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PAPER

The development of joint visual attention: a longitudinal study of gaze following during interactions with mothers and strangers

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Abstract

Two- to 8-month-old infants interacted with their mother or a stranger in a prospective longitudinal gaze following study. Gaze following, as assessed by eye tracking, emerged between 2 and 4 months and stabilized between 6 and 8 months of age. Overall, infants followed the gaze of a stranger more than they followed the gaze of their mothers, demonstrating a stranger preference that emerged between 4 and 6 months of age. These findings do not support the notion that infants acquire gaze following through reinforcement learning. Instead, the findings are discussed with respect to the social cognitive framework, suggesting that young infants are driven by social cognitive motives in their interactions with others.

Introduction

Joint attention is often referred to as a milestone in social cognitive development (Tomasello, 2001), allowing infants to partake in social interactions and follow the gaze directions of others. In addition to enriching the infants' social cognitive repertoire, joint attention has been related to language acquisition (Mundy & Gomes, 1998), emotional regulation (Morales, Mundy, Crowson, Neal & Delgado, 2005), and theory of mind (Baron-Cohen, 1994).

The bulk of research on the development of joint attention has focused on gaze following; the ability to respond to joint attention bids of others. This ability was first investigated by Scaife and Brunner (1975), measuring infants' tendency to follow an adult model's gaze shifts (including both head and eye movements). Gaze following was reported in 30% of the 2-month-olds, increasing with age to include all 14-month-olds. Since then, two additional studies have been published that demonstrate gaze following at 3 months of age (D'Entremont, 2000; D'Entremont, Hains & Muir, 1997), both featuring an adult stranger moving her head and eyes to fixate one of two toys located on either side of her. The assumption that 3-month-olds are sensitive to others' gaze direction received additional support from two related paradigms, looking at emotional responses and attention shifts, both as a function of others' gaze direction. These studies illustrate that 3-month-olds smile more during episodes of joint attention than during episodes where the interaction partner simply looks away (Striano & Stahl, 2005) and that new-borns', young infants', and adults' attention is modified by others' averted gaze (Farroni, Massaccesi, Pividori & Johnson, 2004; Friesen & Kingstone, 1998; Hood, Willen & Driver, 1998).

Several other studies have demonstrated gaze following around 6 months of age (Butterworth & Cochran, 1980; Butterworth & Jarrett, 1991; Gredebäck, Theuring, Hauf & Kenward, 2008). The latter study relied on a novel eye tracking paradigm to investigate gaze following (see also Theuring, Gredebäck & Hauf, 2007; von Hofsten, Dahlström & Fredriksson, 2005), demonstrating that both 5- and 6-month-olds follow a model's gaze even when presented on a computer monitor. As infants become older, the ability to follow gaze becomes more complex. If the targets are placed further away, or are hidden from the infant, gaze following emerges between 8 and 12 months (Corkum & Moore, 1998; Flom, Deák, Phill & Pick, 2004; Moore & Corkum, 1994; Morissette, Ricard & D'ecarie, 1995). Infants below 1 year of age also expect a hidden object behind a barrier based on gaze (Csibra & Volein, 2008), and encode the relationship between the gaze direction and the location or identity of target objects (Senju, Csibra & Johnson, 2008; Senju, Johnson & Csibra, 2006). Between 1 and 2 years of age, infants also gain the ability to follow gaze to targets located behind them and to predict the reappearance of targets based on gaze (Butterworth & Cochran, 1980; Butterworth & Jarrett, 1991; Deák, Flom & Pick, 2000; Flom *et al*., 2004; Moore & Corkum, 1998).

Various perspectives have been used to interpret infants' ability to follow others' gaze. On one hand, gaze

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following is often viewed as a social cognitive action that arises from a desire to perceive what others are looking at (Tomasello, 2001). The social-cognitive framework (Bräuer, Call & Tomasello, 2005) postulates that infants understand that others shift their gazes in order to observe something interesting or unusual. Gaze following is here assumed to serve a communicative role, involving the desire to share intentionality with others (see also Baron-Cohen, 1995; Carpenter, Akhtar & Tomasello, 1998), and the ability to interpret others' deictic references during social interaction (Senju & Csibra, 2008). The social cognitive framework has recently received substantial empirical support. It has been demonstrated that 12-month-olds crawl around barriers to see what an adult model looks at (Moll & Tomasello, 2004) and that 14-month-old infants are more likely to follow gaze if the model's eyes are visible than when the eyes are closed or covered by a blindfold (Brooks & Meltzoff, 2002).

On the other hand, enhanced gaze following abilities have been demonstrated following reinforcement (Moore, Angelopoulos & Bennett, 1997), suggesting that infants' tendency to look in the same direction as others may be shaped through reinforcement learning during infants' early experiences interacting with their mothers. Spontaneous gaze shifts in the direction that the mother attends to (or moves her gaze towards) will often result in interesting sights. This reward is assumed to strengthen the tendency to look in the same direction as the mother (Moore & Corkum, 1994; Triesch, Teuscher, Deák & Carlson, 2006). Empirical support for the involvement of reinforcement learning in gaze following exists in 8- and 9-month-old infants (Corkum & Moore, 1998; Moore *et al.*, 1997). In these studies, infants who did not initially follow gaze, were able to learn, if gaze shifts were followed by an interesting sight along the extension of the model's gaze.

Based on the findings above, it is likely that *both* mechanisms are at work by the end of the first year. However, little is known about which of the two mechanisms is at the core of infants' gaze following. Which mechanism allows infants to *start* paying attention to others' gaze somewhere around 3 to 4 months of age? Numerous authors have pointed out that a better understanding of the origin of gaze following is paramount (Striano & Reid, 2006; Van Hecke & Mundy, 2007). However, to our knowledge only one study, by Senju and Csibra (2008), has attempted to address this issue in early infancy. By using an eye tracking paradigm, Senju and Csibra were able to demonstrate that 6-month-old infants only follow a model's gaze if preceded either by direct gaze contact or infant-directed speech. The authors interpret this finding in support of the social cognitive framework, suggesting that gaze following, at least in part, exerts a communicative role at 6 months of age. However, the same results can also be explained by reinforcement learning principles. Infants may, through interacting with their mothers, have been reinforced to look in the same direction as their mothers, but only following specific cues (referred to as discriminative stimuli), such as direct gaze or infant-directed speech, that often has preceded the rewarded behavior. Clearly, more research is needed to better understand the foundations of gaze following.

In addition, it is currently unknown how infants' gaze following is modulated by the identity of the infant's interaction partner. Some prior studies suggest that infants may be more attentive to strangers (Striano & Bertin, 2005). In their study 5-, 7-, and 9-month-old infants made more gaze shifts towards a stranger's face than the face of their mothers during free play (Striano & Bertin, 2005). This study did not investigate infants' tendency to follow the attention bids of strangers and mothers but focused on how infants monitored social partners. It is perceivable that a similar stranger preference influences infants' gaze following, with more gaze following during interactions with strangers than with mothers. On the other hand, it may be the case that infants get more accustomed to engaging in gaze following activities with their mothers, and thus, become more likely to respond to their attention bids than those of a stranger (as suggested by Morales, Mundy & Rojas, 1998). Gaining a better understanding of how gaze following differs depending on the identity of the model is important for two reasons. First of all, gaze following studies often rely on either the mother or a stranger to interact with the infant; however, little is known about how this variable affects infants' performance (Mundy & Sigman, 2006). Second, manipulating the identity of the person with whom the infants interact allows us to derive tentative predictions that differentiate the reinforcement learning perspective from the social cognitive framework.

According to the reinforcement learning perspective, the mother's face and her gaze shifts represent the most frequent discriminative stimuli that precede the infant's own gaze shift and the subsequent reward (Triesch *et al.*, 2006). Gaze following can therefore be assumed to be most frequent during interaction with the mother as compared to others. However, gaze following is also elicited during interactions with others, and this generalization across stimuli, or contexts, is well documented in the reinforcement learning literature. Through the process of stimulus generalization, similar stimuli also elicit the same response, but to a smaller degree, the frequency of responses being determined by the similarity of the discriminative stimuli (Ghirlanda & Enquist, 2003). If applied to the emergence of gaze following, reinforcement learning principles *alone* (in the absence of social cognitive mechanisms) suggest frequent gaze shifts during interactions with the mother and less frequent gaze following during interactions with a stranger.

The social cognitive framework, on the other hand, makes no clear predictions about the primacy of mothers over strangers. However, if gaze following is related to other social cognitive abilities, then we may expect more gaze following during interactions with strangers than with mothers (Striano & Bertin, 2005). The authors

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interpret this stranger preference as support for the notion that social context and affect may play central parts in the establishment of joint visual attention. This position suggests that joint attention is a precursor of cultural learning and later more advanced forms of social cognitive abilities. It is currently unclear if the same stranger preference is observed when young infants follow the joint attention bids of others, as measured by gaze following.

One possibility to advance our understanding of the origins of gaze following, and the importance of the identity of social partners, is to rely on a longitudinal paradigm and map the emergence of gaze following between 3 and 4 months of age. Several studies have, in fact, used longitudinal designs to investigate gaze following, demonstrating a stability in gaze following abilities from 6 to 24 months of age (Morissette *et al.*, 1995; Mundy, Block, Delgado, Pomares, Van Hecke & Parlade, 2007; Mundy, Delgado, Yale, Messinger, Neal & Schwartz, 2000). However, none of these studies has provided a description of how gaze following emerges (using a longitudinal design). Given the recent focus on young infants' gaze following abilities, it is important to extend these studies with longitudinal data from the time when gaze following first emerges; providing a better understanding of variability of onset and individual development of gaze following abilities in preverbal infants.

To further expand our knowledge of young infants' gaze following abilities, the current study measures 2- to 8-month-old infants' gaze as they interact with a stranger or their mothers, using a prospective longitudinal real life eye tracking design. We ask the following questions: at what age do infants start to follow gaze; how stable are gaze following abilities within individual infants over time, and finally, does infants' gaze following differ between mothers and strangers? The results are discussed with respect to the possible mechanisms that drive the ontogenetic origin of gaze following.

Methods

Participants

Forty families were invited to visit the lab when their infant was 2, 4, 6, and 8 months of age; half participated in the Mother condition and half in the Stranger condition. Families were recruited by mail based on birth records or during visits to local health care centers. In the Mother condition, 17 families participated on all occasions (mean age at first, 68 days, SD = 5.0; second, 121, SD = 6; third, 185, SD = 6; and the fourth visit, 245, SD = 5), whereas 19 families participated on all four occasions in the Stranger condition (mean age at first, 69 days, SD = 8; second, 125, SD = 7; third, 187, SD = 9; and the fourth visit, 245, SD = 6). The four families that did not complete the study participated only at 2 months and they were excluded from the final analyses. Preliminary analyses did not reveal any differences between excluded and included infants with respect to age, attention, or scanning patterns. Each family received a gift voucher (value 13€) following each session.

Stimuli and apparatus

Gaze was measured with a Tobii X50 near infrared eye tracker with an infant add-on (http://www.Tobii.com); precision = 1°, accuracy = 0.5°, sampling rate 50 Hz. During each session infants interacted with a female model (face extending ~5.7° horizontally, ~3.5° vertically) sitting on the opposite side of a table, 2 meters from the infant. This distance was required to match the visual angle of the scene with the requirements of the eye tracker. At the beginning of each session the model placed two toys (extending 4.3° horizontally, 5.4° vertically) on the table (60 cm or 17° apart), removed her hands, and began talking to and smiling at the infant. Once the model perceived that the infant was attending to her face, she turned her eyes and head to either of the toys and said 'wow'. Thereafter, she fixated the toy for approximately 5 seconds without moving or speaking. Following this episode, she moved her eyes and head up in order to reconnect with the infant. This procedure was repeated for as long as the infant was in a good mood and fixated the model's face as she talked to the infant. Infants either interacted with their mothers (Mother condition) or a female stranger (Stranger condition). All participating models were requested to wear discrete clothing. Attention grabbing accessories like jewelry and scarves were removed and their hair was pulled back if it covered parts of their face (see Figure 1).

Procedure

During their first visit each family was presented with a verbal and written description of the study and signed a consent form. The study was approved by the regional ethical committee (in accordance with the ethical standards specified in the 1964 Declaration of Helsinki).

Following a familiarization play session including the infant, his/her parents and the two experimenters, the infant was seated on the lap of one experimenter in front of the eye tracker (50 cm away) while the second experimenter performed a two point calibration procedure. During the session the model took turns interacting with

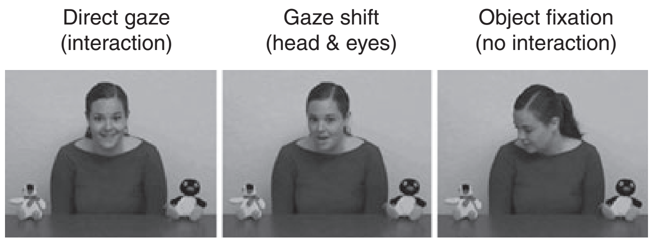

Figure 1 *Example of a gaze shift performed by the stranger.*

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the infant and shifting her gaze to one of the two toys placed on the table in front of her. The model was instructed to change the toy to which she was attending in an unpredictable manner. If the infant's attention deteriorated, the model changed the toys (between three pairs of toys). Toy locations (left/right) and presentation order (of each toy pair) were randomly assigned prior to each session.

Numerous models were used in the current study, including the stranger (Stranger condition)[1] and half of the participating mothers (Mother condition). Several steps were taken to ensure that all models performed the task fluently and in a similar manner. First of all, the models were uninformed about the experimental hypotheses and were therefore naïve to the purposes of the study. Second, mothers were trained prior to each session. This training included (1) a verbal instruction and demonstration performed in the waiting room, (2) a video demonstration of the model's behavior during a typical session of the Stranger condition, and (3) a series of test trials prior to participation. Infants were present but they did not watch the demonstrations. In addition, a second experimenter (holding the baby) monitored the behaviors of all the models and commented on deviations from protocol throughout the session. All infants spent time interacting with the stranger model prior to participation, the term stranger is relative, and should be seen in the light of the familiarity of the mother.

Data reduction

Initial data reduction was performed with a frame by frame analysis of Gaze Reply movies from ClearView (Tobii). These movies include both the location of infants' gaze and the models' performance (time locked, 50 Hz). Onset of each trial was identified and related to infants' fixations (gaze had to remain stable within 2° for 200 ms). Each trial started when the model initiated her gaze shift (here defined to include both head and eye movements) to a toy and ended once she started disengaging from the toy. Thus, each trial included only those segments when the model moved gaze towards and attended to a toy. Trials were included in the final analyses only if infants attentively fixated the model's face before she moved her gaze to either side.

Difference Score (DS) represents the standard measurement of infants' gaze following (Moore & Corkum, 1998). It counts the accuracy of infants' *first* gaze shift from the model to a toy within each trial, subtracting the number of trials with an inaccurate first gaze shift from the number of trials that include an accurate first gaze shift. As such, a DS above zero indicates that more gaze shifts were directed to the attended than to the unattended toy while zero represents random performance. The ability to follow others' gaze (a DS above zero) was assessed using single sample *t*-tests (two-tailed) against random performance, corrected for multiple contrasts (Benjamini & Hochberg, 1995). A possible confound that may influence DS is the number of trials included in each session. To counter this problem, *percentage of accurate gaze shifts* is also reported, and this measure reports the number of accurate gaze shifts divided by the total number of trials included in the current session. Separate analyses were performed for DS and percentage accurate gaze shifts including all gaze shifts within each trial and only the first gaze shift within each trial. No significant differences were found between these two analyses, which is why only the first gaze shift for each trial is included in the analysis below.

In addition, the number of *gaze shifts / trial* and the *latency* of the *first* face to toy fixation shift are also reported. Latency is calculated by subtracting the first frame when the infant fixates the model's face during a trial, after the model starts to turn, from the first frame when the infant fixates either toy (following the initial fixation at the model's face). No differences were observed between the latency of gaze shifts to the attended and the unattended toy; data were aggregated over this variable.

For all of the above-mentioned variables, statistical extraction was performed in a similar manner. Trials where the model did not perform according to instructions were removed (< 5% of all trials) and outliers (two *z*-scores) were substituted with group averages. Data were then aggregated to a single data point for each infant and age. The final matrix for each of the dependent measures was entered into a 4 (age; 2-, 4-, 6-, and 8-months) × 2 (condition; Mother versus Stranger) mixed ANOVA. Significant effects were explored using unequal N HSD post-hoc tests (abbreviations will be used when reporting these post-hoc effects, for example S4 equals the Stranger condition at 4 months). In addition, a multiple regression analysis was performed to evaluate the stability of gaze following abilities using percentage accurate gaze shifts as the dependent variable, and age (4 and 6 months) and condition were used as predictors.

Reliability coding of the models' performance

All gaze shifts (trials) performed by the models were rated for clarity of models' gaze shifts and degree of motion. Twenty percent of these trials (representing an equal proportion of both conditions) were rated by a second coder in order to assess coding reliability. Both coders were blind to the purpose of the study and the performance of each infant. Clarity of models' gaze shifts was evaluated on a 5-point scale ranging from small inhibited movements (1), for example small movements of eyes and head towards one of the toys, to excessive cuing of direction (5), for example leaning towards one of the toys. The two coders agreed on 97.0% of trials. Clarity of models' gaze shifts did not differ between

[1] During the Stranger condition, mothers were standing behind the experimenter who sat with the infant. The mother was not visible to the infant.

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conditions, $F(1, 16) = 0.83$, $p = .37$, $\eta_p^2 = .06$, with an average score of 2.99 ($SD = .01$) for the Stranger condition and 3.03 ($SD = .13$) for the Mother condition. Degree of motion was coded by indicating the extent to which eyes, head, and torso cued location; ranging from eyes only (1) to eyes, head, and torso (3). The two coders agreed on 95.9% of trials. Degree of motion did not differ between the conditions, $F(1, 16) = 2.49$, $p = .13$, $\eta_p^2 = .13$. The average score in the Stranger condition equaled 1.99 ($SD = .01$) and was 2.05 ($SD = .14$) in the Mother condition, demonstrating that models generally cued location with eyes and head only.

Results

Descriptive parameters

On average, sessions included 14 trials (gaze shifts performed by the model) in the Stranger condition and eight trials in the Mother condition, $F(1, 30) = 17.4$, $p < .0002$, $\eta_p^2 = .37$. Although not progressively, the number of trials also changed with age, $F(3, 90) = 3.5$, $p < .02$, $\eta_p^2 = .10$; post-hoc analysis differentiated between 2 and 8 months (each including 10 trials) from 4 and 6 months (each including 12 trials). No interaction effect was observed (see Table 1). At the same time, the average duration of each session ranged from 3.6 minutes (M4 and S8) to 4.7 minutes (S6). Analysis of session duration demonstrated a main effect of age, $F(3, 90) = 4.75$, $p < .005$, $\eta_p^2 = .14$; post-hoc analysis demonstrated that sessions were longer at 2 and 4 months of age than at 8 months, and an interaction between age and condition, $F(3, 90) = 6.05$, $p < .001$, $\eta_p^2 = .17$; post-hoc analysis illustrated longer session durations at S2, S4, and M6 than at S8.

With increased age, infants made more gaze shifts per trial, $F(3, 90) = 24.6$, $p < .0001$, $\eta_p^2 = .45$. Post-hoc tests demonstrated fewer gaze shifts at 2 than at 4, 6, and 8 months, and at 4 compared to 8 months, ranging from 0.32 gaze shifts at 2 months to 1.06 gaze shifts at 8 months (see Figure 2A). In addition, older infants made more gaze shifts per trial in the Stranger condition than in the Mother condition, $F(3, 90) = 3.6$, $p < .05$, $\eta_p^2 = .11$. Post-hoc tests differentiated several age groups, S2 from S6, S8, M6, and M8; S4 from S6 and S8; M2 from S6, S8, and M8; M4 from S8; M6 from S8. However, the number of trials in which the same toy pairs were presented (before the model changed to a new pair of toys) did not differ between conditions but increased with age, $F(3, 90) = 14.3$, $p < .00001$, $\eta_p^2 = .14$, ranging from 7.3 trials/toy pair at 4 months to 5 trials/toy pair at 8 months. Post-hoc tests demonstrated a lower number of trials/pairs of toys at 8 months compared to the other three ages.

Table 1 *Number of trials, session duration (seconds), and the duration of onset between trials (seconds) separately for conditions and ages, SD and range are added as subscripts*

Condition	Age (months)	Number of trials	Session duration	Duration of onset between trials (seconds)
Mother	2	$8_{1,\ 5–11}$	$229_{54,\ 174–368}$	$31_{9,\ 19–53}$
Mother	4	$8_{2,\ 2–13}$	$179_{44,\ 65–240}$	$22_{5,\ 16–32}$
Mother	6	$10_{4,\ 1–18}$	$274_{113,\ 139–602}$	$37_{42,\ 17–187}$
Mother	8	$7_{4,\ 1–14}$	$217_{55,\ 139–323}$	$41_{44,\ 16–192}$
Stranger	2	$13_{7,\ 2–27}$	$279_{122,\ 108–555}$	$30_{32,\ 13–151}$
Stranger	4	$17_{7,\ 6–26}$	$249_{116,\ 76–442}$	$15_{4,\ 9–27}$
Stranger	6	$14_{6,\ 7–30}$	$215_{87,\ 49–476}$	$17_{6,\ 6–28}$
Stranger	8	$13_{5,\ 5–27}$	$171_{52,\ 66–248}$	$14_{4,\ 7–30}$

Note: Duration of onset between trials includes both the trial and the delay between trials. Prolonged intermissions between trials were often caused by inattention, poor eye tracking quality, or general fussiness.

Latency

Infants decreased the latency of their gaze shifts from the face to a toy with increased age, $F(3, 63) = 22.9$, $p < .0001$, $\eta_p^2 = .52$. Post-hoc tests demonstrated higher latencies at 2 than 6 and 8 months; at 4 compared to 6 and 8 months, averaging 3191 ms at 2 months and decreasing to 1412 ms at 8 months (see Figure 2B). A significant interaction effect between age and condition, $F(3, 63) = 3.1$, $p < .05$, $\eta_p^2 = .13$, was also observed. Post-hoc tests demonstrated significantly higher latencies at S2 than S4, S6, S8, and M8; M2 than S6, S8, and M8; M4 than S6, S8, and M8.

Gaze following

Difference scores demonstrated more gaze following when interacting with a stranger than when interacting with the mother, $F(1, 28) = 16.8$, $p < .001$, $\eta_p^2 = .37$, and a significant increase in gaze following with increased age, $F(3, 84) = 9.04$, $p < .0001$, $\eta_p^2 = .24$ (post-hoc tests demonstrated lower DS at 2 than at 4, 6, and 8 months). The same analysis also demonstrated an interaction between condition and age, $F(3, 84) = 5.25$, $p < .005$, $\eta_p^2 = .16$ (post-hoc tests demonstrated lower DS at S2 than M4, M6, and M8; higher DS at S6 than at M2, M4, M6, and M8; higher DS at S8 than at M2 and M6). These results are depicted in Figure 3, including p-values and effect size measures for single sample t-tests used to identify the ages and conditions where infants follow gaze (indicated by a DS that is significantly higher than zero). According to this analysis, infants consistently followed a stranger's gaze from 4 to 8 months of age. Gaze following emerged at the same age during interactions with the mother. However, gaze following was less consistent with non-significant gaze following at both 2 and 6 months and significant gaze following at 4 and 8 months.

Percentage accurate gaze shifts revealed a similar but complementary picture, demonstrating a near significant main effect of condition, $F(1, 30) = 3.99$, $p = .054$, $\eta_p^2 = .12$ (more gaze following in the Stranger condition), a significant increase in gaze following with increased age,

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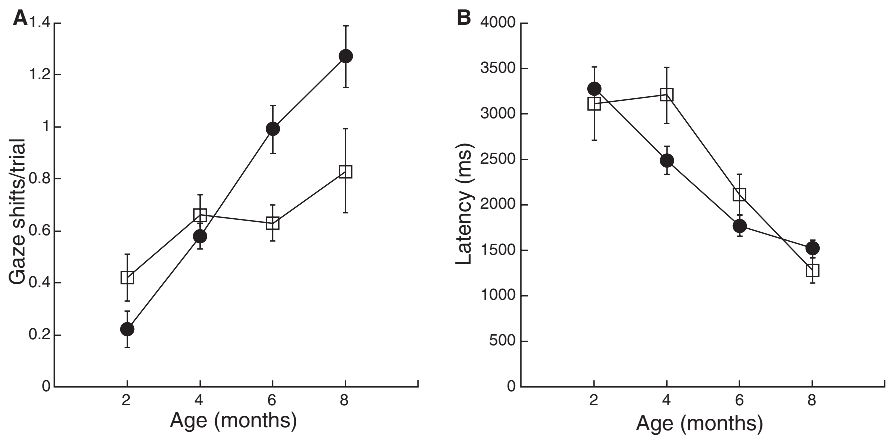

Figure 2 *The average number of gaze shifts per trial (A) and the latency of first face → object gaze shift (B) separately for stranger (closed circles) and mother (open squares) and each age (months). Error bars represent SE.*

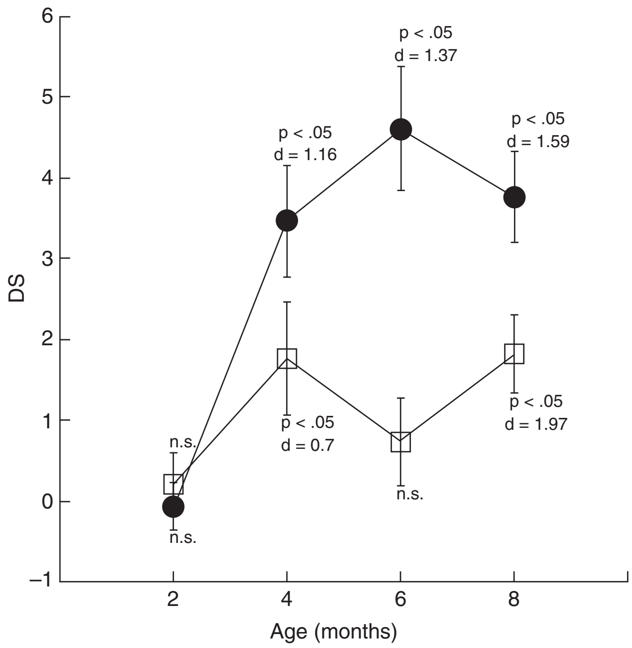

Figure 3 *Difference score (DS) for the stranger (closed circles) and mother (open squares) interactions at each age (months). Error bars represent SE, p-values and Cohen's* d *are based on single sample* t*-tests against a DS of zero.*

$F(3, 90) = 32.5$, $p < .0001$, $\eta_p^2 = .52$ (post-hoc tests illustrated lower percentage accurate gaze shifts at 2 than 4, 6, and 8 months; at 4 than 8 months), and a significant interaction effect between age and condition, $F(3, 90) = 5.5$, $p < .005$, $\eta_p^2 = .15$ (post-hoc tests demonstrated lower percentage accurate gaze shifts at S2 than S4, S6, S8, M4, and M8; at S4 than S6 and S8; at M2 than S6, S8, and M8; at M4 than S6 and S8; at M6 than S6, S8, and M8). For individual differences in percentage accurate gaze shifts, see Figure 4.

As can be seen in Figure 4, as well as in the statistical analyses of DS and percentage accurate gaze shifts, infants were more consistent in their ability to follow others' gaze when interacting with a stranger than during interaction with their own mothers. These differences were also observable when looking at the percentage of infants that increased their gaze following from one age to the next. As can be seen in Table 2, most infants in both conditions increased their gaze following from 2 to 4 months. In addition, most infants increased their gaze following even further; this occurred primarily between 4 and 6 months in the Stranger condition and between 6 and 8 months in the Mother condition. These latter differences were not visible when analyzing DS.

When gaze following data were combined across the two conditions, infants demonstrated consistent gaze following abilities over time. A multiple regression analysis demonstrated that gaze following at 6 months predicted performance at 8 months, $R^2_{adj} = .12$, $F(2, 33) = 3.5$, $p < .05$, $\beta = .41$, $t(2,33) = 3.5$, $p < .05$; gaze following at 4 months did not significantly contribute to gaze following at 8 months.

Discussion

The current study includes three novel elements that enhance our understanding of gaze following. First of all, this is the first study to rely on a prospective longitudinal design to measure the emergence and stability of infants' gaze following between 2 and 8 months of age. Second, no prior study has recorded and analyzed infants' scanning pattern in a gaze following paradigm below 6 months of age, and no prior study has recorded the detailed scanning patterns of infants during live social interactions. All of these aspects of the current study ensure a unique description of the microstructure of gaze following (Aslin, 2007). In addition, no prior study has looked at how infants' gaze following changes over ages with respect to mothers and strangers. Each of these novel aspects of the current study provides valuable information that enhances our understanding of the emergence of gaze following abilities, and each of these will be discussed below.

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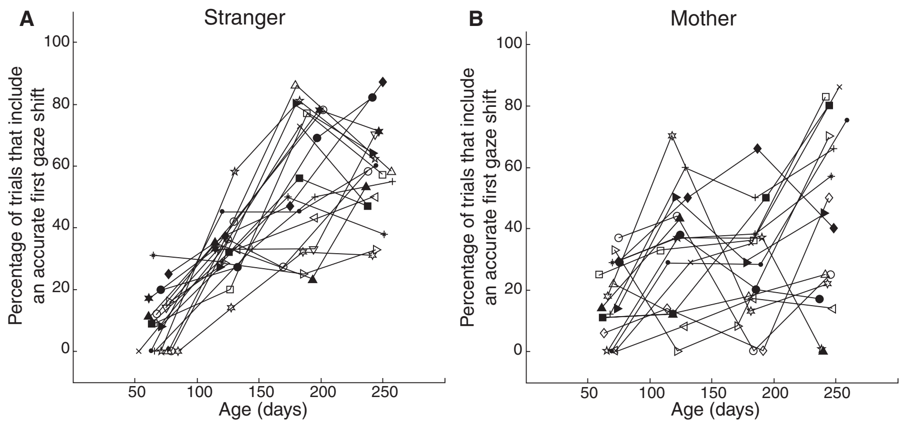

Figure 4 *Individual infants' development of percentage accurate gaze shifts, separately for the Stranger (A) and Mother (B) conditions. Each line represents an infant.*

Table 2 *Percentage of participants that increased gaze following over subsequent ages, as measured by percent accurate gaze shifts (% accurate) and difference scores (DS)*

	% accurate		DS	
Age (months)	Stranger	Mother	Stranger	Mother
2–4	***94***	***87***	***87***	***75***
4–6	***74***	50	53	31
6–8	50	***75***	33	44

Note: Cells in which most infants increased gaze following are marked as bold and italic based on chi-square goodness-of-fit against random performance.

Two-month-olds did not follow the models' gaze in the current context; they made few gaze shifts between the models' faces and the toy and DS scores were close to zero. Four-month-olds, on the other hand, reliably adjusted their gaze to accord with the gaze direction of the model, demonstrating a positive DS and an increase in the percentage of accurate gaze shifts. In fact, most of the infants that participated in the current study increased their gaze following tendency between 2 and 4 months of age, regardless of condition. These findings nicely replicate prior studies documenting gaze following at 3 months (D'Entremont, 2000; D'Entremont et *al*., 1997; Scaife & Bruner, 1975). In addition, gaze following abilities quickly stabilized, with consistent gaze following abilities at 6 and 8 months of age.[2] This stability harmonizes with the findings from prior longitudinal studies that demonstrate consistent gaze following abilities between 6 months and 2 years (Mundy *et al*., 2000).

Prior gaze following studies that have measured the microstructure of infants' gaze at 6 months of age have relied on video presentations of a female stranger shifting her head and eyes to fixate one of two toys located close to the model (Gredebäck *et al*., 2008; Senju & Csibra, 2008). Compared to Gredebäck *et al*., gaze following was more pronounced in the current Stranger condition. In the current study, 6- and 8-month-olds demonstrated an average DS above 4.5 and infants performed more than 1 gaze shift per trial, whereas the 6-month-olds in Gredebäck *et al*. had an average DS of 0.5 and infants performed on average 0.5 gaze shifts per trial. These differences are fairly large given that the scene is highly similar between these two studies, including spatial layout of toys, the location and visual angle of the models' faces. Although not explicitly tested in the current study, we suggest that these differences stem from suppressed response rates in studies that rely on video presentations, depriving infants of 3D visual information, gaze contact, and turn-taking associated with everyday social interactions.

However, not all infants performed at this high level with significant DS scores and persistent gaze following over time. When interacting with their mothers, infants followed gaze from 4 months of age; however, both DS and the percentage accurate gaze shifts were lower than had been established during the interactions with the stranger. This difference can be clearly seen at 4, 6, and 8 months of age in Figure 3; however, post-hoc tests differentiated between conditions only at 6 months of age. These findings demonstrate that infants, at least at 6 months of age, follow a stranger's gaze to a higher degree than the gaze of their mothers. This finding should be related to the developmental lag of gaze following during interaction with mothers compared to strangers depicted in Table 2. From this table it becomes evident that gaze following increases dramatically between 4 and 6 months of age during interactions with strangers, whereas the same improvement is delayed by 2 months during interactions with the infants' own mothers. The different developmental trajectories of gaze following during interactions with mothers compared to strangers are completely novel in the literature, demonstrating a reliable stranger preference.

One additional difference between the two conditions was the number of trials on which infants attended to the models' faces during direct gaze contact, as measured by

[2] It should be noted that the current correlation was found only when aggregating data across conditions. Given the large differences between gaze following abilities at 6 and 8 months in the two conditions, this effect should be interpreted with caution.

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the number of trials that infants participated in. Along the same lines as above, infants demonstrated more sustained attention during interactions with the stranger than during interactions with their respective mothers. There may be a number of factors that influence this difference in sustained attention. The stranger is, by definition, novel and may merit a higher level of attention than the mother. In addition, it may be the case that mothers were better equipped to detect early signs of infant fatigue or distress during direct gaze contact (Mother condition) than the stranger, resulting in an earlier termination of these sessions.

These findings provide a unique platform to discuss the relative role of reinforcement learning principles and the social cognitive framework. As mentioned in the Introduction, it is difficult to perceive how a stranger preference may develop from reinforcement learning *alone* (based on the reappearance of interesting sights along the extension of others' gaze). Instead, these results are consistent with the general assumptions postulated by the social cognitive framework, suggesting that gaze following from 6 months of age (and perhaps even in 4-month-olds) serves a deictic and communicative role during interactions with others.

Having said this, it is still unclear why young infants pay more attention to, and follow the gaze to a higher degree, when the model is a stranger. The motive behind this preference is beyond the scope of this paper. However, at least two alternatives are possible. It may be that infants are simply more interested in the motives and preferences of unfamiliar others. It can, however, also be stipulated that early gaze following skills stem from an ontogenetic pressure to compete or detect the presence of threats. These suggestions are tentative; however, some support for these findings can be found in the animal literature. For example, chimpanzees follow humans' gaze to a higher degree during competition than during cooperation (Gomez, 2005). At the same time Baron-Cohen (1994) references studies performed by Ristau which demonstrate an association between avoidance responses and gaze detection in plovers. In humans, the attachment system (Bowlby, 1969, 1980) is assumed activated during threats of separation. A stranger may well represent a threatening figure that the human infant responds to by means of more attentive gaze following. This response can be a precursor of later (e.g. at 8 months of age) behavioral responses to separation, as noted by Bowlby and others (see also Goodman & Melinder, 2007). Clearly, the cause of the current stranger preference is dependent on further investigations.

However, it is important to note that the literature contains slightly different suggestions as to the exact nature of the social cognitive influence on infants' gaze following. It has been suggested that the primary driving force is an 'intention to share'; focusing on pro-social aspects of social interactions (Carpenter *et al.*, 1998). However, it is equally likely that the social cognitive mechanisms that drive gaze following are mediated by a desire to interpret the deictic references of others, focusing on the need to understand the intentions and desires of others (Senju & Csibra, 2008). The current design does not aim to differentiate these alternative accounts. However, we note that the stranger preference is more easily related to the latter. Thus, we suggest that the social cognitive influences guiding young infants' gaze following (at least in the current context) are more tuned to intentional understanding than pro-social communication.

In a similar manner, the design is not optimized for differentiating the role of phylogenetic and ontogenetic influences on the development of gaze following. However, the fact that infants differentiate their mothers from strangers demonstrates that gaze following is not grounded in innate mechanisms that are insensitive to postnatal experience. Instead, the current finding illustrates how important infants' own experiences are for shaping their early interactions with others.

Alternative perspectives on gaze following

Several alternative hypotheses have been raised that do not receive support from the current dataset. First of all, it is possible to argue that infants simply track the movement of the face and extrapolate its motion. This alternative is not likely for two reasons; first of all, the movements of the mother and the stranger models were trained and standardized, making a simple motion account unlikely to explain the current stranger bias. Second, the latency to shift gaze from the model to either toy (between 1500 and 3500 ms) far exceeds the reactive saccade latencies of similar age infants (Gredebäck, Örnkloo & von Hofsten, 2006), suggesting that additional processing is required to follow gaze. Similar arguments have previously been brought forward by others; however, they did not compare different models and they did not measure gaze with the same detail (D'Entremont, 2000).

In addition, the perceptual-attention account states that the tendency to shift gaze from face to target is modulated by the distance and salience of the targets (D'Entremont, 2000). Along the same lines, Hood *et al.* (1998) argue that infants may find it difficult to disengage from a salient central stimulus (like a face). Applying this logic to our current study, one may suggest that infants performed worse with their mother because she demanded more attention from the infants, making it harder to disengage and follow her gaze. Two lines of evidence suggest that this interpretation is unlikely. First of all, the latency to follow gaze is highly similar between conditions, especially at 6 months where the stranger preference is most pronounced. Second, infants participate in more trials during interaction with strangers than with mothers, suggesting the opposite relationship between attention and gaze following. Clearly, differences in salience of faces and targets affect gaze following

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tendencies; however, this account is unable to explain the current stranger preference.

Summary

We have demonstrated that gaze following abilities emerge between 2 and 4 months of age and that infants' performances are highly stable between 6 and 8 months of age. When presented with a real life adult stranger, infants' gaze following abilities develop uniformly across infants with higher frequencies of gaze following than previously observed in similar studies that rely on video presentations. When interacting with their mothers, gaze following abilities appear less stable, with significant gaze following only at 4 and 8 months and an overall lower frequency of gaze following. These findings do not support the notion that reinforcement learning principles are the only driving force behind the emergence of gaze following. Instead, the findings are interpreted in favor of the social cognitive framework, suggesting that the emergence of gaze following is influenced by social cognitive motives. In summary, the current finding demonstrates that gaze following emerges early in development and that infants between 4 and 6 months of age develop a sensitivity to the context in which gaze following occurs. Young infants follow the joint attention bids of others to a higher degree when interacting with a stranger than during interaction with their own mothers, demonstrating a robust stranger preference.

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References

Aslin, R.N. (2007). What's in a look? *Developmental Science*, **10** (1), 48–53.

Baron-Cohen, S. (1994). How to build a baby that can read minds: cognitive mechanisms in mind reading. *Current Psychology of Cognition*, **13** (5), 513–552.

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. 61–83). Hillsdale, NJ: Lawrence Erlbaum.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, Series B*, **57** (1), 289–300.

Bowlby, J. (1969). *Attachment and loss (Vol. 1), Attachment*. London: Hogarth.

Bowlby, J. (1980). *Attachment and loss (Vol. 3), Loss, sadness, and depression*. New York: Basic Books.

Bräuer, J., Call, J., & Tomasello, M. (2005). All great ape species follow gaze to distant locations and around barriers. *Journal of Comparative Psychology*, **119** (2), 145–154.

Brooks, R., & Meltzoff, A.N. (2002). The importance of eyes: how infants interpret adult looking behavior. *Developmental Psychology*, **38** (6), 958–966.

Butterworth, G., & Cochran, E. (1980). Towards a mechanism of joint visual attention in human infancy. *International Journal of Behavioral Development*, **2**, 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.

Carpenter, M., Akhtar, N., & Tomasello, M. (1998). Fourteen-through 18-month-old infants differentially imitate intentional and accidental actions. *Infant Behavior and Development*, **21** (2), 315–330.

Corkum, V., & Moore, C. (1998). The origins of joint visual attention in infants. *Developmental Psychology*, **34** (1), 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.

D'Entremont, B. (2000). A perceptual-attentional explanation of gaze following in 3- and 6-month-olds. *Developmental Science*, **3** (3), 302–311.

D'Entremont, B., Hains, S.M.J., & Muir, D.W. (1997). A demonstration of gaze following in 3- to 6-month-olds. *Infant Behavior and Development*, **20** (4), 569–672.

Deák, G.O., Flom, R.A., & Pick, A.D. (2000). Effects of gesture and target on 12- and 18-month-olds' joint visual attention to objects in front of or behind them. *Developmental Psychology*, **36** (4), 511–523.

Farroni, T., Massaccesi, S., Pividori, D., & Johnson, M.H. (2004). Gaze following in newborns. *Infancy*, **5** (1), 39–60.

Flom, R., Deák, G., Phill, C.G., & Pick, A.D. (2004). Nine-month-olds share visual attention as a function of gesture and object location. *Infant Behavior and Development*, **27**, 181–194.

Friesen, C.K., & Kingstone, A. (1998). The eyes have it! Reflexive orientating is triggered by nonpredictive gaze. *Psychonomic Bulletin & Review*, **5** (3), 490–495.

Ghirlanda, S., & Enquist, M. (2003). A century of generalization. *Animal Behaviour*, **66** (1), 15–36.

Gomez, J.C. (2005). Species comparative studies and cognitive development. *Trends in Cognitive Sciences*, **9** (3), 118–125.

Goodman, G.S., & Melinder, A. (2007). Child witness research and forensic interviews of young children: a review. *Legal and Criminological Psychology*, **12**, 1–19.

Gredebäck, G., Örnkloo, H., & von Hofsten, C. (2006). The development of reactive saccade latencies. *Experimental Brain Research*, **173** (1), 159–164.

Gredebäck, G., Theuring, C., Hauf, P., & Kenward, B. (2008). The microstructure of infants' gaze as they view adult shifts in overt attention. *Infancy*, **13** (5), 533–543.

Hood, B.M., Willen, J.D., & Driver, J. (1998). Gaze perception triggers corresponding shifts of visual attention in young infants. *Psychological Science*, **9**, 131–134.

Moll, H., & Tomasello, M. (2004). 12- and 18 month-old infants follow gaze to spaces behind barriers. *Developmental Science*, **7** (1), F1–F9.

Moore, C., Angelopoulos, M., & Bennett, P. (1997). The role of movement in the development of joint visual attention. *Infant Behavior and Development*, **20** (1), 83–92.

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Moore, C., & Corkum, V. (1994). Social understanding at the end of the first year of life. *Developmental Review*, **14**, 349–372.

Moore, C., & Corkum, V. (1998). Infant gaze following based on eye direction. *British Journal of Developmental Psychology*, **16**, 495–503.

Morales, M., Mundy, P., Crowson, M.M., Neal, A.R., & Delgado, C.E.F. (2005). Individual differences in infant attention skills, joint attention, and emotion regulation behaviour. *International Journal of Behavioral Development*, **29** (3), 259–263.

Morales, M., Mundy, P., & Rojas, J. (1998). Following the direction of gaze and language development in 6-month-olds. *Infant Behavior and Development*, **21** (2), 373–377.

Morissette, P., Ricard, M., & D'ecarie, T.G. (1995). Joint visual attention and pointing in infancy: a longitudinal study of comprehension. *British Journal of Developmental Psychology*, **13**, 163–175.

Mundy, P., Block, J., Delgado, C., Pomares, Y., Van Hecke, A.V., & Parlade, M.V. (2007). Individual differences and the development of joint attention in infancy. *Child Development*, **78** (3), 938–954.

Mundy, P., Delgado, C., Yale, M., Messinger, D., Neal, R., & Schwartz, H.K. (2000). Responding to joint attention across the 6- to 24-month of age period and early language acquisition. *Journal of Applied Developmental Psychology*, **21**, 283–298.

Mundy, P., & Gomes, A. (1998). Individual differences in joint attention skill development in the second year. *Infant Behavior and Development*, **21** (3), 379–541.

Mundy, P., & Sigman, M. (2006). Joint attention, social competence, and developmental psychopathology. In D. Cicchetti & D.J. Cohen (Eds.), *Developmental psychopathology: Theory and methods* (2nd edn., Vol. 1, pp. 293–332). Hoboken, NJ: John Wiley & Sons.

Scaife, M., & Bruner, J.S. (1975). The capacity for joint visual attention in the infant. *Nature*, **253**, 265–266.

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

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., Johnson, M.H., & Csibra, G. (2006). The development and neural basis of referential gaze perceptions. *Social Neuroscience*, **1** (3–4), 220–234.

Striano, T., & Bertin, E. (2005). Coordinated affect with mothers and strangers: a longitudinal analysis of joint engagement between 5 and 9 months of age. *Cognition and Emotion*, **19** (5), 781–790.

Striano, T., & Reid, V. (2006). Social cognition in the first year. *Trends in Cognitive Sciences*, **10** (10), 471–476.

Striano, T., & Stahl, D. (2005). Sensitivity to triadic attention in early infancy. *Developmental Science*, **8** (4), 333–343.

Theuring, C., Gredebäck, G., & Hauf, P. (2007). Object processing during a joint gaze following task. *European Journal of Developmental Psychology*, **4** (1), 65–79.

Tomasello, M. (2001). *The cultural origins of human cognition*. Cambridge, MA: Harvard University Press.

Triesch, J., Teuscher, C., Deák, G., & Carlson, E. (2006). Gaze following: why (not) learn it? *Developmental Science*, **9** (2), 125–157.

Van Hecke, A.V., & Mundy, P. (2007). Neural systems and the development of gaze following and related joint attention skills. In R. Flom, K. Lee, & D. Muir (Eds.), *Gaze-following: Its development and significance* (pp. 17–52). Mahwah, NJ: Lawrence Erlbaum.

von Hofsten, C., Dahlström, E., & Fredriksson, Y. (2005). 12-month-old infants' perception of attention direction in static video images. *Infancy*, **8** (3), 217–231.

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