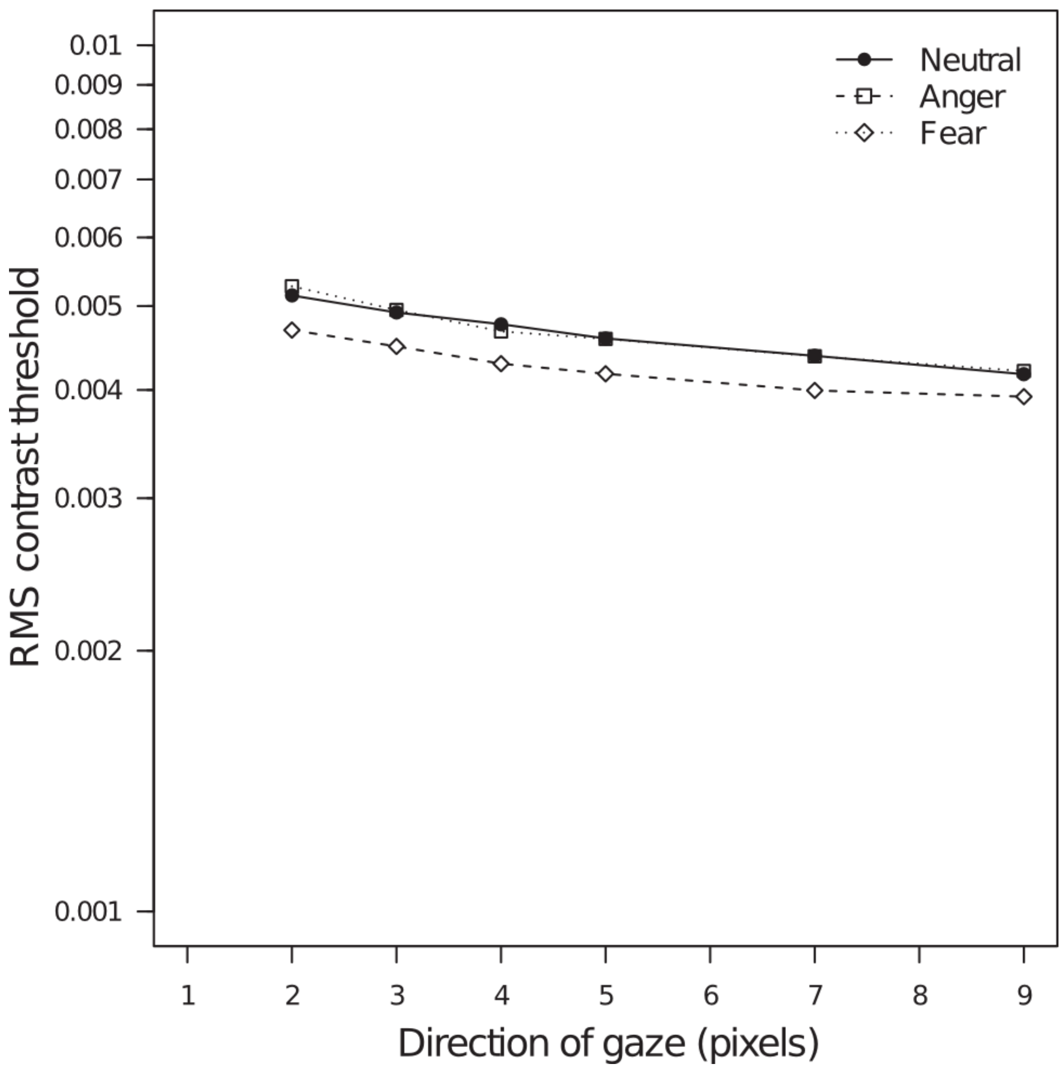


Figure 6. Mean root mean square (RMS) contrast thresholds for the ideal observer ± 1 *SE* as a function of the direction of gaze and expression type. In all cases, the standard error was so small that the error bar was occluded by the data point.

Appendix A

We calculated the residual deviance for each logistic fit (see Dalgaard, 2008; McCullagh & Nelder, 1989). A larger residual deviance reflects greater discrepancy between the model and the data. The residual deviance and residual degrees of freedom for a fit correspond approximately to a χ^2 distribution (see Dalgaard, 2008). A χ^2 probability of less than .05 is typically taken as an indicator of a poor fit. For the current design, the deviance residual corresponding with this probability is 19.65. The largest residual deviance observed in the current experiment was 5.44, which corresponds to a χ^2 probability of .91. Hence, there was no significant discrepancy between the data and the model for any of the fits in the current study.

Appendix B

The ideal observer's task was as follows: on every trial, we presented a face from the main experiment with a particular direction of gaze (2, 3, 4, 5, 7, or 9 pixels, left or right), emotion (neutral, angry, fearful), identity, and root mean square (RMS) contrast. RMS contrast is defined as:

$$rms = \left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2\right]^{\frac{1}{2}}$$

where *n* is the number of pixels in the image, x_i is the intensity of pixel *i* (normalized so that $0 \leq x_i \leq 1$), and $\overline{x}$ is the mean normalized pixel intensity (Peli, 1991). Using the optimal decision rule (Tjan et al., 1995), the ideal observer selected the most likely direction of gaze (left or right). Using QUEST, a Bayesian adaptive threshold estimator, the RMS contrast for the next trial was adjusted based on the correctness of the ideal observer's response, such that correct responses generally led to lower (less visible) contrast levels (Watson & Pelli, 1983). Each contrast threshold was estimated based on 240 trials, and we estimated 25 thresholds per condition. Finally, note that in the absence of noise, the ideal observer will never respond incorrectly at any contrast level, so we added Gaussian white noise (RMS contrast = 0.28) to the stimulus on every trial. A new noise sample was generated for each trial, so that the appearance of the noise varied randomly across trials.

Chapter 6 - Discussion

Summary

In the current thesis, I examined the development of sensitivity to the direction of eye gaze during middle childhood, and examined how development differs in high-functioning adults with autism spectrum disorder (ASD). In Study 1 (three experiments), I examined fine-grained sensitivity to horizontal differences in gaze relative to an object in the environment (triadic gaze) in 6-, 8-, 10-, 14-year-olds, and adults. In Experiment 1, thresholds for detecting horizontal differences in triadic gaze were around 2° at age 6, and decreased gradually thereafter, reaching a statistically adult-like value of around 1° by 10 years of age. In both children and adults, sensitivity was higher when the target was at midline than when it was in the periphery, and there was a bias to judge gaze toward peripheral targets as being directed farther into the periphery than it actually was. In Experiment 2, increasing the range of deviations of gaze from the target did not improve 6-year-olds' thresholds, a finding which suggests that the higher thresholds for younger children in Experiment 1 were not an artifact of omitting trials for which the deviation of gaze was very large and therefore easy to detect. In Experiment 3, 8-year-olds were less accurate than adults in matching the direction of eye gaze between simultaneously-presented faces, a result suggesting that developmental changes in sensitivity to triadic gaze reflect, at least in part, developmental changes in sensitivity to eye position. As in Experiment 1, both children's and adults' accuracy was better when the faces were fixating a target near midline than when the target was in the periphery. Together, these data suggest that until around 10 years of age, children's ability to judge the focus of others' visual attention is limited by immature sensitivity to triadic gaze.

In Study 2, I measured the horizontal and vertical ranges of directions of gaze leading to the perception of direct gaze (the cone of gaze) in adults, and in 6-, 8-, 10-, and 14-year-olds. The horizontal cone of gaze was large (around 8.5º) at age 6, and narrowed to a statistically adult-like value of around 6º by age 8. In contrast, the vertical cone of gaze was already statistically adult-like at age 6, with only a small linear reduction thereafter. By age 8, the vertical cone of gaze was significantly larger than the horizontal cone of gaze, as it is in adults. In both children and adults, the horizontal cone of gaze was centered on the bridge of the participant's nose, whereas the vertical cone of gaze was centered around 1º below the participants' eye height. These results suggest that although some aspects of sensitivity to direct and averted gaze appear to be adult-like at age 6, this sensitivity is not fully adult-like until age 8, and that developmental trajectories differ between horizontal and vertical judgments of direct and averted gaze.

In Study 3 (two experiments) I examined the effect of voice cues on the width of the cone of gaze in adults and children aged 6 and 8 years. In Experiment 1, the horizontal cone of gaze was wider in 6-year-olds than it was in 8-year-olds and adults, with no difference between the latter two. The horizontal cone of gaze of 6-year-olds was narrower when participants heard object-directed voice cues (e.g., “I see that.”) than when they heard participant-directed (e.g., “I see you.”) voice cues or no voice. However, this effect was not observed in 8-year-olds or adults, and even with the object-directed voice cues, 6-year-olds' cone of gaze was wider than that of 8-year-olds and adults. In Experiment 2, the effect of voice cues was the same in adults as in 6-year-olds in Experiment 1 when the task was made more difficult by limiting the duration of exposure to the face. Together, these results suggest that both children and adults combine information from gaze and voice cues when making judgments of gaze, and that the integration can allow more adult-like judgments of gaze in young children.

In Study 4, I examined the effects of face inversion (i.e., turning the face upside down) and facial expression on the width of the horizontal cone of gaze in high-functioning adults with and without autism spectrum disorder (ASD). The cone of gaze was narrower for upright than for inverted faces, but only in the typical group. There was no difference between groups in the width of the cone of gaze for upright faces, but the cone of gaze for inverted faces was narrower in the ASD group than in the typical group. In both the typical and ASD groups, the cone of gaze was wider for angry faces than for neutral or fearful faces. This effect was present for upright faces, but not inverted faces. An ideal observer analysis indicated that the wider cone of gaze for angry faces does not reflect a lack of information available to perform the task. Combined, these results suggest that in high-functioning adults with ASD, the perception of eye gaze is not tuned to be finer for upright than for inverted faces, but that information is nevertheless integrated across expression and gaze. Studies 1-4 are the first to investigate the development of fine-grained sensitivity to triadic gaze during middle childhood, the development of fine-grained sensitivity to horizontal and vertical differences between direct and averted gaze during middle childhood, the influence of voice cues on fine-grained sensitivity to direct and averted gaze during middle childhood, and the influences of facial expression and face inversion on fine-grained sensitivity to direct and averted gaze in high-functioning adults with ASD.

Typical Adults

The current results replicate and extend the results of previous investigations of sensitivity to the direction of gaze in typical adults. Previous work indicates that adults can detect horizontal differences of approximately 1º in triadic gaze for a target at midline, and that sensitivity is slightly lower for targets in the periphery (e.g., Symons et al., 2004). Also, adults possess a bias to perceive gaze toward peripheral objects as being directed farther into the periphery than it actually is (Symons et al., 2004). The same pattern was present in adults in Study 1 (Experiment 1). The finding in Study 1 (Experiment 3) that adults' accuracy in detecting mismatches in the direction of gaze between simultaneously presented faces was better when the faces fixated targets near midline than when the targets were in the periphery provides the first evidence that adults' poorer sensitivity to triadic gaze for targets in the periphery may be driven, at least in part, by lower sensitivity to differences in eye position for peripheral directions of gaze.

Previous work also indicates that although adults are highly sensitive to horizontal differences in triadic gaze (e.g., Symons et al., 2004), they judge gaze to be direct over a relatively wide horizontal range (approximately 5.5º) of directions of gaze (e.g., Gibson & Pick, 1963). Previous work also indicates that the horizontal cone of gaze is centered on the bridge of the participant's nose (e.g., Gibson & Pick, 1963). The results of Studies 2 and 3 replicate this pattern in adults. The results of Study 2 also provide the first evidence that the vertical cone of gaze is larger than the horizontal cone of gaze, and that the vertical cone of gaze is centered below the height of the participant's eyes. The dimensions of adults' horizontal and vertical cone of gaze match the dimensions of an adult human's face when viewed at a typical conversational distance. Hence, the sizes of adults' horizontal and vertical cone of gaze may reflect calibration of adults' judgments to match the dimensions of the participant's own face. This calibration may reduce social costs associated with attributing averted gaze when gaze is actually direct (e.g., missing an opportunity to interact with a person who wishes to do so) without seriously inflating social costs associated with attributing direct gaze when gaze is actually averted (e.g., attempting to interact with a person who is not interested in doing so). This calibration could involve tuning of responses within brain regions implicated in processing of direct and averted gaze (e.g., mPFC; see Carlin & Calder, 2012) by experience with horizontal and vertical deviations from direct gaze.

Previous studies also indicate that adults' judgments of direct and averted gaze are modulated by contextual information, including voice cues and facial expression. For example, the cone of gaze is wider when participants hear a voice saying the participant's own name than when participants hear a different person's name, a pattern that could arise from an increase in the width of the cone of gaze when hearing one's own name and/or a decrease when hearing a different person's name (Stoyanova et al., 2010). Also, the cone of gaze is wider for angry faces than for fearful or neutral faces, with no difference between the latter two, a result suggesting that adults may have a bias to interpret threatening signals as self-directed (Ewbank et al., 2009). Study 3 (Experiment 2) is the first to examine the effect of participant-directed (e.g., “I see you.”) and object-directed voice cues (e.g., “I see that.”) on the width of adults' horizontal cone of gaze, in comparison to a control condition in which no voice cues were presented. The finding in Study 3 (Experiment 2) that adults' cone of gaze was narrower when participants heard object-directed voice cues than when they heard participant-directed voice cues or no voice provides the first evidence that object-directed voice cues can decrease the width of adults' cone of gaze. In view of the finding that the same region of mPFC is activated when individuals hear a voice saying their own name, and when they perceive direct gaze (Kampe et al., 2003), it seems possible that the effect of object-directed voice cues on judgments of gaze in Study 3 is mediated by responses in mPFC. The finding in Study 4 that typical adults' cone of gaze is wider for angry faces than for fearful or neutral faces replicates previous findings in typical adults (Ewbank et al., 2009), and supports the hypothesis that typical adults possess a bias to interpret threatening signals as being self-directed. This bias could involve responses in brain regions involved in processing of direct and averted gaze, and in processing of threatening stimuli (e.g., amygdala, see Senju & Johnson, 2009).

Finally, previous work indicates that typical adults' thresholds for detecting differences between leftward and rightward gaze (Jenkins & Langton, 2003; Schwaninger et al., 2005) are lower for upright faces than for inverted faces, a pattern suggesting that mechanisms underlying adults' visual sensitivity to the direction of gaze (e.g., responses in STS) are tuned by experience with upright faces. In Study 4, we found for the first time that the cone of gaze is narrower for upright faces than for inverted faces, a result suggesting that, like sensitivity to differences between leftward and rightward gaze (Jenkins & Langton, 2003; Schwaninger et al., 2005) sensitivity to direct and averted gaze is tuned to be finer for upright than inverted faces. This result is not surprising given that judgments of direct and averted gaze are likely to be constrained, to at least some extent, by visual sensitivity to differences in the direction of gaze.

Typical Development

The current thesis provides the first information on the development of sensitivity to the direction of eye gaze after age 6. Previous studies indicate that children exceed chance in making explicit judgments of large differences in triadic gaze at 2-3 years of age (e.g., Doherty et al., 2009), and that children aged 2 to 6 years are less accurate than adults in judging which of three objects spaced 10º apart an adult is looking at (Doherty et al., 2009). The finding in Study 1 (Experiment 1) that 6-year-olds were able to detect horizontal differences of around 2º in triadic gaze provides the first evidence that young children can detect small differences in triadic gaze. However, the finding in Study 1 (Experiment 1) that thresholds for triadic gaze were not statistically adult-like until age 10 provides the first evidence that sensitivity to triadic gaze develops gradually throughout mid childhood. The finding in Study 1 (Experiment 3) that 8-year-olds were less accurate than adults in detecting horizontal differences in the direction of gaze between simultaneously presented faces provides the first evidence that children's sensitivity to triadic gaze is limited, at least in part, by immature sensitivity to eye position. Finally, the findings in Study 1 (Experiments 1 and 3) that, like adults, children were more sensitive to differences in the direction of gaze around midline than in the periphery suggest that children and adults may use a qualitatively similar mechanism to decode the direction of gaze. Together, these results suggest that until around age 10, immature sensitivity to triadic gaze will limit children's ability to judge the focus of others' visual attention.

Previous studies indicate that by 2-3 years of age, children first exceed chance in making explicit judgments about large differences between direct and averted gaze (Doherty et al., 2009; Lee et al., 1998). The finding in Studies 2 and 3 that the horizontal cone of gaze narrows by approximately 50% (from approximately 8.5º to approximately 6º) between 6 and 8 years of age provides the first evidence that judgments of horizontal differences between direct and averted gaze undergo considerable refinement after age 6. However, the findings in Study 2 that the size of the vertical cone of gaze was adult-like at age 6, and that the horizontal and vertical cone of gaze were centered on the same positions (i.e., the bridge of the participant's nose for the horizontal cone of gaze, and slightly below the participant's eye height for the vertical cone of gaze) in adults and children provide the first evidence that at least some aspects of children's sensitivity to direct and averted gaze are adult-like at age 6. Studies 2 and 3 also indicate that the dimensions of adults' horizontal and vertical cone of gaze roughly match the width and height of an adult human's face, respectively. Although the sizes of the vertical and horizontal cone of gaze are adult-like at ages 6 and 8, respectively (Studies 2 and 3), a child's cone of gaze is likely to be larger than the child's own face at these ages, because 6- and 8-year-olds' heads are smaller than those of adults (e.g., Meredith, 1953; Nellhaus, 1968). Finally, the finding in Study 3 that 6-year-olds' horizontal cone of gaze was narrower when they heard object-directed voice cues (e.g., “I see that.”) than when they heard participant-directed voice cues (“I see you.”) or no voice provides the first evidence that young children integrate information from gaze and voice when making judgments of gaze, and that the integration can allow more adult-like judgments of eye gaze in young children. Together, these results suggest that until around age 8, immature sensitivity to differences between direct and averted gaze will limit children's ability to judge whether or not others are paying attention to the child.

Developmental changes in children's ability to discriminate the direction of gaze could reflect differences in attentiveness, motivation, and/or understanding of the tasks. However, at least three patterns in the current thesis provide evidence against these hypotheses: first, in all studies including children, there were no age differences in performance on catch trials designed to assess attentiveness and/or motivation. Second, all children met the same criteria as adults on practice trials designed to assess understanding of the task. Third, the horizontal cone of gaze narrowed considerably between ages 6 and 8, but there was no corresponding change in the vertical cone of gaze, a result inconsistent with developmental changes in general cognitive factors. Hence, it seems unlikely that developmental changes in children's sensitivity to the direction of eye gaze reflect solely changes in attentiveness, motivation, and/or understanding of the tasks.

The different developmental trajectories observed for judgments of triadic gaze (Study 1) and judgments of direct and averted gaze (Studies 2 and 3) may reflect developmental changes in different underlying mechanisms. The improvement in sensitivity to triadic gaze observed between 6 and 10 years in Study 1 (Experiments 1 and 2) seems likely to reflect improvements in one or more aspects of visual sensitivity. For example, higher sensitivity to differences in eye position (i.e., the position of the iris within the visible sclera) could allow higher sensitivity to differences in triadic gaze. Evidence consistent with this hypothesis comes from the finding in Study 1 (Experiment 3) that accuracy in discriminating the direction of gaze between simultaneously presented faces was higher in adults than in 8-year-olds, in whom sensitivity to triadic gaze was not yet adult-like. Improvements in sensitivity to eye position could in turn reflect improvements in general mechanisms of shape and/or object perception. Support for this hypothesis comes from findings that before 10 years of age, the age at which children's sensitivity to horizontal differences in triadic gaze first becomes statistically adult-like, children are less sensitive than adults to differences in spatial relations in both face and non-face visual stimuli (e.g., Baudouin et al., 2010; Hadad, Maurer, & Lewis, 2010a; Hadad, Maurer, & Lewis, 2010b). Improvements in sensitivity to eye position could also reflect refinements in mechanisms specialized for the visual analysis of gaze signals (e.g., responses in STS) (see Carlin & Calder, 2012). Improvements in sensitivity to triadic gaze could also involve improvements in the ability to triangulate the target of gaze based on the perceived direction of gaze, which could in turn reflect refinements in general mechanisms of shape and/or object processing, and/or refinements in brain regions implicated in joint attention (e.g., responses in mPFC) (see Carlin & Calder, 2012).

The considerable narrowing of the horizontal cone of gaze (from around 8.5° to around 6°) observed between 6 and 8 years could also be driven primarily by refinements in visual sensitivity. However, three patterns in the current thesis provide evidence against this hypothesis: first, in Study 1, both 6- and 8-year-olds were able to detect shifts of approximately 2° in triadic gaze, a value smaller than the distance between the centre and outer edge of adults' horizontal cone of gaze (around 2.75°) in Studies 2 and 3. This pattern suggests that 6-year-olds' visual sensitivity is high enough for their cone of gaze to be much smaller than it was in Studies 2 and 3. Second, if the narrowing of the horizontal cone of gaze between 6 and 8 years of age had been driven solely by changes in visual sensitivity, one might expect to observe a corresponding reduction in thresholds for triadic gaze. However, in Study 1 (Experiment 1), there was little to no change between 6 and 8 years of age in thresholds for triadic gaze. Finally, the finding in Study 3 (Experiment 1) that 6-year-olds' cone of gaze was narrower when participants heard object-directed voice cues (e.g., “I see that.”) than when they heard participant-directed voice cues (e.g., “I see you.”) or no voice provides evidence that non-visual cues can decrease the width of 6-year-olds' cone of gaze. Hence, it seems unlikely that the narrowing of the horizontal cone of gaze between 6 and 8 years of age is driven solely by changes in visual sensitivity.

The narrowing of the horizontal cone of gaze between ages 6 and 8 could also reflect changes in children's interpretation of gaze cues (i.e., decisions about whether gaze is direct or averted when the perceived direction of gaze is ambiguous). For small horizontal deviations from direct gaze, young children may be able to detect the shift of gaze, but may nevertheless perceive direct gaze, whereas older children and adults may perceive averted gaze. This difference in interpretation could reflect a difference in the perceived social costs of erroneously attributing direct gaze when a person's gaze is actually averted (e.g., experiencing embarrassment after attempting to interact with a person who is not interested in doing so). These perceived costs may be lower in younger children for several reasons, including higher egocentrism (i.e., a failure to appreciate that others may have interests that are unrelated to oneself) (e.g., Piaget 1926; 1930), a tendency among caregivers to avoid imposing these social costs on younger children, and less experience with individuals who would impose these costs on the child (e.g., unfamiliar children who the child might encounter at school). Increases during childhood in the perceived costs of erroneously attributing direct gaze may affect children's interpretation of gaze cues so that children will be less likely to perceive direct gaze when gaze is slightly averted. This change may account for the considerable narrowing of the horizontal cone of gaze observed between 6 and 8 years of age. A change in children's interpretation of gaze signals could reflect refinements in mPFC, a brain region implicated in the perception of direct versus averted gaze, and in several other aspects of social perception and cognition, including reasoning about the mental states of others (see Carlin & Calder, 2012; Senju & Johnson, 2009).

A comparison of the developmental trajectories observed for judgments of eye gaze in the current thesis with those observed for judgments of facial expression and facial identity in previous studies reveals a pattern consistent with a distributed face processing system in which there is partial functional segregation and partial functional overlap among parts of the system (see Carlin & Calder, 2012; Haxby, Hoffman, & Gobbini, 2000). Accuracy in judgments of gaze (e.g., sensitivity to triadic gaze in Study 1), facial expression (e.g., Gao & Maurer, 2010) and facial identity (e.g., Mondloch, Geldart, Maurer, & Le Grand, 2003) improves during middle childhood. This general improvement could reflect refinements in functionally overlapping mechanisms underlying the perception of more than one of these facial signals (e.g., responses in STS, FG; see Haxby et al., 2000). However, the developmental trajectories observed for judgments of eye gaze differ from those observed previously for facial expression and identity. Accuracy in recognizing at least some facial expressions (e.g., anger and sadness; Gao & Maurer, 2010), and performance on some face recognition tasks (e.g., recognizing faces across changes in viewpoint, and discriminating faces based on differences in spacing among facial features; Mondloch et al., 2003; Mondloch, Le Grand, & Maurer, 2002) does not become adult-like until after age 10. In contrast, all aspects of sensitivity to eye gaze measured in the current thesis were adult-like at or before age 10. These differences suggest at least some degree of functional segregation between neural mechanisms underlying developmental changes in judgments of eye gaze, and those underlying developmental changes in judgments of facial expression and facial identity.

Factors limiting children's sensitivity to dyadic and triadic gaze. The results of the current thesis suggest that different factors may limit children's sensitivity to dyadic and triadic gaze. In Study 1, children's thresholds for discriminating differences in triadic gaze first became adult-like around age 10. Children's sensitivity to the alignment of abutting lines (Vernier acuity; Skoczenski & Norcia, 1999) and the spacing between the eyes (Baudouin, Gallay, Durand, & Robichon, 2010) first becomes adult-like at around the same age. Also, in Study 1, 8-year-olds' thresholds for discriminating differences in triadic gaze (approximately 2º) were approximately twice as large as those of adults (approximately 1º), and 8-year-olds needed differences in the direction of gaze (8.0º) approximately twice as large as those of adults (4.8º) to exceed 75% accuracy in discriminating the direction of gaze between simultaneously-presented faces. These results suggest that children's sensitivity to triadic gaze may be limited primarily by their visual sensitivity to differences in eye position. Improvements in this sensitivity could reflect the maturation of the visual system (e.g., increasing neural inhibition; Leventhal et al., 2003; Pinto, Jones, Hornby, & Murphy, 2010; Thiele, Herrero, Distler, & Hoffmann, 2012), and/or tuning driven by the accumulation of experience with face and non-face stimuli, and/or social feedback received in response to erroneous judgments of gaze. In contrast, children's judgments of dyadic gaze may be limited primarily by immaturities in their interpretation of gaze cues. In Studies 2 and 3, 6-year-olds' cone of gaze was much wider (approximately 8.5º) than that of adults, even though 6-year-olds in Study 1 were able to detect differences in triadic gaze (approximately 2º) small enough for their cone of gaze to be as narrow as that of adults (approximately 5.5º). Also, in Studies 2 and 3 children's cone of gaze narrowed considerably between ages 6 and 8, but in Study 1 there was no corresponding reduction in children's thresholds for triadic gaze within this age range. Finally, in Study 3, hearing object-directed voice cues (e.g., “I see that.”) decreased the width of 6-year-olds' cone of gaze. These voice cues seem unlikely to affect children's visual sensitivity to the direction of gaze, but could affect children's interpretation of gaze cues. Together, these results suggest that whereas children's judgments of triadic gaze are limited primarily by visual sensitivity, children's judgments of dyadic gaze are limited primarily by their interpretation of gaze cues.

Atypical Development

The results of the current thesis provide the first precise estimates of the width of the cone of gaze in high-functioning adults with autism spectrum disorder (ASD), and provide the first information on the influences of face inversion and facial expression on the width of the cone of gaze in this population. Previous studies investigating accuracy in discriminating the direction of gaze in individuals with ASD indicate that given sufficient differences between direct and averted gaze and a long duration of exposure to the stimulus, individuals with ASD can make normal judgments of direct and averted gaze (Ashwin et al., 2009; Senju et al., 2008). However, there is also evidence that both children and adults with ASD are less accurate than controls in discriminating small differences between direct and averted gaze (Campbell et al., 2006; Dratsch et al., 2013; Gepner et al., 1996; Howard et al., 2000; Webster & Potter, 2008; 2011). Although previous studies have not investigated the influence of a model’s facial expression on judgments of eye gaze, previous research suggests that the influence of gaze direction on behavioural and neural indices of expression perception is atypical in children with ASD (Akechi et al., 2009; 2010). Also, one study indicates that performance on a visual search task involving judgments of eye gaze is distorted by face inversion in typically developing children, but not in children with ASD (Senju et al., 2008).

The finding in Study 4 of no difference between high-functioning adults with and without ASD in the width of the cone of gaze for upright faces replicates previous findings that, under at least some conditions, individuals with ASD can make normal judgments of direct and averted gaze (Ashwin et al., 2009; Senju et al., 2008). However, the finding in Study 4 that face inversion increased the width of the cone of gaze in typical adults, but not in adults with ASD, provides the first evidence that, unlike typical adults (e.g., Jenkins & Langton, 2003; Schweinberger et al., 2005), but similar to children with ASD (Senju et al., 2008), sensitivity to the direction of gaze is not higher for upright than for inverted faces in high-functioning adults with ASD. This pattern could reflect abnormal tuning of mechanisms involved in the visual analysis of gaze signals (e.g., responses in STS) by experience with upright faces (see Carlin & Calder, 2012). Finally, the finding in Study 4 that in both groups, the cone of gaze was wider for angry faces than for fearful or neutral faces provides the first evidence that, like typical adults (Ewbank et al., 2009), adults with ASD may possess a bias to interpret threatening signals as being self-directed. In conjunction with previous studies reporting that the influence of the direction of gaze on processing of facial expression is abnormal in children with ASD (Akechi et al., 2009; 2010), this pattern may indicate that mechanisms underlying interactions between expression and gaze (e.g., responses in amygdala, see Carlin &

Calder, 2012) are developmentally delayed in high-functioning individuals ASD, so that these interactions are atypical in childhood, but normalize by adulthood. Alternatively, the results could indicate that interactions between gaze and expression are unidirectional in ASD, so that the influence of expression on the perception of gaze is normal, but the opposite influence is atypical.

Comparison of Dyadic and Triadic Gaze

Although judgments of both dyadic and triadic gaze depend to some degree on sensitivity to differences in eye position, these two types of judgments seem likely to involve different cognitive and/or visual processing. Specifically, judgments of triadic gaze involve triangulation between the direction of a person's gaze and a target in the environment, whereas judgments of dyadic gaze require using the direction of a person's gaze to form an impression about whether or not one is being looked at. This impression may reflect, at least in part, the subjective interpretation of gaze cues. Support for this hypothesis comes from findings that adults' cone of gaze is much wider (approximately 5.5º; e.g., Gibson & Pick, 1963) than their threshold for discriminating horizontal shifts of triadic gaze (approximately 1º; e.g., Symons et al., 2004). This was also true in 6-year-olds in Studies 2 and 3, in whom the horizontal cone of gaze was much wider (approximately 8.5º) than that of adults, even though 6-year-olds in Study 1 were able to detect differences in triadic gaze (approximately 2º) small enough for their horizontal cone of gaze to be as narrow as that of adults (approximately 5.5º). Also, in adults and children in previous studies (Ewbank et al., 2009; Rhodes et al., 2012; Stoyanova et al., 2010) and in Study 3, the cone of gaze was modulated by social contextual information. Finally, in Studies 2 and 3, children's cone of gaze narrowed considerably between ages 6 and 8, but in Study 1 there was no corresponding reduction in thresholds for triadic gaze within this age range. Hence, judgments of dyadic gaze may depend to a greater extent on the subjective interpretation of gaze cues than judgments of triadic gaze.

Implications for Social Interaction

The results of the current thesis have important implications for real-world social interactions involving typical adults. Adults' high sensitivity to triadic gaze in Study 1 suggests that in real-world social interactions, adults are likely to be quite precise in using the direction of eye gaze to judge the focus of others' visual attention. However, the finding in Study 2 that the dimensions of adults' horizontal and vertical cone of gaze match the width and height of an adult human's face suggests that in real-world interactions, an adult will be likely to infer that another person is looking at the adult when the person is looking anywhere on the adult's own face. Also, the finding in Study 3 (Experiment 2) that object-directed voice cues (e.g., “I see that.”) decreased the width of adults' cone of gaze, and the finding in Study 4 that adults' cone of gaze was wider for angry faces than for fearful or neutral faces, suggest that in real-world social interactions, typical adults are able to take into account relevant contextual information from the visual and auditory modalities when making judgments of whether or not others are paying attention to them.

The current results also have implications for social interactions involving children. The lower sensitivity to triadic gaze observed in younger children in Study 1 suggests that younger children are likely to be less precise than older children and adults in using the direction of gaze to infer the target of others' visual attention, and in making inferences about others preferences and/or intentions (Argyle & Cook, 1976; Einav & Hood, 2006; Kendon, 1967; Lee et al., 1998), and in combining information from gaze and voice cues to learn the names of objects (e.g., Tomasello & Farrar, 1986). Also, the finding in Studies 2 and 3 that 6-year-olds' horizontal cone of gaze was much wider than that of older children and adults suggests that in real-world social interactions, 6-year-olds may be more likely to infer that a person is paying attention to the child when the person is actually attending to something else in the environment. This could make 6-year-olds less likely than older children and adults to attribute deception to a person displaying averted gaze (Einav & Hood, 2008; McCarthy & Lee, 2009), or less likely to notice when a person's gaze is averted toward an interesting object in the environment (Argyle & Cook, 1976; Kendon, 1967). It could also make 6-year-olds more likely than older children and adults to attribute the intent to communicate, dominate or threaten to someone who is not paying attention to the child (Argyle & Cook, 1976; Kendon, 1967). However, the finding in Study 3 that hearing object-directed voice cues (e.g., "I see that.") decreased the width of 6-year-olds' cone of gaze suggests that when both gaze and object-directed voice cues are present, 6-year-olds will be less likely to erroneously perceive direct gaze, and may therefore make social judgments more similar to those of older children and adults.

Finally, the current results have implications for social interactions involving high-functioning adults with ASD. The finding in Study 4 of no difference between adults with and without ASD in the width of the cone of gaze for upright faces suggests that high-functioning adults with ASD will be as likely as typical individuals to infer that other people are looking at them during naturalistic social interactions. Also, the finding in Study 4 that the cone of gaze was modulated normally by facial expression in the ASD group suggests that in real-world social interactions, individuals with ASD may take into account at least some emotional contextual information from the visual modality when making judgments of whether or not people are looking at them.

Limitations and Future Research

The results of the current thesis leave several additional questions open for future research. One remaining question is whether the results would have differed if the stimuli had been more realistic than the static, two-dimensional photographs presented in each study (e.g., three-dimensional and/or dynamic faces). Including binocular depth cues could enhance sensitivity to the direction of gaze by providing more information about the spatial layout of the eye region, and including motion cues could enhance sensitivity by engaging mechanisms involved in processing of biological motion (e.g., responses in

STS). However, in the current thesis, typical adults' thresholds for discriminating differences in triadic gaze (Study 1), and the width of their horizontal cone of gaze (Studies 2 and 3), were similar to corresponding measurements obtained in previous studies using live models, which were both three-dimensional and dynamic (e.g., Gibson & Pick, 1963; Symons et al., 2004). Hence, the inclusion of binocular depth cues and motion cues does not appear to influence adults' judgments of triadic gaze and their judgments of direct and averted gaze. Nevertheless, three-dimensional and dynamic faces may appear to be more realistic than two-dimensional and static faces, a difference that might have more effect on judgments of gaze in typically developing children and/or individuals with ASD than in typical adults, and that might modulate the influence of the direction of gaze on cognition, attention, and/or affect (Hietanen et al., 2008). Future studies could evaluate these possibilities by testing typical adults, typically developing children, and individuals with ASD with three-dimensional and dynamic faces.

It is also interesting to consider whether the results would have differed if the stimuli had been photographs of children's faces instead of the photographs of young adults presented in each study. Young adults and children are faster and more precise in recognizing faces from their own age group than they are for faces of older or younger individuals (e.g., Hills, 2012; Hills & Lewis, 2011, but also see Mondloch, Maurer, & Ahola, 2006; Macchi Cassia, Pisacane, & Gava, 2012). This advantage in recognizing faces from one's own age group may reflect tuning by recent biased experience with faces from one's own age group. A similar advantage could be present for judgments of eye gaze. For example, children's and adults' sensitivity to differences in triadic gaze may be higher, and/or their cone of gaze may be narrower, for faces from the participant's own age group than for faces of younger or older people. Future studies could evaluate these possibilities by testing children and adults with faces from the participant's own age group, and with the faces of younger and older people.

Another remaining question is whether children's sensitivity to the direction of gaze is tuned to be better for upright than for inverted faces, to the same extent as it is in typical adults (Jenkins & Langton, 2003; Schwaninger et al., 2005). Accuracy in discriminating facial identity is higher for upright faces than for inverted faces in typical adults (e.g., Yin, 1969). However, this effect is smaller in children than in adults until at least 8 years of age (e.g., Carey & Diamond, 1977; de Heering, Rossion, & Maurer, 2012). The effect of face inversion on sensitivity to facial identity and the direction of gaze may reflect tuning by experience with upright faces. Hence, it is possible that, like the effect of face inversion on judgments of facial identity, the effect of inversion on judgments of eye gaze emerges gradually as children accumulate experience with upright faces. Future studies could investigate this question by measuring the effect of face inversion on judgments of eye gaze in children.

A final remaining question is how neural mechanisms underlying sensitivity to the direction of gaze change during early development, and how the development of these mechanisms might differ in individuals with ASD. Following prolonged exposure (adaptation) to a particular direction of gaze, typical adults display repulsive aftereffects in which perceived head orientation is shifted in a direction opposite to that of the adapting direction (e.g., Calder et al., 2008). Previous studies using visual adaptation and computational modelling suggest that neural mechanisms underlying the perception of head orientation degrade during healthy aging (e.g., Wilson, Mei, Habak, & Wilkinson, 2011). It seems possible that neural mechanisms underlying the perception of head orientation and/or eye gaze are refined during childhood, and that this refinement is abnormal in individuals with ASD. Future studies could investigate these possibilities by using visual adaptation and computational modelling to evaluate neural mechanisms underlying the perception of head orientation and/or eye gaze in typically developing children and individuals with ASD. In addition, neuroimaging studies have identified a network of brain regions implicated in processing of eye gaze in typical adults, and have begun to describe the functional organization of the network (see Carlin & Calder, 2012; Senju & Johnson, 2009, for reviews). However, very little is known about the typical development of this network, and about how this network may develop differently in individuals with ASD. Future studies could investigate these questions by using fMRI to examine the neural network involved in gaze processing in children and individuals with ASD.

Conclusions

In the current thesis, I examined the development of sensitivity to the direction of gaze during childhood, and examined how development differs in high-functioning adults with autism spectrum disorder (ASD). Specifically, I investigated sensitivity to horizontal differences in gaze toward objects in the environment (triadic gaze) during middle childhood (Study 1), sensitivity to horizontal (Studies 2 and 3) and vertical (Study 2) differences between direct and averted gaze during middle childhood, the influence of voice cues on sensitivity to horizontal differences between direct and averted gaze during middle childhood (Study 3), and the influences of facial expression and face inversion on sensitivity to differences between direct and averted gaze in high-functioning adults with ASD (Study 4).

Sensitivity to the direction of gaze toward objects in the environment (triadic gaze) improved gradually after age 6, and became statistically adult-like by age 10 (Study 1, Experiments 1 and 2). These developmental changes are driven, at least in part, by improvements in sensitivity to eye position (Experiment 3). The horizontal range of directions of gaze leading to the perception of direct gaze (the cone of gaze) narrowed considerably after age 6, and was statistically adult-like by age 8 (Studies 2 and 3, Experiment 1). In contrast, the vertical cone of gaze was adult-like at age 6, and was larger than the horizontal cone of gaze by age 8 (Study 2). The horizontal cone of gaze of 6-year-olds was narrower when participants heard object-directed voice cues (e.g., “I see that.") than when they heard participant-directed (e.g., "I see you.") voice cues or no voice (Study 3, Experiment 1). The effect of voice cues was the same in adults as in 6-year-olds when the task was made more difficult by limiting the duration of exposure to the face (Study 3, Experiment 2). Finally, face inversion increased the width of the horizontal cone of gaze in typical adults, but not in high-functioning adults with ASD (Study 4). However, the width of the cone of gaze for upright faces was normal in the ASD group, and the cone of gaze was normally modulated by facial expression in this group (Study 4).

The results provide the first evidence that fine-grained sensitivity to the direction of gaze changes considerably during middle childhood. The improvement in sensitivity to triadic gaze observed between ages 6 and 10 (Study 1) may allow improvements in children's ability to judge which target in the environment others are attending to, and may therefore allow more accurate inferences about others' interests and/or intentions. In addition, the decrease in the width of the horizontal cone of gaze observed between ages 6 and 8 (Studies 2 and 3) may allow more adult-like inferences about whether or not others are paying attention to the child, which may in turn allow more adult-like inferences about whether a person is dominating, threatening, deceiving, and/or attempting to communicate with the child. Also, the finding that the horizontal cone of gaze of 6-year-olds was narrower when participants heard object-directed voice cues (e.g., "I see that.") than when they heard participant-directed (e.g., "I see you.") voice cues or no voice

(Study 3) provides the first evidence that children integrate information from gaze and voice when making judgments of gaze, and that the integration can allow more adult-like social judgments in young children. The results also provide the first evidence that developmental trajectories differ considerably between different aspects of sensitivity to the direction of gaze, with some aspects (e.g., the vertical cone of gaze) already adult-like at age 6, and others (e.g., thresholds for discriminating horizontal differences in triadic gaze) not becoming statistically adult-like until age 10. This pattern suggests that the oldest age at which children's social judgments are limited by immature sensitivity to the direction of gaze will differ between different aspects of sensitivity, and that different visual, cognitive and/or neural mechanisms may underlie developmental changes in different aspects of sensitivity. Finally, the finding that the cone of gaze was wider for angry faces than for fearful or neutral faces in high-functioning adults with ASD provides the first evidence that, like typical adults, adults with ASD possess an adaptive bias to interpret threatening signals as self-directed (Study 4). However, the absent effect of face inversion on judgments of direct and averted gaze among adults with ASD suggests that their perception of eye gaze may not rely on the same type of visual processing as in typical individuals.

References

Adams, R. B., Jr, & Kleck, R. E. (2003). Perceived gaze direction and the processing of facial displays of emotion. *Psychological Science, 14,* 644-647.

Akechi, H., Senju, A., Kikuchi, Y., Tojo, Y., Osanai, H., & Hasagawa, T. (2009). Does gaze direction modulate facial expression processing in children with autism spectrum disorder? *Child Development, 80,* 1134-1146.

Akechi, H., Senju, A., Kikuchi, Y., Tojo, Y., Osanai, H., & Hasegawa, T. (2010). The effect of gaze direction on the processing of facial expressions in children with autism spectrum disorder: An ERP study. *Neuropsychologia, 48,* 2841-2851.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Arlington, VA: American Psychiatric Publishing.

Anstis, S. M., Mayhew, J. W., & Morley, T. (1969). The perception of where a face or television ‘‘portrait’’ is looking. *American Journal of Psychology, 82,* 474-489.

Argyle, M., & Cook, M. (1976). *Gaze and mutual gaze.* New York: Cambridge University Press.

Ashwin, C., Ricciardelli, P., & Baron-Cohen, S. (2009). Positive and negative gaze perception in autism spectrum disorders. *Social Neuroscience, 4,* 153-164.

Baron-Cohen, S., & Goodhart, F. (1994). The ‘‘seeing leads to knowing’’ deficit in autism: The Pratt and Bryant probe. *British Journal of Developmental Psychology, 12,* 397-402.

Baron-Cohen, S., Campbell, R., Karmiloff-Smith, A., Grant, J., & Walker, J. (1995). Are children with autism blind to the mentalistic significance of the eyes? *British Journal of Developmental Psychology, 13*, 379-398.

Baron-Cohen, S., Baldwin, D., & Crowson, M. (1997). Do children with autism use the speaker's direction of gaze (SDG) strategy to crack the code of language? *Child Development, 68,* 48-57.

Baron-Cohen, S., Wheelwright, S., Hill, J., Raste, Y., & Plumb, I. (2001). The reading the mind in the eyes test revised version: A study with normal adults, and adults with Asperger syndrome of high-functioning autism. *Journal of Child Psychology and Psychiatry, 42*, 241-251.

Baudouin, Y. Y., Gallay, M., Durand, K., & Robichon, F. (2010). The development of perceptual sensitivity to second-order relations in children. *Journal of Experimental Child Psychology, 107*, 195-206.

Bindemann, M. A., Burton, M., & Langton, S. R. H. (2008). How do eye gaze and expression Interact? *Visual Cognition, 16*, 708-733.

Bock, S. W., Dicke, P., & Thier, P. (2008). How precise is gaze following in humans? *Vision Research, 48*, 946-957.

Butterworth, G., & Cochran, E. (1980). Towards a mechanism of joint visual attention in human infancy. *International Journal of Behavioral Development*, *3*, 253-272.

Butterworth, G., & Jarrett, N. (1991). What minds have in common is space. Spatial mechanisms serving joint visual attention in infancy. *British Journal of Developmental Psychology, 9,* 55-72.

Butterworth, G., & Itakura, S. (2000). How the eyes, head, and hand serve definite reference? *British Journal of Developmental Psychology, 18,* 25-50.

Calder, A. J. et al. (2002) Reading the mind from eye gaze. *Neuropsychologia, 40*, 1129-1138.

Calder A. J., Jenkins, R., Cassel, A., & Clifford, C. W. G. (2008). Visual representation of eye gaze is coded by a nonopponent multichannel system. *Journal of Experimental Psychology: General, 137*, 244-261.

Campbell, R., Lawrence, K., Mandy, W., Mitra, C., Jeyakuma, L., & Skuse, D. (2006). Meanings in motion and faces: Developmental associations between the processing of intention from geometrical animations and gaze detection accuracy. *Development and Psychopathology, 18*, 99-118.

Carey, S., & Diamond, R. (1977). From piecemeal to configurational representation of faces. *Science*, *195*, 312-313.

Carlin, J. D., Rowe, J. B., Kriegeskorte, N., Thompson, R., Calder, A. J. (2012). Direction-sensitive codes for observed head turns in human superior temporal sulcus. *Cerebral Cortex, 22,* 735-744.

Carlin, J. D., & Calder, A. J. (2012). The neural basis of eye gaze processing. *Current Opinion in Neurobiology, 23,* 450-455.

Carlin, J. D., Calder, A. J., Kriegeskorte, N., Nili, H., Rowe, J. B. (2011) A head view-invariant representation of gaze direction in anterior superior temporal sulcus. *Current Biology, 21*, 817-1821.

Cline, M. G. (1967). The perception of where a person is looking. *American Journal of Psychology, 80*, 41-50.

Conty, L., N'Dyiaye, K., Tijus, C. & George, N. (2007). When eye creates the contact! ERP evidence for early dissociation between direct and averted gaze motion processing. *Neuropsychologia, 45*, 3024-3037

Corkum, V., & Moore, C. (1998). The origins of joint visual attention in infants. *Developmental Psychology, 34*, 28-38.

Csibra, G., & Volein, A. (2008). Infants can infer the presence of hidden objects from referential gaze information. *British Journal of Developmental Psychology, 26*, 1-11.

Dalton, K. M., Nacewicz, B. M., Johnstone, T., Schaefer, H. S., Gernsbacher, M. A., & Goldsmith, H. H. (2005). Gaze fixation and the neural circuitry of face processing in autism. *Nature Neuroscience, 8*, 519-526.

de Heering, A., Rossion, B., & Maurer, D. (2012). Developmental changes in face recognition during childhood: evidence from upright and inverted faces. *Cognitive Development, 27*, 17-27.

Doherty, M. J., Anderson, J. R., & Howieson, L. (2009). The rapid development of gaze judgment ability at 3 years. *Journal of Experimental Child Psychology, 104*, 296-312.

Dratsch, T., Schwartz, C., Yanev, K., Schilbach, L., Vogeley, K., & Bente, G. (2013). Getting a grip on social gaze: Control over others' gaze helps gaze detection in high-functioning autism. *Journal of Autism and Developmental Disorders, 43*, 286-300.

Einav, S., & Hood, B. M. (2006). Children's use of the temporal dimension of gaze for inferring preference. *Developmental Psychology, 42*, 142-152.

Einav, S., & Hood, B. M. (2008). Tell-tale eyes: Children's attribution of gaze aversion as a lying cue. *Developmental Psychology, 44*, 1655-1667.

Elsabbagh, M., Mercure, E., Hudry, K., Chandler, S., Pasco, G., Charman, T., Pickles, A., Baron-Cohen, S., Bolton, P., & Johnson, M. H. (2012). Infant neural sensitivity to dynamic eye gaze is associated with later emerging autism. *Current Biology, 22*, 338-342.

Emery, N. J. (2000). The eyes have it: the neuroethology, function and evolution of social gaze. *Neuroscience and Biobehavioral Reviews, 24*, 581-606.

Engell, A.D., & Haxby, J.V. (2007) Facial expression and gaze-direction in human superior temporal sulcus. *Neuropsychologia, 45*, 3234-3241

Ewbank, M. P., Jennings, C. & Calder, A. J. (2009). Why are you angry with me? Facial expressions of threat influence perception of gaze direction. *Journal of Vision, 9*, 1-

7.

Fang, F., Murray, S. O., & He, S. (2007). Duration-dependent fMRI adaptation and distributed viewer-centered face representations in human visual cortex. *Cerebral Cortex, 17*, 1402-1411.

Falck-Ytter, T., & von Hofsten, C. (2011). *How special is social looking in ASD? A review.* In O. Braddick, J. Atkinson, & G. Innocenti (Eds.), Progress in brain research (Vol. 189, pp. 225-238). Burlington: Academic Press.

Farroni, T., Johnson, M. H., Brockbank, M., & Simion, F. (2000). Infants' use of gaze direction to cue attention: The importance of perceived motion. *Visual Cognition, 7*, 705-718.

Farroni, T., Csibra, G., Simion, F., & Johnson, M. H. (2002). Eye contact detection in humans from birth. *Proceedings of the National Academy of Sciences, 99*, 9602-9605.

Farroni, T., Johnson, M. H., & Csibra, G. (2004). Mechanisms of eye gaze perception during infancy. *Journal of Cognitive Neuroscience, 16*, 1320-1326.

Farroni, T., Massaccesi, S., Pividori, D., & Johnson, M. H. (2004). Gaze following in newborns. *Infancy, 5*, 39-60.

Gamer, M., & Hecht, H. (2007). Are you looking at me? Measuring the cone of gaze. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 705-715.

Gao, X., & Maurer, D. (2010). A happy story: developmental changes in children's sensitivity to facial expressions of varying intensities. *Journal of Experimental Child Psychology, 107,* 67-86.

George, N., Driver, J., & Dolan, R. J. (2001) Seen gaze-direction modulates fusiform activity and its coupling with other brain areas during face processing. *Neuroimage 13,* 1102-1112.

Gepner, B., de Gelder, B., & de Schonen, S. (1996). Face processing in autistics: Evidence for a generalised deficit? *Child Neuropsychology, 2,* 123-139.

Gibson, J. T., & Pick, A. D. (1963). Perception of another person’s looking behavior. American *Journal of Psychology, 76*, 386-394.

Graham, R., & LaBar, K. S. (2012). Neurocognitive mechanisms of gaze-expression interactions in face processing and social attention. *Neuropsychologia, 50*, 553-566.

Grice, S. J., Halit, H., Farroni, T., Baron-Cohen, S., Bolton, P., & Johnson, M. H. (2005). Neural correlates of eye-gaze detection in young children with autism. *Cortex, 42,* 342-353.

Hadad, B., Maurer, D., & Lewis, T. L. (2010a). The development of contour interpolation: Evidence from subjective contours. *Journal of Experimental Child Psychology, 106*, 163-176.

Hadad, B., Maurer, D., & Lewis, T. L. (2010b). The effects of spatial proximity and collinearity on contour integration in adults and children. *Vision Research, 50*, 772-

778.

Hall, E. T. (1966). *The Hidden Dimension.* New York: Doubleday.

Haxby, J. V., Hoffman, E. A., & Gobbini, M. I. (2000). The distributed neural system for face perception. *Trends in Cognitive Sciences, 4*, 223-233.

Hains, S. M. J., & Muir, D. W. (1996). Infant sensitivity to adult eye direction information. *Child Development, 67*, 1940-1951.

Hietanen, J. K., Leppänen, J. M., Peltola, M. J., Linnaaho, K., & Ruuhiala, H. J. (2008). Seeing direct and averted gaze activates the approach-avoidance motivational brain systems. *Neuropsychologia, 46*, 2423-2430.

Hills, P. J. (2012). A developmental study of the own-age face recognition bias in children. *Developmental Psychology, 48*, 499-508.

Hill, P. J., & Lewis, M. B. (2011). The own-age face recognition bias in children and adults. *Quarterly Journal of Experimental Psychology, 64*, 17-23.

Howard, M. A., Cowell, P. E., Boucher, J., Broks, P., Mayes, A., & Farrant, A. (2000). Convergent neuroanatomical and behavioural evidence of an amygdala hypothesis of autism. *NeuroReport, 11*, 2931-2935.

Jenkins, R., & Langton, S. R. H. (2003). Configural processing in the perception of eye-gaze direction. *Perception, 32*, 1181-1188.

Johnson, S., Ok, S., & Luo, Y. (2007). The attribution of attention: Nine-month-olds' interpretation of gaze as goal-oriented action. *Developmental Science, 10*, 530-537.

Jones, W. B. A., Carr, K. B. A., & Klin, A. (2008). Absence of preferentially looking to the eyes of approaching adults predicts level of social disability in 2-year-old toddlers with autism spectrum disorder. *Archives of General Psychiatry, 65*, 946-954.

Joseph, R. M., Ehrman, K., McNally, R., & Keehn, B. (2008). Affective response to eye contact and face recognition ability in children with ASD. Journal of the International *Neuropsychological Society, 14*, 947-955.

Kaartinen, M., Puura, K., Mäkelä, T., Rannisto, M., Lemponen, R., Helminen, M., Salmenin, R., Himanen, S., & Hietanen, J. K. (2012). Autonomic arousal to direct gaze correlates with social impairments among children with ASD. *Journal of Autism and Developmental Disorders*, *42*, 1917-1927.

Kampe, K. K., Frith, C. D., & Frith, U. (2003). "Hey John": signals conveying communicative intention toward the self activate brain regions associated with 'mentalizing'' regardless of modality. *Journal of Neuroscience, 23*, 5258-5263

Kawashima, R., Sugiura, M., Kato, T., Nakamura, A. Hatano, K. Ito, K., Fukuda, H., Kojima, S., & Nakamura, K. (1999). The human amygdala plays an important role in gaze monitoring. A PET study. *Brain*, *122*, 779-783

Kendon, A. (1967). Some functions of gaze-direction in social interaction. *Acta Psychologica, 26*, 22-63.

Klin, A., Jones, W., Schultz, R., Volkmar, F., & Cohen, D. (2002).Visual fixation patterns during viewing of naturalistic social situations as predictors of social competence in individuals with autism. *Archives of General Psychiatry, 59*, 809-816.

Kyläiinen, A., & Hietanen, J. K. (2006). Skin conductance responses to another person's gaze in children with autism. *Journal of Autism and Developmental Disorders, 36*, 517-525.

Leekam, S., Baron-Cohen, S., Perrett, D., Milders, M., & Brown, S. (1997). Eye-direction detection: A dissociation between geometric and joint attention skills in autism. *British Journal of Developmental Psychology, 15*, 77-95.

Kobayashi, H., & Kohshima, S. (1997). Unique morphology of the human eye. *Nature 387*, 767-768.

Lee, K., Eskritt, M., Symons, L. A., & Muir, D. (1998). Children's use of triadic eye gaze information for ‘‘mind reading’’. *Developmental Psychology, 34,* 525-539.

Lord, C. (1974). The perception of eye contact in children and adults. *Child Development, 45*, 1113-1117.

Macchi Cassia, V., Pisacane, A., & Gava, L. (2012). No own-age bias in 3-year-old children: more evidence for the role of early experience in building face-processing biases. *Journal of Experimental Child Psychology, 113*, 372-382.

Meredith, H. V. (1953). Growth in head width during the first twelve years of life. *Pediatrics, 12*, 411-429.Milders, M., Hietanen, J. K., Leppänen, J. M., & Braun, M. (2011). Detection of emotional faces is modulated by the direction of eye gaze. *Emotion, 11*, 1456-1461.

McCarthy, A., & Lee, K. (2009). Children's knowledge of deceptive gaze cues and its relation to their actual lying behavior. *Journal of Experimental Child Psychology, 103*, 117-134.

Mondloch, C. J., Geldart, S., Maurer, D., & Le Grand, R. (2003). Developmental changes in face processing skills. *Journal of Experimental Child Psychology, 86*, 67-84.

Mondloch, C. J., Maurer, D., & Ahola, S. (2006). Becoming a face expert. *Psychological Science, 17*, 930-934.

Natu, V. S., Jiang, F., Narvekar, A., Keshvari, S., Blanz, V., O'Toole, A. J. (2010). Dissociable neural patterns of facial identity across changes in viewpoint. *Journal of Cognitive Neuroscience, 22*, 1570-1582.

Nellhaus, G. (1968). Head circumference from birth to eighteen years. *Pediatrics, 41*, 106-114

Nichols, K. A., & Champness, B. G. (1971) Eye gaze and GSR. J*ournal of Experimental Social Psychology, 7*, 623-626

Pageler, N. M., Menon, V., Merin, N. M., Eliez, S., Brown, W. E., & Reiss, A. L. (2003) Effect of head orientation on gaze processing in fusiform gyrus and superior temporal sulcus. *Neuroimage 20*, 318-329.

Pelphrey, K. A., Sasson, N. J., Reznick, J. S., Paul, G., Goldman, B. D., & Piven, J. (2002). Visual scanning of faces in autism. *Journal of Autism and Developmental Disorders, 32*, 249-261.

Pelphrey, K. A., Morris, J. P., & McCarthy, G. (2005). Neural basis of eye gaze processing deficits in autism. *Brain, 128,* 1038-1048.

Perrett, D. I., Smith, P. A. J., Potter, D. D., Mistlin, A. J., Head, A. S., Milner, A. D., & Jeeves, M. A. (1985). Visual cells in the temporal cortex sensitive to face view and gaze direction. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, *223*, 293-317.

Perrett, D. I., Hietanen, J. K., Oram, M. W., Benson, E. T., & P. J. Rolls (1992). Organization and functions of cells responsive to faces in the temporal cortex. *Philosophical Transacations: Biological Sciences*, *335*, 23-30.

Perrett, D. I., Oram, M. W., Harries, M. H., Bevan, R., Hietanen, J. K., Benson, P. J., & Thomas, S. (1991). Viewed-centred and object-centred coding of heads inthe macaque temporal cortex. *Experimental Brain Research, 86*, 159-173.

Piaget, J. (1926). *The language and thought of the child.* New York: Harcourt, Brace, & World. (Original work published 1923).

Piaget, J. (1930). *The child's conception of the world.* New York: Harcourt, Brace, & World. (Original work published 1926).

Redcay, E., Dodell-Feder, D., Pearrow, M. J., Mavros, P. L., Kleiner, M., Gabrieli, J. D. E., & Saxe, R. (2010). Live face-to-face interaction during fMRI: a new tool for social cognitive neuroscience. *Neuroimage, 50*, 1639-1647.

Redcay, E., Kleiner, M., Saxe, R. (2012). Look at this: the neural correlates of initiating and responding to bids for joint attention. *Frontiers in Human Neuroscience, 6,* 1-14.

Rhodes, G., Addison, B., Jeffery, L., Ewbank, M., & Calder, A. J. (2012). Facial expressions of threat influence perceived gaze direction in 8-year-olds. *Public Library of Science One, 7,* e49317.

Sato, W., Yoshikawa, S. Kochiyama, T., & Matsumura, M. (2004) The amygdala processes the emotional significance of facial expressions: an fMRI investigation using the interaction between expression and face direction. *Neuroimage, 22*, 1006-1013.

Schilbach, L., Wilms, M., Eickhoff, S. B., Romanzetti, S., Tepest, R., Bente, G., Shah, N. J., Fink, G. R., Vogeley, K. (2010. Minds made for sharing: initiating joint attention recruits reward-related neurocircuitry. *Journal of Cognitive Neuroscience*, *22,* 2702-2715.

Schwaninger, A., Lobmaier, J. S., & Fischer, M. H. (2005). The inversion effect on gaze perception reflects processing of component information. *Experimental Brain Research*, *167*, 49-55.

Senju, A., Tojo, Y., Yaguchi, K., Hasegawa, T. (2005). Deviant gaze processing in children with autism: An ERP study. *Neuropsychologia, 43*, 1297-1306.

Senju, A., Csibra, G., & Johnson, M. H. (2008). Understanding the referential nature of looking: Infants' preference for object-directed gaze. *Cognition, 108,* 303-319.

Senju, A., Kikuchi, Y., Hasegawa, T., Tojo, Y., & Osanai, H. (2008). Is anyone looking at me? Direct gaze detection in children with and without autism. *Brain and Cognition, 67*, 127-139.

Senju, A., & Johnson, M. H. (2009). The eye contact effect: Mechanisms and development. *Trends in Cognitive Sciences*, *13*, 127-134.

Skoczenski, A. M., & Norcia, A. M. (1999). The development of VEP Vernier acuity and grating acuity in human infants. *Investigative Ophthamology and Vision Science*, *40*, 2411-2417.

Smith, A. D., Hood, B. M., & Hector, K. (2006). Eye remember you: Gaze direction modulates face recognition in a developmental study. *Developmental Science, 9*, 465-472.

Spezio, M. L., Adolphs, R., Hurley, R. S. E., & Piven, J. (2007). Analysis of face gaze in autism with ''Bubbles''. *Neuropsychologia, 45*, 144-151.

Stoyanova, R. S, Ewbank, M. P., Calder, A. J. (2010). ''You talkin' to me?'': self-relevant auditory signals influence perception of gaze direction. *Psychological Science, 21*, 1765-1769.

Symons, L. A., Hains, S. M. J., & Muir, D. W. (1998). Look at me: five-month-old infants' sensitivity to very small deviations in eye gaze during social interactions. *Infant Behavior & Development*, *21*, 531-536.

Symons, L. A., Lee, K., Cedrone, C. C., & Nishimura, M. (2004). What are you looking at? Acuity for triadic eye gaze. *Journal of General Psychology*, *131*, 451-469.

Thayer, S. (1977). Children's detection of on-face and off-face gazes. *Developmental Psychology, 13*, 673-674

Tomasello, M., & Farrar, M. J. (1986). Joint attention and early language. *Child Development*, *57,* 1454-1463.

Wallace, S., Coleman, M., Pascalis, O., & Bailey, A. (2006). A study of impaired judgment of eye-gaze direction and related face processing deficits in autism spectrum disorders. *Perception, 35*, 1651-1664.

Webster, S., & Potter, D. D. (2008). Brief report: Eye direction detection improves with development in autism. *Journal of Autism and Developmental Disorders*, *38*, 1184-1186.

Webster, S., & Potter, D. D. (2011). Gaze perception develops atypically in children with autism. *Child Development Research*, Article ID 462389, 1-9.

Wicker, B., Perrett, D. I., Baron-Cohen, S., & Decety, J, (2003) Being the target of another's emotion: a PET study. *Neuropsychologia*, *41*, 139-146

Wilson, H. R., Mei, M., Habak, C., & Wilkinson, F. (2011). Visual bandwidths for face orientation increase during healthy aging. *Vision Research, 51*, 160-164.

Yin, R. K. (1969). Looking at upside-down faces. *Journal of Experimental Psychology, 81,* 141-145.