



Differing patterns of face processing in infants at elevated likelihood of autism

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ABSTRACT

Typical development shows early biases in face attention during infancy, characterized by face inversion effects and increased attention to the left side of the face. In autism spectrum disorder (ASD), face scanning patterns often differ, with reduced inversion effects and left-side biases. The current study examined inversion effects, side biases, and pupil responses in EL and TL infants at 7, 10, and 13 months using linear mixed modeling. TL infants showed greater looking to the left side of the face than EL infants both over the full trial duration and in the 500–1000 ms trial window. Also, in the 500–1000 ms window, a significant left versus right side difference was observed only in the TL group. Pupil responses revealed an interaction between group and age, with EL infants showing a larger pupil size increase over time. These findings suggest that elevated ASD likelihood may be linked to early face-processing differences, such as reduced left gaze bias and greater pupil increases in infancy. Further research is necessary to determine if these patterns are specific to faces or reflect broader atypicalities in hemispheric asymmetry and autonomic function, and how these differences may contribute to later emerging features of ASD.

1. Introduction

Faces are among the most socially salient visual stimuli in an infant's environment. From the very beginning of life, an infant's visual world is saturated with faces. Past research has shown that newborns will track face-like stimuli more than other patterns, just minutes after birth (Goren et al., 1975). Head-mounted eye-trackers reveal that within the first three months of life, about 25 % of an infant's visual experience includes looking at faces (Sugden et al., 2014), and even by 11 months, faces still make up about 20 % of their visual experience (Jayaraman et al., 2015). This early exposure to faces is crucial and supports infants as they continue to extract

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significant information from faces, such as recognizing identities (e.g., [Pascalis et al., 1998](#)) and distinguishing their mother's face from that of a stranger (e.g., [Bushnell et al., 1989](#)).

1.1. Early face processing patterns in typical development

The way in which an infant visually engages with faces may help constrain how a face is processed and understood, forming the foundation for social cognition. Early visual biases, for example, help drive the development of specialized neural and attentional systems for face perception, which continue to refine throughout infancy and childhood ([de Haan & Nelson, 1999](#); [Rose et al., 2008](#)). By adulthood, we exhibit persistent patterns in face processing. For instance, inverted faces are recognized more slowly and with a greater rate of errors compared to upright faces (e.g., [Leder & Bruce, 2000](#); [Rhodes et al., 1993](#)). This is thought to occur because faces are processed configurally or holistically, and inverting a face disrupts this mechanism ([Freire et al., 2000](#)). This disruption of holistic processing when faces are inverted has been taken as a hallmark of mature face expertise. Thus, the presence, or absence, of an inversion effect provides insight into the development of specialized face processing mechanisms.

An inversion effect can be seen in infancy ([Bhatt et al., 2005](#); [Rose et al., 2008](#); [Turati et al., 2004](#)). Even newborn infants show preferential looking and attend more to upright faces and/or face-like stimuli ([Johnson et al., 1991](#); [Mondloch et al., 1999](#); [Valenza et al., 1996](#)), and this has also been seen during fetal development, with babies in utero orienting more towards upright face-like stimuli compared to inverted images ([Reid et al., 2017](#)). By six months of age this preference seems to become more specific to faces rather than to all broadly face-like (i.e., top-heavy) stimuli ([Chien, 2011](#)). Infants also begin to show evidence of neural differentiation between upright and inverted faces, and while this effect appears initially tuned to familiar faces at 6 months ([Balas et al., 2010](#)), it generalizes to unfamiliar faces by eight months ([Otsuka et al., 2007](#)). Eye-tracking studies of attentional patterns also show consistent differences for upright and inverted faces by the end of the first year of life ([Oakes & Ellis, 2013](#)). Taken together, these findings provide compelling evidence that in typical development, differences in processing upright and inverted faces emerge early in infancy and continue to strengthen with development, which indicates that infants are tuning into the relational features that distinguish upright faces from non-social or less familiar stimuli.

Another signature of specialized face processing is the left-side bias, a bias to look, from a viewer's perspective, to the left side of a face. This attentional bias has been found in adults (e.g., [Butler et al., 2005](#)) and becomes more pronounced across middle childhood (e.g., [Balas & Moulson, 2011](#)). During the first year of life, typically developing infants also begin to show a bias towards the left side when viewing faces, with a tendency to fixate first (e.g., [Guo et al., 2009](#)) and longer (e.g., [Liu et al., 2011](#); [Wheeler, 2010](#)) on the left side of the face. The left-side bias may be associated with specialization of the right hemisphere in face processing, as information from the left visual field is projected to the right hemisphere of the brain ([Maurer et al., 2002](#)). The right hemisphere bias for processing faces has been reliably seen in adults based on lesion studies, neuroimaging, and electroencephalography (EEG) methods, but infant findings related to this bias appear mostly in attentional patterns rather than studies using neural measures (for a review, see [Rossion & Lochy, 2022](#)).

1.2. Atypical configural face processing in autism

Autism spectrum disorder (ASD) is a neurodevelopmental condition characterized by difficulties with social communication and the presence of restricted and repetitive behaviors. It has been well-documented that autistic individuals show differences in face processing and face scanning as compared to their non-autistic peers (e.g., [Falck-Ytter, 2008](#); [Griffin et al., 2025](#); [Ma et al., 2021](#); [Pelphrey et al., 2002](#); for a review, see [Griffin et al., 2021](#)).

A recent synthesis of existing research on the face inversion effect in ASD found that autistic individuals' face processing is less affected by inversion, particularly in tasks involving emotion recognition ([Griffin et al., 2023](#)). Some studies suggest that this reduced inversion effect is due to a preference for featural over configural processing ([van der Geest et al., 2002](#)). In line with this theory, [Falck-Ytter \(2008\)](#) examined the inversion effect in a study with autistic preschoolers by analyzing gaze duration and pupil dilation in response to both upright and inverted faces. Their results showed that autistic children were more likely than non-autistic children to fixate on the same facial features across both upright and inverted presentations, indicating a local processing bias. For pupil dilation, autistic children showed larger pupil responses to inverted faces than to upright faces; however, no difference in pupil size between upright and inverted conditions was seen for their non-autistic peers. Notably, this pupil size differentiation was a more pronounced around one second into the stimulus presentation, a time point that has been discussed in relation to peak dilation latency during cognitive tasks (see [Beatty & Wagoner, 1978](#); [Bloom & Mudd, 1991](#)).

An atypical inversion effect in autistic individuals may reflect differences in the development of configural face processing mechanisms that enable the integration of facial features into a coherent whole. This could have cascading effects on social cognition, as holistic face processing supports rapid interpretation of identity, as well as the ability to efficiently decode subtle nonverbal cues from faces, such as emotional expressions and gaze direction, which are essential for navigating social interaction. Over development, reduced reliance on configural information may interfere with the tuning of attentional and perceptual systems to socially relevant information, potentially contributing to the well-documented difficulties autistic individuals experience with face recognition, emotion recognition, mentalizing, and other aspects of social cognition including the holistic interpretation of complex social signals (e.g., [Behrmann et al., 2006](#); [Corbett et al., 2014](#)). These broader difficulties may lead to downstream challenges in face-to-face interaction (see [Gehdu et al., 2024](#)). In this context, differences in the inversion effect may go beyond a perceptual processing difference, but could indicate, as some suggest, a foundational divergence in the early development of the social brain (e.g., [Hadjikhani et al., 2007](#)).

Studies examining inversion effects in unaffected family members of autistic individuals indicate that differences in face processing may not be limited to individuals with a clinical diagnosis but rather could be related to features of a broader autism phenotype (e.g., Sysoeva et al., 2018). Another well-studied approach to understanding how these differences might relate to having an autistic family member is prospective studies with infants who have an older sibling diagnosed with autism (often referred to as elevated likelihood or EL infants). Longitudinal studies with EL infants indicate that approximately 20 % later receive an autism diagnosis, while an additional subset exhibits subclinical levels of autistic traits or broader social-communicative differences (Jones et al., 2014; Ozonoff et al., 2011, 2023). Past research has found that EL and typical likelihood (TL) infants show early differences in social attention and interaction (for reviews, see Cleary et al., 2023; Jones et al., 2014; e.g., Dawson et al., 2005; Tye et al., 2022), suggesting that disruptions in face processing may be detectable in these infants well before a subset might receive a formal autism diagnosis.

Two studies by Di Giorgio and colleagues (2016, 2021) suggested atypical inversion sensitivity may be detectable in EL infants from birth. Di Giorgio et al. (2016) found that when upright and inverted face-like patterns were presented side-by-side, TL newborns preferred upright while EL newborns preferred inverted. These findings were interpreted as evidence that the early subcortical mechanisms that orient infants toward social stimuli may be disrupted from birth in EL, potentially setting an atypical trajectory for the development of face perception from the very first days of life (Di Giorgio et al., 2016).

Follow-up work by Di Giorgio et al. (2021) used the same preferential looking procedure to examine these face inversion effects in 4-month-old EL and TL infants, and surprisingly, at this later stage, EL and TL infants did not show significant differences in looking time to upright vs. inverted face-like patterns. This raises the possibility that learning mechanisms may compensate for early disruptions in EL infants, or alternatively, that the stimuli or methods used in the 4-month-old study were not sensitive enough to detect subtle differences in face processing. It was found that EL infants exhibited greater variability in their responses, suggesting that perhaps some of these infants may continue to display early disruptions while others may show more typical development, reflecting the heterogeneous nature of the EL group (Di Giorgio et al., 2021). It is important to note that neither study by Di Giorgio and colleagues (2016, 2021) followed the EL infants to the age of an ASD diagnosis, so it also cannot be determined how the subset of ASD outcome infants might have influenced the results from both studies.

Side biases to faces have also been examined in autistic individuals and their first degree relatives, with several studies pointing to atypicalities in both neural and attentional measures of lateralization (e.g., Dundas et al., 2012a, 2012b; Jung et al., 2016; Keehn et al., 2015). For example, in autistic adults and adolescents, Dundas et al. (2012a) found no evidence of the typical left-side bias when processing faces during a gender identification task, a bias that was present in their non-autistic peers. Dundas et al. (2012b) extended this work to 11-month-old infants as well and found that TL infants, but not EL infants, showed a bias in attention towards the left side of faces. As in Di Giorgio et al. (2016, 2021), no information about ASD outcomes was included, making it difficult to rule out the influence of EL infants with a later diagnosis on the group differences. Together, altered inversion effects and reduced left-gaze biases may indicate disruptions in the early development of specialized face processing networks. These disruptions could arise from a variety of factors, such as altered attentional biases, reduced social motivation, or atypical neural lateralization. Identifying early perceptual markers such as atypical inversion sensitivity or gaze lateralization may inform early detection efforts and guide interventions targeting social attention.

1.3. The current study

In the present study we aimed to examine the development of inversion effects and left-side biases in attention over the first year of life, focusing on how ASD likelihood relates to the presence or absence of these patterns. Using eye-tracking technology, we examined the processing of upright and inverted faces in a sample of 7-, 10-, and 13-month-old infants with and without an older sibling diagnosed with ASD, who contributed one or more timepoints.

While research has demonstrated that autistic children and adults often show a reduced inversion effect (e.g., Griffin et al., 2023), fewer studies have examined whether this pattern is already evident in infancy, and to our knowledge, no studies have examined this in this age group (see Di Grigio et al., 2016, 2021 for earlier ages). Given that early differences in inversion sensitivity could reflect broader alterations in configural face processing, understanding how EL infants process upright and inverted faces across the first year of life may provide insight into emerging atypicalities in social attention and perception. Therefore, the first aim of this study was to analyze overall looking time to upright and inverted faces to assess the development of face inversion effects in these TL and EL groups. Based on past work, we hypothesized that TL infants would show looking time differences to upright compared to inverted faces by at least 13 months (Rose et al., 2008; Turati et al., 2004), while EL infants would be less affected by inversion, consistent with findings in autistic children and adults, and display no significant difference in looking time between upright and inverted faces (see Griffin et al., 2023).

The second aim was to investigate the development of the left gaze bias by comparing looking times to the left and right halves of upright and inverted faces. TL infants show a left gaze bias for faces by 11 months, reflecting early specialization in face processing (Dundas et al., 2012b). This bias might be expected to become more pronounced with age, particularly when viewing upright faces, as configural processing mechanisms strengthen. However, it remains unclear whether this developmental trajectory is altered in EL infants. Prior research suggests that this bias may be absent or reduced in EL infants at 11 months (Dundas et al., 2012b), and the current work will ask how this might change from 7 to 13 months. Based on findings by Dundas et al. (2012b), we hypothesized that EL infants would show no side bias for either upright or inverted faces at any age while TL infants would develop a left gaze bias by 13 months.

Furthermore, with research suggesting that EL infants may show subtle early differences in gaze allocation that diminish over time potentially due to compensatory processes (Nyström et al., 2017; Viktorsson et al., 2024), we analyzed attentional responses both

within the full trial window and during the initial 0–500 and 500–1000 ms windows (i.e., Nyström et al., 2017) to capture early orienting. We expected that the strongest patterns of group differences in this bias would occur in the initial presentation window, reflecting alterations in early attention allocation in EL infants.

The third aim was to explore pupillary responses to upright and inverted faces. Based on previous findings in autistic children by Falck-Ytter (2008), we expected a larger pupil response to inverted faces in the EL group compared to the TL group. Alternatively, we might expect to see larger pupils in response to faces in the EL group regardless of orientation (e.g., Wagner et al., 2016), which might reflect an overall increased processing load/arousal, or we might expect more constricted pupils when viewing face stimuli as has been seen in autistic toddlers and children (12–72 months; Anderson et al., 2006), possibly reflecting less interest in social stimuli or a more locally-driven processing style.

Although past studies have examined inversion effects, left side biases, and pupillary responses to faces at individual time points with EL and TL infants, no work has examined these face processing patterns together and longitudinally across this age range in infancy, and this can help explore changes in processing of faces over time as they differ by group. Taken together, this work has the potential to support the identification of developmental trajectories of early visual attention and face processing that can then be used to identify individuals who might show early difficulties in these domains that relate to elevated likelihood for autism and autism-related characteristics.

2. Method

2.1. Study design

The Infant Sibling Project, a longitudinal collaborative project between Boston Children's Hospital and Boston University, invited families to participate in a set of primary visits at 6-, 9-, 12-, 18-, 24-, and 36 months, with data collected using a variety of measures, including EEG, eye-tracking, and behavioral assessments. TL families were recruited primarily from the lab's participant registry, a database of families who signed up to be contacted about upcoming studies when their children were the appropriate age (with initial sign-ups taking place, for example, at local newborn nurseries and family events). EL families were recruited using a variety of methods, including from local autism clinics and autism family community events. Following their primary study visits at the first time points (6, 9, and 12 months), families were invited to participate in a set of supplemental study visits that included additional eye-tracking and neural measures within a month of their primary infant visit, and the current study is focused on an eye-tracking task from these additional study sessions.

Based on a targeted power of 85 % and an estimated effect size of 0.86 for differences in left gaze bias in TL and EL infants (e.g., Dundas et al., 2012b) at a significance level of 0.05, a sample size of approximately 20 EL and 20 TL infants was expected to be sufficient to detect meaningful differences. EL infants were those with an older sibling with idiopathic autism spectrum disorder (no known genetic cause). TL infants had one or more typically developing older siblings and no known family history of autism, defined as no first-degree relatives with ASD. Diagnosis of ASD for the EL proband and confirmation that the TL proband was not diagnosed with ASD were established using parent-reported, age-specific screening tools prior to enrollment. For probands greater than 48 months of age, the Social Communication Questionnaire (Rutter et al., 2003) was applied, while for those under 48 months, the Pervasive Developmental Disorders Screening Test-II (Siegel, 2004) was used.

2.2. Participants

The final sample included infants at elevated likelihood for autism (EL, $n = 31$; 17 male) and typical likelihood infants (TL, $n = 43$; 22 male). Study sessions for this supplemental lab visit took place when infants were, on average, 7, 10, and 13 months (see Table 1). To be included in the current sample, infants had to contribute adequate eye-tracking data at one or more time points (see Data

Table 1
Demographic Characteristics.

	TL	EL
Infant age (M_{days} , SD)		
7 months	218.27 (16.89)	215.90 (17.81)
10 months	298.17 (15.67)	297.57 (17.10)
13 months	388.53 (14.09)	395.45 (15.16)
Infant sex (% , n)		
Male	51.2 (22)	54.8 (14)
Female	48.8 (21)	45.2 (17)
Infant race (% , n)		
White	86 (37)	83.9 (26)
Black or African American	7 (3)	3.2 (1)
Asian	0 (0)	3.2 (1)
Mixed race	7 (3)	9.7 (3)
Infant ethnicity (% , n)		
Non-Hispanic	95.3 (41)	87.1 (27)
Hispanic	4.7 (2)	12.9 (4)

Processing). Insufficient eye-tracking data led to the exclusion of a small number of data points for TL infants (7 months: $n = 2$; 10 months: $n = 2$; 13 months: $n = 3$), while no EL infants were excluded at any time point for this reason.

Additionally, EL infants were required to be followed to 24 months or older to determine ASD outcome; two EL infants were therefore excluded for not returning for a lab visit at 24 months or older. Final clinical assessments for EL infants included the review of lab visit videos and Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000) scores by a licensed clinical psychologist, and following this review, 12 of 31 EL infants received a clinical judgment of ASD (EL+). One additional TL infant was excluded for receiving a positive clinical judgment of ASD.

Table 2 shows the number of TL and EL infants who contributed data at 1, 2, or 3 time points. Among the included infants, 50 contributed data at 7 months (TL: $n = 30$; EL-: $n = 12$; EL+: $n = 8$), 55 contributed data at 10 months (TL: $n = 25$; EL-: $n = 13$; EL+: $n = 7$), and 58 infants contributed data at 13 months (TL: $n = 38$; EL-: $n = 12$; EL+: $n = 8$). As described above, only a small number of infants were excluded for insufficient eye-tracking data. Missing data also resulted from some participants not starting this supplemental study at the earliest time point and/or not returning for later supplemental visits (TL: $n = 13$ at 7 months, $n = 8$ at 10 months, $n = 3$ at 13 months; EL-: $n = 6$ at 7 months, $n = 6$ at 10 months, $n = 7$ at 13 months; EL+: $n = 4$ at 7 months, $n = 4$ at 10 months, $n = 4$ at 13 months).

Table 1 provides demographic information for TL and EL infants, including age, sex, race, and ethnicity. The current protocol was approved by the Institutional Review Boards of Boston Children's Hospital and Boston University and informed consent was obtained from the parent(s) of each infant participant. This protocol adhered to the principles of the Declaration of Helsinki.

2.3. Stimuli and apparatus

Stimuli were 12 color images of faces (6 male, 6 female) with neutral expressions from publicly available databases, including the Productive Aging Lab Face Database (Minear & Park, 2004) and the Face Recognition Technology (FERET) database of facial images (Phillips et al., 1998, 2000). Infants viewed faces on a Tobii T-120 eye-tracker using Tobii Studio software for presentation (Tobii Technology AB; www.tobii.com). The eye tracker collected gaze location and pupil diameter data for both eyes at 120 Hz.

2.4. Procedure

Infants were seated on a caregiver's lap in a dimly lit room 60 cm from the eye-tracking monitor. Following an initial 5-point calibration procedure, each face was presented upright and inverted for 3.5 sec each, totaling 24 trials. This duration and number of trials aligned with past work by Falck-Ytter (2008) and was selected to balance the need for reliable pupillometry and gaze attention measurements with infants' limited attention spans (see also Oakes & Ellis, 2013). A white screen appeared between stimuli and remained until the experimenter advanced to the next trial once tracking was confirmed. Two semi-randomized orders were used, one beginning with an upright image and the other with an inverted image, and stimuli progressed such that for every pair of stimuli shown, one was upright and one was inverted. Stimulus order was counterbalanced across participants.

2.5. Data processing

Areas of Interest (AOIs) were drawn around the face and the left and right halves of the face. Total looking time to each of these AOIs was calculated for each infant, separately for upright and inverted faces. Data were preprocessed using a custom-made Python script (Python Programming Language; www.python.org), which extracted and summed gaze duration and calculated average pupil diameter for each AOI.

With total presentation time for upright and inverted faces at 42 s (3.5 sec x 12 faces), data was examined for each orientation to confirm that infants were attending for at least 25 % of the presentation time for each orientation (≥ 10.5 s). If an infant had insufficient data for upright or inverted faces at any age, their data from that age was not included in subsequent analyses.

2.6. Statistical analysis

The primary statistical analyses for this study were conducted using linear mixed-effects modeling (LMM) to account for the longitudinal design and repeated measures within subjects across multiple time points. Intraclass correlation coefficients were

Table 2
Number of Participants Contributing One, Two, or Three Time Points.

Number of time points	TL	EL
Three time points	23	12
Two time points	14 (4, 2, 8)	7 (3, 1, 3)
One time point	6 (1, 0, 5)	12 (5, 3, 4)

Note. For participants with data at two time points, the numbers in parentheses represent those who contributed data at combinations of 7 and 10 months, 7 and 13 months, or 10 and 13 months, respectively. For participants with data at a single time point, the numbers in parentheses indicate those who contributed data exclusively at 7, 10, or 13 months, respectively.

calculated for each outcome measure and further demonstrated the need for LMM. LMM accommodates the inclusion of random effects, such as individual variation, and effectively handles missing data, which is common in longitudinal studies. The use of LMM also allows for the modeling of interactions between fixed effects, making it particularly useful for examining developmental trajectories across multiple age points. Participant was included in the models as a random-intercept effect.

Three main outcome measures were evaluated, 1) total looking duration to upright and inverted faces (to assess face inversion effects), 2) looking duration to the left and right sides of faces (to investigate left gaze bias in face processing), and 3) pupil diameter (to assess processing load). Models included fixed effects of group (EL, TL), orientation (upright, inverted), age (7, 10, 13 months), region (left, right) and the interactions among these variables to assess developmental differences in face processing. Preliminary analyses revealed no main effect of sex for attention to faces (males: $M = 25.67$ s, $SE = .89$; females: $M = 27.40$ s, $SE = .94$; $F(1, 72) = 1.78$, $p = .19$), nor for pupil response to faces (males: $M = 3.31$ mm, $SE = .07$; females: $M = 3.27$ mm, $SE = .07$; $F(1, 72) = .134$, $p = .72$), and therefore sex was not included in subsequent statistical models.

For measures of looking duration, outcome measures were calculated across three time windows: 1) the full trial duration (3.5 s per stimulus), 2) the initial 500 ms of the trial (0–500 ms window), and 3) the second 500 ms of the trial (500–1000 ms window). By including the full trial period and these two periods of early attention (see Nystrom et al., 2017), the statistical analysis was designed to capture both overall attentional engagement and rapid, early face processing mechanisms, as past work has shown this early window is important for understanding subtle differences in processing by EL infants that can be masked when looking across the full trial (e.g., Nystrom et al., 2017).

Analyses are presented with and without the subset of EL infants with a later diagnosis of ASD (EL+). Due to the small number of EL+ infants at each time point (i.e., $n = 7-8$), outcome was not included as a factor in the analyses, as it was determined to be unlikely to yield stable estimates (see Barr et al., 2013; Matuschek et al., 2017).

3. Results

3.1. Attention to faces

3.1.1. Full Trial

3.1.1.1. Overall attention. LMM for looking duration to the face was conducted and the saturated model is reported, which included group (TL, EL), orientation (upright, inverted), age (7, 10, 13 months), and all two-way and three-way interactions as fixed factors.

There was a significant main effect of age, $F(2, 281.47) = 5.93$, $p = .003$, but no other main effects or interactions ($ps > .12$), with pairwise comparisons showing a significant decrease in looking to the full face from 7 to 13 months ($M_{diff} = 3003$ ms, $SE = 892$, $t(301) = 3.37$, $p = .003$). The removal of EL+ infants did not change the results, with the main effect of age remaining significant ($p < .001$) and no other significant main effects or interactions ($ps > .14$).

3.1.1.2. Attention to left vs. right. LMM for looking duration to the left and right sides of the face was conducted and the saturated model included group (TL, EL), orientation (upright, inverted), age (7, 10, 13 months), and region (left, right), and all two-, three-, and four-way interactions as fixed factors. No significant main effects were found ($ps > .25$).

There was a significant interaction between group and region, $F(1, 572.73) = 4.72$, $p = .030$ (see Fig. 1A). Follow-up pairwise comparisons showed that the TL group looked more at the left side of the face as compared to the EL group ($M_{diff} = 1949.19$ ms, $SE =$

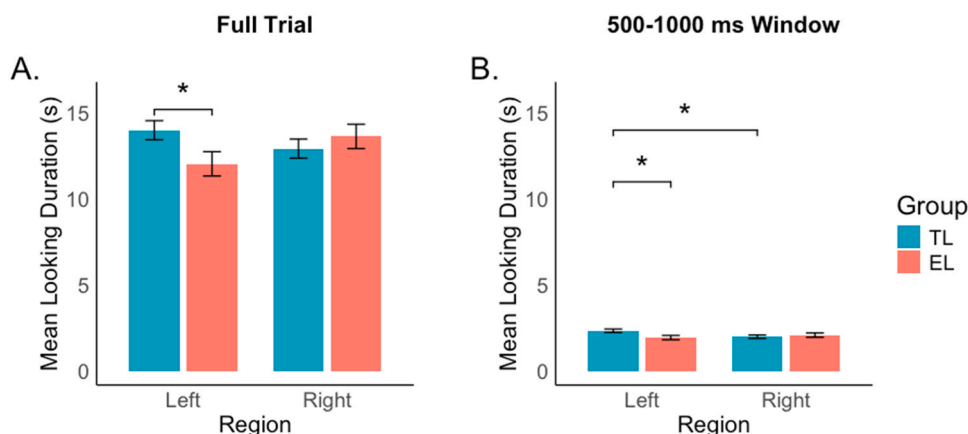


Fig. 1. Estimated marginal means for total looking duration (in seconds) to the left and right sides of the face for the TL (blue) and EL (red) groups showing group $\times$ region interactions for (A) the full trial ($p = .030$) and (B) the 500–1000 ms window of stimulus presentation ($p = .031$). Significant between-group differences were found for looking to the left side of the face for both time windows, and a significant within-group difference was found in TL for looking to the left vs. right. Error bars represent one standard error above and below the mean. * $p < .05$.

917, $t(228) = 2.13$, $p = .035$), with no group difference in attention to the right side of the face ($p = .44$). Within group pairwise comparisons showed no differences in looking duration between left and right sides of the face for either group ($ps > .106$). No other significant interactions were found ($ps > .33$).

When removing EL+ infants, the interaction between group and region became non-significant ($p = .093$), and a main effect of group became significant, $F(1, 442) = 4.20$, $p = .041$, with the TL group showing more looking to the face than the EL group ($M_{diff} = 1580$ ms, $SE = 771$).

3.1.2. Initial attention to faces (0–500 ms, 500–1000 ms)

3.1.2.1. Overall attention, 0–500 ms and 500–1000 ms. To examine initial attention to faces, we conducted LMMs for looking duration to the full face during the first 0–500 ms and then for 500–1000 ms. The saturated models included group (TL, EL), orientation (upright, inverted), and age (7, 10, 13 months). There were no significant effects or interactions for any of the factors in either of the LMMs ($ps > .05$). Removing EL+ infants did not change these results for either time window ($ps > .09$).

3.1.2.2. Attention to left vs. right, 0–500 ms. LMM for looking duration to the left and the right sides of the face during the first 500 ms was conducted, and the saturated model included group (TL, EL), region (left, right), orientation (upright, inverted), and age (7, 10, 13 months). There was a main effect of group, $F(1, 63.39) = 4.99$, $p = .029$, showing that the TL group looked more during the first 500 ms than the EL group ($M_{diff} = 252$ ms, $SE = 115$ ms). See Fig. 2A.

A significant age by region interaction was also found, $F(1, 556.08) = 3.23$, $p = .040$. Follow-up pairwise comparisons showed greater looking to the left at 10 months compared to 7 months ($M_{diff} = 329$ ms, $SE = 150$ ms, $t(642) = -2.20$, $p = .028$), and at 10 months, more looking to the left side of the face than the right ($M_{diff} = 328$ ms, $SE = 150$ ms, $t(588) = 2.85$, $p = .005$). See Fig. 2B.

When removing EL+ infants, the main effect of group remained significant, showing more overall looking by the TL group than the EL group, $F(1, 43.93) = 4.89$, $p = .032$. However, the interaction between age and region was no longer significant with these infants removed ($p = .086$).

3.1.2.3. Attention to Left vs. Right, 500–1000 ms. LMM for looking duration to the left and the right sides of the face during the 500–1000 ms time window was conducted and the saturated model included group (TL, EL), region (left, right), orientation (upright, inverted), and age (7, 10, 13 months). There were no significant main effects found ($ps > .17$).

As in the full trial, there was a significant interaction between group and region, $F(1, 612) = 4.66$, $p = .031$ (see Fig. 1B). Follow up pairwise comparisons showed that, consistent with full trial findings, the TL group looked more at the left side than the EL group ($M_{diff} = 398$ ms, $SE = 164$, $t(251) = 2.43$, $p = .016$), and the two groups did not differ in their looking to the right side of the face ($p = .579$). Additionally, the TL group looked more to the left than the right side of the face ($M_{diff} = 347$ ms, $SE = 142$, $t(593) = 2.45$, $p = .015$), whereas the EL group showed no difference in looking time to the left vs. right ($p = .438$). After removing EL+ infants, the interaction between group and region was no longer significant ($p = .092$).

3.2. Pupil response to faces

LMM for average pupil size for the full trial period, with the full face as the area of interest, was conducted and the saturated model included group (TL, EL), orientation (upright, inverted), age (7, 10, 13 months), and all two-way, and three-way interactions as fixed factors.

A main effect of age was found, $F(2, 251.5) = 31.95$, $p < .001$. Pairwise comparisons showed that pupil size significantly increased

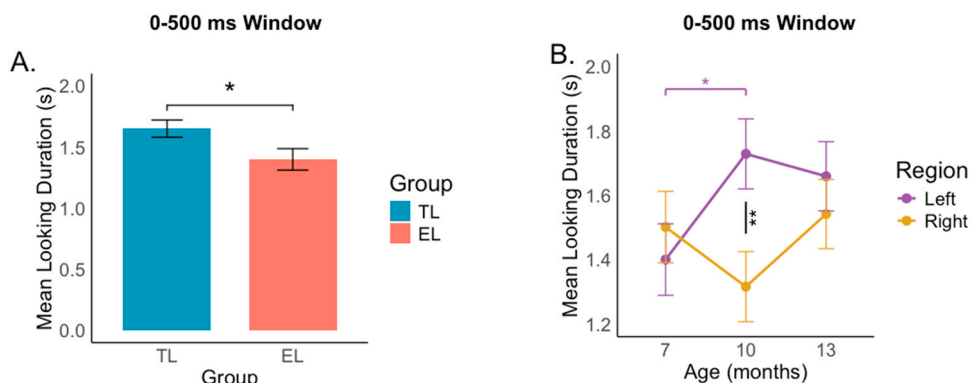


Fig. 2. Estimated marginal means for total looking duration (in seconds) to the face during the 0–500 ms window. (A) A significant main effect of group was found, with TL (blue) looking longer than EL (red) infants ($p = .029$). (B) A significant interaction between region and group was found ($p = .040$), with greater looking to the left side (purple) vs. right side (orange) of the face at 10 months, and a significant increase in time looking to the left side from 7 to 10 months. Error bars represent one standard error above and below the mean. * $p < .05$ ** $p < .01$.

across age, with an increase from 7 to 10 months ($M_{diff} = .11$ mm, $SE = .03$, $t(262) = 3.93$, $p < .001$), followed by another increase between 10 and 13 months ($M_{diff} = .11$ mm, $SE = .03$, $t(263) = 4.17$, $p < .001$). Overall, there was an increase of .23 mm (M_{diff}) from 7 to 13 months ($SE = .03$, $t(265) = 7.82$, $p < .001$).

The interaction between age and group was significant, $F(2, 251.5) = 3.99$, $p = .020$, showing that this age effect was more pronounced for the EL group, with EL infants having a more significant increase in pupil size across age (see Fig. 3). For both groups, pairwise comparisons showed significant increases in pupil size from 7 to 10 months, 10–13 months, and also when comparing 7 and 13 months (see Table 3 for t -test results). No differences were found when directly comparing TL and EL at any age ($ps > .36$).

When removing EL+ infants, the main effect of age remained significant ($p < .001$), but there was no longer a significant interaction between age and group ($p = .439$).

4. Discussion

In the current study, we explored early looking patterns and attentional biases in infants at typical and elevated likelihood of receiving a later ASD diagnosis (TL and EL) as they viewed upright and inverted faces. EL and TL infants showed clear differences in visual attention when viewing faces. Specifically, while no inversion effects were found for either group, EL infants demonstrated reduced leftward gaze compared to TL infants, suggesting early differences in configural face processing and attentional lateralization. These differences emerged not only across the full viewing duration but were also evident within the first second of stimulus presentation, highlighting both rapid and sustained alterations in face processing mechanisms. Additionally, across the entire trial duration, pupil size increased more with age in the EL group compared to the TL group, suggesting that EL infants may engage in different levels of cognitive effort or autonomic arousal when processing faces, independent of initial gaze allocation patterns. This aligns with previous work showing increased pupil dilation during face perception in EL infants (Wagner et al., 2016) and may be associated with heightened arousal or cognitive demands (Falck-Ytter, 2008). Together, these findings indicate that while early gaze patterns are useful in capturing momentary shifts in attention, pupil responses provide a broader index of sustained processing differences across the full viewing period.

4.1. Face inversion effects

Contrary to our expectations, we did not observe a significant face orientation effect in either group. We had hypothesized, based on prior research with infants (e.g., Oakes & Ellis, 2013), that the TL group would demonstrate differentiation in looking behavior between upright and inverted faces by 13 months, whereas EL infants would show no significant difference between upright and inverted faces, indicating a reduced sensitivity to orientation as has been found in autistic individuals (e.g., see Griffin et al., 2023). One explanation for our findings is that infants' scanning behaviors in response to inverted versus upright faces were not sufficiently differentiated. Eye-tracking studies have shown that younger infants tend to scan both upright and inverted faces similarly, with a stronger reliance on local feature-based processing rather than holistic or configural processing (Gallay et al., 2006; Oakes & Ellis, 2013). If infants in our study were still at a stage where they relied on featural cues over holistic cues, this could explain the absence of a strong orientation effect. Further, prior studies that are focused on the first year of life have indicated that the emergence of orientation effects is gradual, shifting from familiarity-based preferences for upright faces in younger infants to novelty-based preferences for inverted faces in older infants (e.g., Kato & Konishi, 2013). This transition may explain why orientation effects were not observed consistently in our sample, as infants between 7 and 13 months may be undergoing a developmental shift in how they process

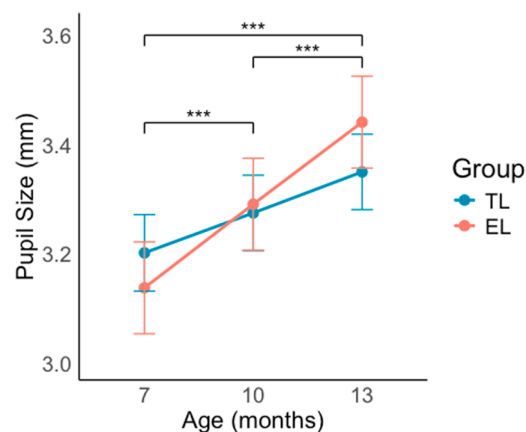


Fig. 3. Estimated marginal mean for pupil size (in millimeters) for the full trial in response to face stimuli in TL (blue) and EL (red) infants at 7, 10, and 13 months of age. A significant main effect of age ($p < .001$) and a group $\times$ age interaction ($p = .020$) were found. Pupil size increased significantly from 7 to 10 months, 10–13 months, and 7–13 months. Error bars represent one standard error above and below the mean. *** $p < .001$.

Table 3

Pupil dilation: Pairwise comparisons across age for TL and EL infants.

Group	Age Comparison	M_{diff} (SE)	t (df)	p
TL	7 vs. 10 months	.068 (.033)	2.05 (257.5)	.041
	10 vs. 13 months	.078 (.032)	2.44 (258.3)	.015
	7 vs. 13 months	.145 (.033)	4.35 (259.4)	< .001
EL	7 vs. 10 months	.154 (.046)	3.37 (266.4)	< .001
	10 vs. 13 months	.150 (.045)	3.37 (264.4)	< .001
	7 vs. 13 months	.304 (.047)	6.50 (268.4)	< .001

Note: Based on estimated marginal means from linear mixed-effects modeling. Mean difference between ages was computed as pupil size at the older age minus pupil size at the younger age.

inverted faces.

Some eye-tracking studies with infants have used extended trial durations, such as Gallay et al. (2006), which presented faces for 10 s with infants at 4-months of age, and Kato and Konishi (2013), which used 30-second trials with infants from 6 to 12.5 months of age. While side biases may be better detected by examining initial attention, differences in gaze allocation between upright and inverted faces may be more pronounced in longer trials. Our study used shorter 3.5-second trials based on Falck-Ytter (2008), which may have encouraged a broader scanning strategy that de-emphasized orientation-based differences in infants.

4.2. Left gaze bias and early attention allocation

A secondary aim of the current study was to investigate the development of the left gaze bias by comparing looking times to the left and right halves of both upright and inverted faces. We hypothesized that TL infants would develop a left gaze bias by 13 months (Dundas et al., 2012b). We also predicted that EL infants would show no such side bias in gaze (i.e., Dundas et al., 2012b), regardless of face orientation, in line with prior research showing differences in the lateralization patterns of neural responses to faces among some EL infants compared to TL infants (Keehn et al., 2015).

In our sample, TL infants looked more to the left than EL infants, both overall (full trial) and in the early 500–1000 ms window. While past work found greater left-side gaze for upright compared to inverted faces (Liu et al., 2011), we did not observe this effect. When examining the initial left gaze bias during the 500–1000 ms window of face processing, the TL group showed a significant bias toward the left side (greater looking to the left vs. right halves of the face), while the EL group did not, consistent with full trial findings from Dundas et al. (2012b) with 11-month-old EL infants. However, this left-side bias was not observed within the TL group when looking at the full trial. Similarly, findings by Nyström et al. (2017) demonstrated reduced looking in EL infants during the first 300–1000 ms following direct gaze initiation, though not over longer intervals, and other findings with toddlers who later develop autism also reveal subtle group differences in gaze timing during dynamic interactions that are not evident when observing attentional patterns within the entire video (Viktorsson et al., 2024).

Overall, our results support the notion that the development of lateralized face processing mechanisms may be disrupted or different in EL infants. The development of this hemispheric lateralization has been found to become specialized for faces over time. Guo et al. (2009) found that 6-month-old infants exhibit a general left gaze bias across both objects and faces. Work by Keehn et al. (2015) examined lateralization of EEG coherence during face viewing separately for EL infants with and without an ASD diagnosis and found that by 12 months, TL infants show a strong right-lateralized response, EL+ show a strong left-lateralized response, and EL- show an intermediate response that is left-lateralized, but significantly different from both other groups. This study points to subtle differences that can be found when taking into account EL infants with a later ASD diagnosis.

Situated among the past literature, our findings support the idea that early gaze biases observed in TL infants in our study may be driven by underlying neural asymmetries rather than simple perceptual adaptation to the onset of the stimulus. The reduced left side bias in EL infants could indicate disruptions in this developmental trajectory, affecting how attention is allocated to social and/or configural stimuli in ASD.

4.3. Pupil dilation differences in EL infants

In addition to gaze allocation differences, we found pupil size increased more with age in the EL group compared to the TL group. Notably, however, we did not observe an effect of face orientation on pupil size in either group—contrasting with prior work by Falck-Ytter (2008), who reported larger pupil responses to inverted compared to upright faces in autistic preschoolers, interpreted as evidence of heightened cognitive effort. This discrepancy may be due to developmental differences in when such inversion effects on the pupil response emerge or may reflect differences in task design. Pupil dilation is often used as a marker of cognitive effort (Granholm et al., 1997; Kaldy & Blaser, 2020; Mathôt, 2018), but it can also reflect a range of processes, including arousal, novelty detection, and affective salience (Jackson & Sirois, 2009; Mathôt, 2018). Our observation of a steeper age-related increase in pupil size in EL infants aligns with prior work showing elevated pupil responses to faces in EL infants, regardless of outcome (Wagner et al., 2016) and may suggest early alterations in arousal or attentional engagement during face processing. Other studies in autistic children have also found atypical pupil responses to faces, but sometimes in different directions (Anderson et al., 2006; Martineau et al., 2011; Nuske et al., 2014). One possibility is that these differences reflect early alterations in the functioning of the locus coeruleus–norepinephrine (LC-NE) system, which plays a key role in modulating arousal and attention (Keehn et al., 2013a, 2013b; Bast et al., 2018) and/or that

these response patterns may reflect a less automatic and more cognitively effortful face processing in autism (Nuske et al., 2014), potentially involving a more featural or piecemeal approach (Anderson et al., 2006). Future work should investigate how these dynamics unfold across development and how they relate to later social and cognitive outcomes.

4.4. Strengths and limitations

The current study contributes to a growing body of work investigating early visual attention and autonomic markers in infants at elevated likelihood (EL) for autism. One notable strength is the use of both gaze-tracking and pupillometry, allowing us to capture rapid shifts in attention as well as sustained physiological engagement with faces. Additionally, we analyzed both full trial durations and early time windows, enabling us to detect subtle attentional differences that may be obscured in aggregate data.

A question that is important to consider from the current study relates to the composition of our participant groups. Namely, while previous studies have identified the ASD diagnosis rate among infants with an older sibling with ASD as approximately 20 % (Ozonoff et al., 2011, 2024), our sample showed a higher rate of 39 % for infants in the elevated likelihood group. Our composition is consistent with other work from this same longitudinal cohort with prior studies using attentional disengagement tasks (e.g., Wagner et al., 2023), and as recently discussed by Ozonoff et al. (2023), this increased representation of positive outcomes may be partly due to a higher retention rate for participants diagnosed with autism compared to typically developing participants.

Despite the elevated representation of EL+ infants, the size of this group remained small at each time point, which limited our ability to include outcome as a fixed factor in the models. As such, interpretations are constrained to effects associated with elevated likelihood, not ASD diagnosis. Findings from analyses excluding EL+ infants are presented as preliminary and should be interpreted with caution.

Second, the relatively short trial duration (3.5 s) may have limited our ability to detect inversion effects that have emerged in studies using longer stimuli presentations (e.g., Kato & Konishi, 2013). While this shorter duration was appropriate for maintaining infant engagement across a multi-task battery (as in Falck-Ytter, 2008), it may have constrained the emergence of orientation-based differences in visual scanning.

Finally, our use of multiple face identities was intended to sustain infant attention through increased stimulus variability (see Oakes & Ellis, 2013), but this design choice differs from prior studies that used repeated presentation of the same face with altered features (e.g., Dundas et al., 2012b). Such methodological differences may influence the detection of configural processing effects like the left gaze bias and should be considered when comparing findings across studies.

4.5. Future directions

Future research should build on these findings by examining whether early attentional lateralization (e.g., left gaze bias) and age-related changes in pupil responses can reliably predict ASD outcomes. In particular, studies with larger samples of EL+ infants are needed to evaluate the diagnostic specificity and predictive validity of these early markers. Multi-site collaborations or data pooling efforts may help address this need, provided that methodological consistency across datasets can be maintained.

Additional work is also needed to clarify the functional significance of pupil dilation differences in EL infants. Some prior studies have observed atypical pupil responses in EL infants regardless of later ASD outcome (e.g., Wagner et al., 2016), suggesting that these differences may relate to broader features of the autism phenotype. Future studies should aim to disentangle whether age-related increases in pupil size reflect differences in cognitive effort, autonomic arousal, or both, and whether these responses are specific to face stimuli or generalize to other domains (e.g., Arora et al., 2021).

Moreover, the temporal dynamics of attention should remain a key focus. Our findings and those of others (e.g., Nyström et al., 2017; Viktorsson et al., 2024) suggest that early attentional differences may be most detectable in narrow time windows. Future work should continue to investigate subtle alterations in visual attention mechanisms that might be masked when data are aggregated across longer time periods, particularly during the first second of face viewing.

Greater attention should also be paid to how different aspects of stimulus design, such as trial duration, number of unique identities, and stimulus complexity, affect the emergence of configural and lateralized processing. Trials of varying lengths may help disentangle rapid orienting effects from sustained processing, and repeated use of a single face identity could enhance sensitivity to subtle differences in gaze patterns. Trials of varying lengths and controlled stimulus repetition (as in Dundas et al., 2012b or Falck-Ytter, 2008) may help isolate the contributions of early perceptual mechanisms versus higher-order face processing strategies. Future research with a sufficiently powered EL+ group should continue to explore the potential of initial left gaze bias as a predictor of ASD outcomes, particularly focusing on whether this bias is specific to face processing or indicative of broader atypicalities in hemispheric asymmetry in ASD (see English et al., 2023).

These metrics, left gaze bias and pupil size change, may also be useful as markers of early intervention effectiveness. Recent work demonstrates that pupil-based measures of arousal and stimulus responsivity are associated with intervention-related gains in social attention in autistic preschoolers, suggesting that pupillometry can provide a mechanistic index of intervention-related change (Bast et al., 2025). If future studies establish that early-emerging left gaze biases similarly reflect functional underlying attentional or hemispheric processing differences, they too may be useful as dynamic indicators of intervention response.

4.6. Conclusion

The current study offers insight into early visual processing and attentional patterns in infants at typical and elevated likelihood for

ASD. Although face inversion effects were not observed, EL infants demonstrated (1) reduced left gaze bias, indicating early differences in attentional lateralization during face viewing and (2) a greater age-related increase in pupil size, suggesting developmental differences in cognitive effort or autonomic engagement compared to TL infants. These patterns contribute to our understanding of how early visual attention and physiological responses may diverge in infants at elevated likelihood for autism.

While our analyses were limited by sample size constraints, especially within the EL+ group, the current results point to several promising avenues for future investigation. In particular, left gaze bias and pupil dilation may offer complementary markers of early neurodevelopmental differences, and their combined use may strengthen efforts to identify early predictors of neurodivergence. Continued research using fine-grained temporal analyses, larger longitudinal samples, and similar methodologies across cohorts will be critical in advancing our understanding of how these early attentional and physiological markers relate to later social and cognitive development.

CRedit authorship contribution statement

Helen Tager-Flusberg: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing. **Anthony Westendorf:** Formal analysis, Writing – original draft. **Jennifer Wagner:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Writing – review & editing. **Chloe Brittenham:** Data curation, Formal analysis, Validation, Visualization, Writing – original draft. **Charles A. Nelson:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

None.

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Data availability

Data will be made available on request.

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