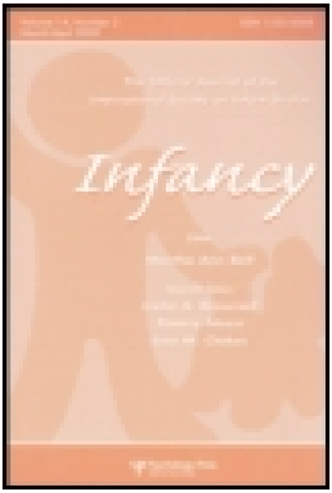

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The Microstructure of Infants' Gaze as They View Adult Shifts in Overt Attention

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We presented infants (5, 6, 9, and 12 months old) with movies in which a female model turned toward and fixated 1 of 2 toys placed on a table. Infants' gaze was measured using a Tobii 1750 eye tracker. Six-, 9-, and 12-month-olds' first gaze shift from the model's face (after the model started turning) was directed to the attended toy. The 5-month-olds performed at random. Following this initial response, 5-, 6-, and 9-month-olds performed more gaze shifts to the attended target; 12-month-olds performed at random. Infants at all ages displayed longer looking times to the attended toy. We discuss a number of explanations for 5-month-olds' ability to follow a shift in overt attention by an adult after an initially random response, including the possibility that infants' initial gaze response strengthens the representation of the objects in the peripheral visual field.

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Developing the motivation to follow others' gaze direction represents a major advancement in infants' early social cognition, with which they take their first steps toward perceiving the intentions and goals of others (Bräuer, Call, & Tomasello, 2005; Tomasello, Carpenter, Call, Behne, & Moll, 2005). The emergence of gaze following was originally described by Scaife and Bruner (1975). An adult model made eye contact with an infant before shifting head and eyes to fixate a new location. Gaze following was reported in 30% of the 2-month-olds, increasing with age to include all 14-month-olds. Since then numerous papers have reported on infants' gaze following. It has been established that 3-month-old infants reliably follow gaze if a model turns to one of two highly salient targets that are located close to the model (D'Entremont, 2000; D'Entremont, Hains, & Muir, 1997)—an effect that has also been observed in many studies at 6 months of age (Morales, 2000; Morales, Mundy, Crowson, Neal, & Delgado, 2005; Morales, Mundy, & Rojas, 1998). Live social interaction is not necessary for perceived gaze to affect infants' attention. Infants produce faster reactive gaze shifts to a reappearing target following a static face with congruent rather than incongruent gaze (Farroni, Mansfield, Lai, & Johnson, 2003; Hood, Willen, & Driver, 1998).

If the targets are placed further away from the model, or hidden from the infant, gaze following emerges between 8 and 12 months of age (Corkum & Moore, 1998; Flom, Deák, Phill, & Pick, 2004; Moore & Corkum, 1994; Morissette, Ricard, & D'ecarie, 1995). In the following year infants extend their gaze following to a wide range of contexts, including gaze shifts to locations outside their own visual field, and the ability to predict the reappearance of targets based on others' gaze direction (Butterworth & Cochran, 1980; Butterworth & Jarrett, 1991; Deák, Flom, & Pick, 2000; Flom et al., 2004; Moore & Corkum, 1998; Woodward, 2003).

Gaze following is often analyzed by coding the direction of infants' first head turn (Flom et al., 2004) from video. This is a comparatively crude measure because eye and head movements are independently controlled (von Hofsten, Dahlström, & Fredriksson, 2005; von Hofsten & Rosander, 1997), and head movements sometimes only account for a fraction of the total scanning amplitude (Grönqvist, Gredebäck, & von Hofsten, 2006). To accurately determine gaze direction, eye movements must be measured. In gaze following studies this is generally achieved by coding eye direction from video (D'Entremont et al., 1997). However, with this method, even trained observers can only separate gaze into a few broad regions (Aslin & McMurray, 2004), making it difficult to capture the richness of infants' gaze. Coders are often forced to analyze the macrostructure of infants' gaze (e.g., whether infants look to the left or right; Aslin, 2007).

Recent advances in eye tracking technology make it possible to measure the microstructure (including scanning patterns, fixation durations, and saccade latencies; Aslin, 2007) of gaze following with a higher spatial (1 visual degree) and temporal (50 Hz) resolution. In the first study to use eye tracking to measure infants' gaze following, von Hofsten, Dahlström, and Fredriksson (2005) demonstrated that 1-year-olds follow a model's gaze to a target object even when presented as a still picture and even when the attended object is surrounded by several distracters (at a distance of 10 visual degrees). Recently, Theuring, Gredebäck, and Hauf (2007) demonstrated that 1-year-old infants also follow others' gaze direction in movies. This later study also demonstrates a brief enhancement of object processing for attended versus nonattended objects (see also Reid & Striano, 2005; Woodward, 2003).

No detailed information about the microstructure of the infant's gaze following exists below 12 months of age, and here we intend to fill this gap. The infant's gaze is recorded with a near infrared remote eye tracker while he or she is presented with movies of a model that first looks straight ahead and thereafter turns to fixate one of two stationary toys (without vocalization). The combination of eye tracking and movies are optimal for maintaining a high spatial and temporal accuracy in both recording and analyzing the relationship between the model's attention and the infants' gaze.

METHOD

Participants

Sixty-four healthy full-term infants, recruited by mail based on birth records, participated in the final sample. Participants were sixteen 12-month-olds (*M* age = 12 months, 1 day, *SD* = 9 days), sixteen 9-month-olds (*M* age = 9 months, 8 days, *SD* = 5 days), sixteen 6-month-olds (*M* age = 6 months, 0 days, *SD* = 1 day), and sixteen 5-month-olds (*M* age = 5 months, 2 days, *SD* = 2 days). In addition, eight 12-month-olds, seven 9-month-olds, eleven 6-month-olds, and three 5-month-olds were tested but were not included in the final sample because of fussiness, inattentiveness, or technical problems. Inattentive infants did not attend to the calibration or quickly got bored of both the attention-grabbing and experimental movies. The excluded infants' ages did not differ from their respective age groups.

Stimuli and Apparatus

Gaze was measured using a Tobii 1750 near infrared eye tracker with an infant add-on (www.Tobii.com) with a precision of 1°, accuracy of 0.5°, and sampling rate of 50 Hz. During calibration a blue-and-white sphere expanded and contracted at nine locations on the screen (see Falck-Ytter, Gredebäck, & von Hofsten, 2006).

The stimuli consisted of 24 movies (6 toy pairs × 2 locations × 2 possible attended objects) of a female model (face extended 9.4°) moving her gaze (which we define here as including both eye and head movements) to fixate one of two toys (see Figure 1a). Each movie included a 5-sec segment in which the model looked

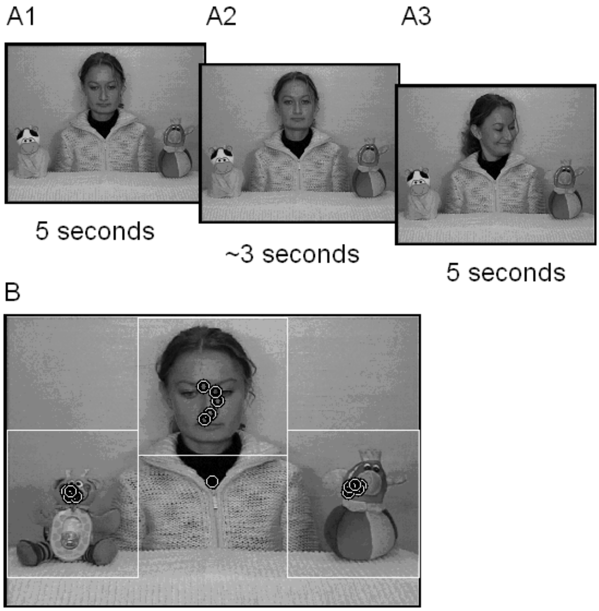

FIGURE 1 (a) Successive events of each movie: a still picture of the model looking at the table (1), the model looks up and turns (2), and finally a still picture of the model fixating the attended toy (3). (b) The three areas of interest with example fixation data from a 9-month-old infant depicted as circles. Stimuli were presented in color. Note that the model's eyes are visible throughout each movie, even though it can be difficult to perceive in these reduced images. The distance from the nearest eye to the toy in Figure 1a (3) is ~5.9°.

down at the table, a looking up phase (~1.5 sec), and a turning phase (~1.5 sec), at the end of which the model fixated one of the two toys (5 sec). The model initially had a neutral facial expression and smiled when looking at the toy. She remained silent throughout the study.

Procedure

The study was approved by the ethics committee at the Research Council in the Humanities and Social Sciences and therefore in accordance with the ethical standards specified in the 1964 Declaration of Helsinki. As each family entered the lab, parents were informed about the procedure and signed a consent form. Infants were seated in a car safety seat and placed on the parent's lap approximately 50 cm from the Tobii monitor. Each infant was presented with six movies, each containing a single gaze shift toward a target. The infant always saw the same toy pair, and the same toy was always attended. However, the location of the two toys was reversed according to an ABBABA design. Toy sets, their initial placement, and the attended toy were randomized across participants. Each family spent 15 to 20 min in the lab.

Data Reduction

Data were separated into a baseline block (B), including the model's fixation of the table and the upward movement of the head before attention was directed to either toy (~6.5 sec), and a gaze direction block (GD) including the model's turn and subsequent fixation of a toy (~6.5 sec). The scene was divided into three areas of interest (AOI) covering the face (11.1° × 16.3°) and each of the two toys (12.8° × 14.3°; see Figure 1b). Infant gaze data were reduced to a sequence of AOI fixations, and the shifts between these fixations. A fixation is defined as a constant gaze within a 50-pixel (~1°) diameter area for at least 200 msec. The 200 msec criteria was based on adult (Engel, Anderson, & Soechting, 1999) and infant (Gredebäck, Örnkloo, & von Hofsten, 2006) reactive saccade latencies.

The standard measure of gaze following, the *standard difference score* (standard DS; Corkum & Moore, 1998; Moore & Corkum, 1998), was calculated for each infant as the number of times the first GD block face to toy fixation shift went to the attended toy, minus the number of times it went to the unattended toy. In addition, we calculated a *late difference score* (late DS), providing a measure of the accuracy of all the remaining face to toy fixations in each trial. The late DS is calculated in the same way as the standard DS but using these later gaze shifts. Both the standard and late DS are supplemented with percentages correct gaze shift (face to attended toy / face to attended and unattended toy). We also report, for each AOI, *fixation durations, latencies,* and *gaze shift counts* (the mean number of fixation shifts per trial between each AOI pair).

Analysis was performed using general linear models with Scheffé post hoc tests, correlated *t* tests and single-sample *t* tests. Model fit was checked by inspecting diagnostic scatter plots, using standardized residuals (Grafen & Hails, 2002); all *t* tests were two-tailed and corrected for multiple contrasts (Benjamini & Hochberg, 1995).

RESULTS

Infants fixated the model's face and then made a saccade to either of the two toys in the GD block in the vast majority of presented trials (89% of trials for 12-month-olds, 87% for the 9-month-olds, 95% for the 6-month-olds, and 82% for the 5-month-olds). Infants did not improve their gaze following over successive trials, nor did they learn to predict which toy the model would fixate during the GD block. Because of this, all data were collapsed across trials in the following analysis.

The standard DS increased with age, $F(3, 60) = 2.9$, $p < .05$, $\eta^2 = 0.13$ (Figure 2a). Subsequent *t* tests against random performance demonstrated significant standard DS at 6 months (standard DS = 1.56, 66% correct), $t(15) = 3.82$, $p < .05$, $d = 0.96$; at 9 months (standard DS = 1.62, 73% correct), $t(15) = 3.20$, $p < .05$, $d = 0.8$; and at 12 months of age (standard DS = 2.6, 76% correct), $t(15) = 5.04$, $p < .05$, $d = 1.26$. Standard DS at 5 months of age (standard DS = 0.5, 57% correct) did not differ from zero, $t(15) = 0.86$, $p > .05$. The late difference score (late DS), on the other hand, decreased with age, $F(1, 54) = 2.98$, $p < .05$, $\eta^2 = 0.15$ (Figure 2b). Five-month-olds (late DS = 1.14, 73% correct) performed significantly above random, $t(15) = 2.93$, $p < .05$, $d = 0.78$; as did 6-month-olds (late DS = 0.81, 62% correct), $t(15) = 1.89$, $p < .05$, $d = 0.47$; and 9-month-olds (late DS = 1.0, 71% correct), $t(15) = 2.45$, $p < .05$, $d = 0.7$; but not 12-month-olds (late DS = –0.4, 38% correct), $t(15) = -1.10$, $p > .05$.

We performed some additional tests on the 5-month data to examine some hypotheses concerning the nonsignificant standard DS (see discussion). It was unlikely to be due to a lack of power. A power test indicated that given the observed variation in the sample, we had a 95.3% chance of detecting an effect as large as that found for the 6-month group, if such an effect had existed. There was no correlation between individual's standard DS and his or her number of transitions contributing to the late DS, $F(1, 14) = 0.34$, $p > .05$, and all but two of the sixteen 5 month-olds made late gaze shifts. A longer latency to perform the first face to toy gaze shift was not a predictor of increased chance of success, $\chi^2(1, N = 72) = 0.23$, $p > .05$ (logistic regression using likelihood ratio test).

On average, 5-month-olds performed 2.6 (SD = 1.4) gaze shifts between the three AOIs on each included trial, whereas 6-month-old and 9-month-old infants

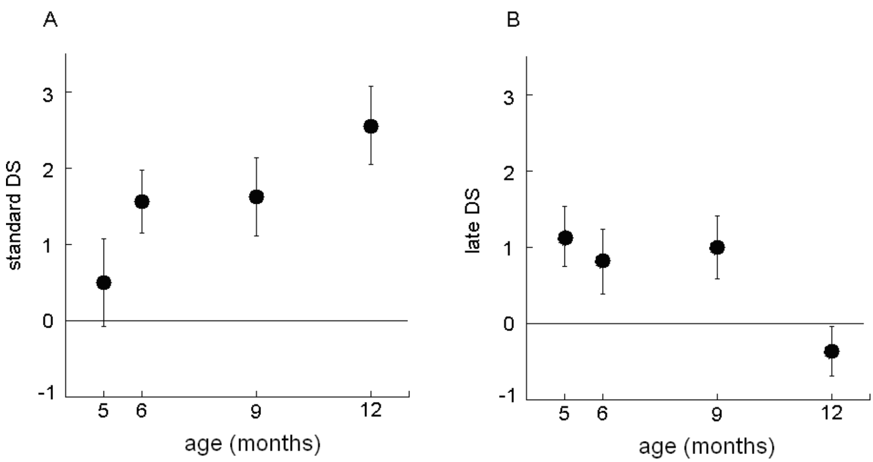

FIGURE 2 Standard difference score (a) and late difference score (b). Error bars show standard error. The tendencies of standard difference score to increase and late difference score to decrease with age are significant (see text).

both performed 2.8 (SD = 1.6) gaze shifts, and 12-month-olds performed 3.4 (SD = 1.9) gaze shifts. Infants spent more time fixating the face during the baseline (M = 2,859 msec) than during the GD block (M = 2,303 msec), $F(1, 60) = 8.5$, $p < .05$; $\eta^2 = 0.12$. Infants usually fixated the face at the beginning of each trial, waiting on average 3,077 msec before looking at either toy. During the GD block infants waited on average 3,266 msec before shifting their gaze from the face to either toy. This first fixation of a toy in the GD block (following a fixation at the model's face) lasted on average 636 msec. Neither of these latencies displayed significant difference over age or AOI (comparing the attended and unattended toy).

Infants fixated the attended and unattended toy to an equal degree in the baseline block but the length of this toy fixation increased with age, $F(3, 60) = 5.4$, $p < .05$, $\eta^2 = 0.21$; post hoc tests differentiated the 12-month-olds from 5- and 9-month-olds ($p < .05$). In the GD block infants fixated the attended toy to a higher degree than the unattended toy (see Figure 3), $F(1, 60) = 25.7$, $p < .05$, $\eta^2 = 0.30$. No age differences were found.

DISCUSSION

If gaze following was measured solely using standard DS (as is often the case) we would conclude that gaze following emerges between 5 and 6 months of age, replicating previous studies that have reported on gaze following at 6 months (Morales,

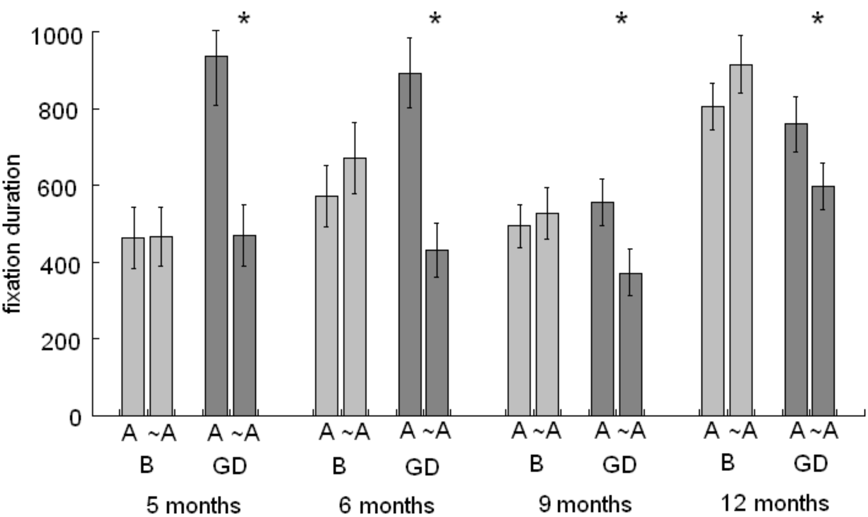

FIGURE 3 Fixation durations at the attended (A) and unattended targets (~A) during baseline (B) and gaze direction blocks (GD). Significant differences are reported with * (see text). Error bars represent standard error.

2000; Morales et al., 2005; Morales et al., 2000; Morales et al., 1998), as well as 9 months (Corkum & Moore, 1998; Flom et al., 2004; Moore, Angelopoulos, & Bennett, 1997; Moore & Corkum, 1994) and 12 months of age (Morissette et al., 1995) using the standard "live" gaze following paradigm and video analysis. On the other hand, overall duration of fixation revealed no differences in infants' gaze following between 5 and 12 months of age—all infants preferred to fixate the attended toy during the GD block. This apparent conflict arises because neither measurement adequately captures the detailed microstructure of infant gaze.

A more detailed analysis reveals that 5-month-olds first gaze shift from the model's face to a toy during the GD block was to a random toy. Five-month-olds fixated both the model's face and one of the toys before they accurately followed gaze direction. This is a robust but puzzling finding that was not explicitly predicted by theory. As such we can only offer a series of potential hypotheses that require further investigation. The most straightforward hypothesis is that 5-month-olds may require more time to process gaze direction, so processing is not complete when they made their initial gaze shift from the face to a toy. Once they fixate the face for a second time they complete the processing required to accurately perceive and follow gaze direction. However, this hypothesis predicts a correlation that was not found, namely between the latency of the first face to toy gaze shift and the probability of the shift being to the attended toy.

The second hypothesis is that infants who are poor at perceiving gaze direction may stop making gaze shifts between the toys and the face, leaving only high-performance infants to influence late DS. Again this hypothesis predicts a correlation that was not found, namely between 5-month-olds' standard DS and their number of late gaze shifts, and in fact all but two of the sixteen 5-month-olds contributed to the late gaze shift data.

The final hypothesis we offer relates to the fact that infants' gaze following is not solely dependent on the perception of the model but also on the structure of the environment and the saliency of the targets. For example, infants are more likely to follow others' gazes if the targets are close by and visible (D'Entremont, et al., 1997; Morales, 2000) than if they are far off or hidden from the infants (Corkum & Moore, 1998; Flom et al., 2004; Moore & Corkum, 1994; Morissette et al., 1995). D'Entremont (2000) demonstrated that both 3- and 6-month-old infants performed more accurate gaze shifts when the targets were close to the model than when they were further away and suggested that perceiving both the model's gaze and the target enhances gaze following.

It may be that while the 5-month-olds are fixating the model's face, their peripheral perception of the toy pair does not activate a strong enough representation of the toys to provide the necessary contextual support for gaze following. Once they have made one exploratory gaze shift away from the model's face to one of the toys, however, their representation of the pair of toys is strengthened sufficiently to allow the detection of the relationship between the model's gaze and the toys. Gaze following then becomes possible for the 5-month-olds at the same level as the older infants. This hypothesis makes the plausible assumption that, because they have seen the toy pair over a number of trials, even if the first shift is to the unattended toy, the representation of both toys is strengthened.

The fact that the 12-month-olds show positive standard DS but no late DS indicates a much shorter interest in gaze following at this age. Perhaps the 12-month-olds have all the information they need to have about the model and her gaze direction already after their first fixation shift. They follow gaze accurately and use the remaining part of each trial to scan the scene for other interesting objects (or events).

Another noteworthy result is the fairly long latency to shift gaze from the model's face to either of the two toys (~ 3 sec). This exceeds the gaze presentation times used in some other studies, such as 2.5 sec (Reid & Striano, 2005) and 1 sec (Farroni, Johnson, & Csibra, 2004). After these intervals many of the infants that participated in this study had not yet completed their initial coding of the model's face. Future studies of gaze following should possibly prolong the length of directed gaze presentation.

A similar argument may explain why our gaze following latencies are much shorter than those reported by Striano and Stahl (2005). In their study, which involved a live model fixating an object in ~3-sec bursts, 6-month-olds took about 16 sec to follow gaze. Based on the findings reported here it seems possible that their model's rapid disengagement from the attended toy (and subsequent refixation on the infant) disrupted gaze following and increased the latency to follow gaze. There are, however, other possible explanations for the latency differences. It is possible that our eye-tracking technique captures brief gaze shifts that a human coder easily misses. Alternatively, gaze following latency may be genuinely shorter in our situation because a video-depicted person is inherently less interesting than a real individual, meaning the infant's gaze leaves the model faster, leading to faster latencies and more gaze following. It is difficult to disentangle these alternative hypotheses without further experiments. Ongoing research projects will tackle these issues by recording infants' gaze as they interact with a live model. This is made possible by a new generation of eye trackers allowing careful measurements of the microstructure of gaze during real social interactions (Tobii x50).

In summary, 6-, 9-, and 12-month-olds' first gaze shift from the model's face (standard DS) was most often directed to the attended toy, whereas 5-month-olds performed at random. Later gaze shifts from the model's face within each trial (late DS) were most often directed to the attended target at 5, 6, and 9 months of age, whereas 12-month-olds performed at random. Among other explanations, it is possible that these differences are not primarily caused by differences in the ability to perceive and follow others' gaze direction but rather are related to the developing ability to represent objects in peripheral vision. This new finding was made possible by the detailed description of gaze dynamics provided by eye-tracking technology. Future eye-tracking studies that systematically explore more variables than this initial descriptive study will no doubt uncover further such nuances.

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