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Social motivation predicts gaze following between 6 and 14 months

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Abstract

Infants vary in their ability to follow others' gazes, but it is unclear how these individual differences emerge. We tested whether social motivation levels in early infancy predict later gaze following skills. We longitudinally tracked infants' (N = 82) gazes and pupil dilation while they observed videos of a woman looking into the camera simulating eye contact (i.e., mutual gaze) and then gazing toward one of two objects, at 2, 4, 6, 8, and 14 months of age. To improve measurement validity, we used confirmatory factor analysis to combine multiple observed measures to index the underlying constructs of social motivation and gaze following. Infants' social motivation—indexed by their speed of social orienting, duration of mutual gaze, and degree of pupil dilation during mutual gaze—was developmentally stable and positively predicted the development of gaze following—indexed by their proportion of time looking to the target object, first object look difference scores, and first face-to-object saccade difference scores—from 6 to 14 months of age. These findings suggest that infants' social motivation likely plays a role in the development of gaze following and highlight the use of a multi-measure

Guangyu Zeng and Tiffany S. Leung have contributed equally.

approach to improve measurement sensitivity and validity in infancy research.

1 | INTRODUCTION

Joint visual attention—mutually focusing on objects or events in the environment with other people—allows infants to share experiences with individuals from whom they can learn about the world, thereby facilitating infants' cognitive and social development (Brooks & Meltzoff, 2005, 2008; Gredebäck et al., 2010; Morales et al., 2000; Mundy & Gomes, 1998). *Gaze following*—the ability to follow a social partner's line of sight—is an essential step in forming joint attention. Gaze following develops rapidly in the first year after birth (D'Entremont et al., 1997; Del Bianco et al., 2019; Farroni et al., 2004; Gredebäck et al., 2010). However, there are large individual differences in the development of gaze following during this period (Astor et al., 2020; Schietecatte et al., 2012). These individual differences in infants' gaze following ability appear to be positively associated with later social skills, such as language acquisition and communication between 1 and 3 years of age (Morales et al., 1998; Mundy et al., 2007), emotion regulation abilities at 2 years of age (Morales et al., 2005), and theory of mind skills at 4.5 years of age (Brooks & Meltzoff, 2015). These findings suggest gaze following may be a foundational social skill. While some infants are better at attending to and interpreting gaze cues than others (Jones & Klin, 2013; Thorup et al., 2016), the mechanism driving such individual differences is unclear. Here, we explored the influence of social motivation on gaze following using a multi-measure approach to improve measurement.

1.1 | Learning mechanism and social motivation in gaze following development

According to the social reinforcement learning hypothesis, the development of social cognitive skills, such as gaze following, are theorized to be driven by a learning mechanism that is active during social interaction (Carlson & Triesch, 2004; Deák et al., 2013; Dunst et al., 2010; Ishikawa et al., 2020; Jones et al., 2011; Silverstein et al., 2019; Triesch et al., 2006; Zhang et al., 2020). More specifically, following others' gaze leads to positive outcomes associated with joint engagement to an object including sharing in the discovery of interesting objects or events, as well as continued attention and feedback from the adult partner (e.g., eye contact, smiles, infant-directed speech; Carlson & Triesch, 2004; Deák et al., 2014; Moore, 2008; Peña et al., 2014; Triesch et al., 2006). These outcomes are theorized to serve as rewards that facilitate the further acquisition of gaze following skills.

This learning mechanism may help interpret seemingly inconsistent findings in gaze following emergence and development, given that it holds no assumption about how gaze following manifests initially (Deák, 2015; Ishikawa et al., 2020). For example, using more naturalistic stimuli, 6-month-olds follow others' gaze when it is preceded by a communicative signal (e.g., direct gaze, infant-directed vocalizations; Gredebäck et al., 2010; Senju & Csibra, 2008). However, others report infants do not gaze follow without lower-level perceptual cues, such as motion (e.g., head turns, hand movements), until about 1 year of age (Astor et al., 2021; Deák et al., 2014; Moore et al., 1997). The social reinforcement learning hypothesis suggests that infants' early apparent gaze cueing attention may be initially driven primarily by low-level perceptual cues (head motion), but infants gradually learn to follow the social cues (i.e., eye gaze) as the rewards of doing so are repeatedly associated with the gaze cues rather than the perceptual cues. Despite being partially perceptually-driven, early gaze cuing (e.g., about 2 and 4 months of age, Astor et al., 2021; Gredebäck et al., 2010) may be a rudimentary form of gaze following; therefore, to understand the early emergence of gaze following, it is critical to investigate its early development.

Moreover, given the social rewards of gaze following, the learning process of gaze following may be associated with infants' social motivation—including individual differences in seeking, orienting to, and maintaining social interactions (Astor et al., 2020; Chevallier et al., 2012). Such an association may be realized in two (non-mutually-exclusive) ways: First, infants with higher social motivation may perceive the positive social outcomes linked to gaze following (e.g., smiles, contingent interactions) as more rewarding, which reinforces their future tendency to follow others' gazes (Deák et al., 2014; Ishikawa et al., 2020); second, infants with higher social motivation may be more motivated to attend to, and interact with, others, which may facilitate more social interactions and thereby give them more opportunities to acquire gaze following skills (Peña et al., 2014; Simpson et al., 2016).

Yet it is unclear whether early social motivation predicts gaze following emergence in infancy. While a computational simulation study's findings similarly suggest a social motivation component involved in the development of gaze following (Ishikawa et al., 2020), there are few empirical tests in human infants. To complement these approaches, there is a need for direct and valid measures of social motivation and longitudinal gaze following studies in human infants—particularly across the first year—to determine whether social motivation predicts gaze following development.

1.2 | Measures of social motivation in infancy

Infants' social motivation can be indexed by behavioral and physiological measures of individual differences in attention to social stimuli (Williams et al., 2019). Social orienting (i.e., the degree to which social stimuli capture and hold attention) and social reward processing (i.e., the extent to which social stimuli are intrinsically rewarding) may be captured with eye tracking in infancy, enabling a high degree of experimental control and measurement precision (Zeng et al., in press).

1.2.1 | Social orienting

Social orienting can be measured by infants' saccadic latency—a measure of speed of attention orienting (attention capture)—and total look duration (attention holding) to faces (Adler & Gallego, 2014; Bronson, 1991; Gluckman & Johnson, 2013; Sasson et al., 2008; Telford et al., 2016). These gaze measures of social information during simulated social interaction tasks—which reveal infants' preference for social stimuli over other non-social objects presented simultaneously—are commonly used as indicators of social motivation (Chevallier et al., 2015; Vernetti et al., 2018). Infants who show faster and longer attention to social stimuli (e.g., faces with direct gaze) are believed to have better social orienting skills (Adler & Gallego, 2014; Gluckman & Johnson, 2013; Jones & Klin, 2013; Williams et al., 2019). Moreover, eye tracking studies report that infants who are later diagnosed with autism spectrum disorder—a developmental disorder often characterized by disrupted social motivation (American Psychiatric Association, 2013)—showed diminished attention to dynamic faces simulating a mutual gaze experience (i.e., with direct eye gaze) from 2 to 6 months of age (Jones & Klin, 2013). Together, these findings suggest that eye tracking measures of social attention can capture the social orienting component of social motivation during early infancy (Chevallier et al., 2012, 2015).

1.2.2 | Social reward processing

The social reward processing component of social motivation can be indexed by physiological measures of autonomic arousal levels (e.g., pupil dilation) in response to social stimuli (Cheng et al., 2021; DiCriscio & Troiani, 2021; Tummeltshammer et al., 2019). Pupil dilation reflects neural activity involved in reward processing (Laeng et al., 2012). Therefore, pupil dilation to social stimuli may indicate the processing of social rewards (Sepeta et al., 2012; Trezza et al., 2010). For example, 1- to 5-year-old children's pupil dilation when seeing an adult who needs help positively predicted their likelihood and latency to provide help (Hepach et al., 2019). Pupil dilation in response to social stimuli may also index social motivation in younger infants. Seven-month-olds who have greater pupil dilation to videos of their mother, compared to those with less pupil dilation, are better at learning when reinforced with socially rewarding videos (Tummeltshammer et al., 2019). Together, these findings suggest that pupil dilation to social stimuli may be a useful indicator of the social reward processing component of social motivation from infancy onward.

1.3 | Current study

While the developmental importance of gaze following is established, less is known about the developmental precursors of gaze following, and the role of social motivation in this developmental process. To this end, we tested the social reinforcement learning hypothesis by exploring the role of social motivation in facilitating the development of gaze following between 2 and 14 months of age. We used remote eye tracking to track infants' gaze behaviors while observing videos of an actress directing her gaze at the camera toward the infant, simulating mutual gaze. We measured infants' social motivation during this simulated mutual gaze period, by examining how quickly and how long infants looked at the woman's face (i.e., social orienting) and their pupil dilation (i.e., social reward processing). Likewise, we used three measures to assess infants' gaze following ability (Astor et al., 2020; Ishikawa & Itakura, 2019; Senju & Csibra, 2008): how long infants looked at the target (i.e., object the social partner is looking at) compared to the control (i.e., object the social partner is not looking at), how frequently infants first looked at the target compared to the control object, and how frequently infants shifted their gaze from a social partner's face to the target compared to the control object. We used structural equation modeling (SEM) to extract the common variance from different observed measures and formed two latent factors, one indexing social motivation and the other indexing gaze following ability. Compared to using single measures, using a latent factor reduces measurement error and improves construct validity and sensitivity (DiStefano & Hess, 2005). We then tested whether the latent factor of social motivation developmentally predicted the latent factor of infants' gaze following with SEM. We predicted that infants with higher levels of social motivation at younger ages, compared to those with lower levels, would show better gaze following abilities later in development.

2 | METHODS

2.1 | Participants

Families were recruited from the Miami-Dade Area, through community events and online advertisements. Infants ($N = 82$; 37 females) participated at 2, 4, 6, 8, and 14 months of age (see Table 1 for Demographics at each age). Our sample was racially and ethnically diverse: 60% Hispanic/Latino,

TABLE 1 Sample sizes, mean and SDs of age, and infants' sex in each age group.

		Age (weeks)		Sex	
Age group (months)	*N*	Mean	*SD*	Female *N*	Male *N*
2	45	8.57	1.07	18	27
4	49	17.65	0.82	21	28
6	59	26.27	1.35	26	33
8	49	34.99	0.96	20	29
14	40	59.94	1.65	20	20

Note: Number of infants contributing data to each measure of gaze following at each age (*N*).

Abbreviation: *SD*, standard deviation.

63% White, 21% Black, and 9% multi-racial. See Table S1 for detailed demographics. Infants were full-term (born at ≥37 weeks of gestation) and healthy. All infants contributed usable data to at least one measure, but some infants had missed visits due to sickness, scheduling conflicts, or families moving. Table 1 reports the sample sizes and demographics at each age for all completed visits. The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from the infants' caregivers before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board for Human Subject Research at the University of Miami.

2.2 | Materials

Infants were randomly assigned to view six gaze following videos out of a larger set of 24 videos (Senju & Csibra, 2008; Figure 1a). Before each trial, a rotating colorful ball with music attracted infants' gaze to the center of the screen. Once infants' gaze was centered on the ball, the stimulus video played (for examples, see Videos S1 and S2). In the stimulus videos, a woman looked down for ~2 s (Baseline Phase), then looked into the camera (directing her gaze toward the infant), raised her eyebrows, and remained still with a neutral expression for ~2 s, simulating mutual gaze (Eye Contact Phase), then shifted her gaze to one of two objects (6-s Gazing Phase). There were 6 pairs of unique objects (e.g., yellow duck, red cup) with each repeated in 4 videos, counterbalancing object locations and gaze directions. Each video was 1280 × 720 pixels (51 × 28 cm) and appeared on a 1280 × 720 pixels (51 × 28 cm) screen (see Supporting Information S1 and Table S3 for further details about stimuli).

We recorded infants' eye gaze and pupil diameters via corneal reflection using a Tobii TX300 eye tracker (sampling rate: 300 Hz) while the videos played on a remote 58.4 cm monitor with integrated eye tracking technology. The test room had a constant illumination of 202 lux, achieved by standard overhead lights. We extracted data from three rectangular areas of interest (AOIs; Figure 1b): two identical object AOIs (i.e., target object: the object that the model looked at; control object: the object that the model did not look at; 272 × 331 pixels, visual angle of 10.21° × 12.11°), and the face AOI (i.e., the model's face; 340 × 443 pixels, visual angle of 12.88° × 16.34°). The AOIs were identical across trials. The spatial layouts of each video are provided in Table S3. Fixations at each AOI were defined by the I-VT fixation filter in Tobii Studio software, which defined fixations by a velocity threshold of 30°/s, discarded fixations <100 ms, and merged adjacent fixations with a maximum time gap of 75 ms and a maximum angle of 0.5° (Tobii Technology).

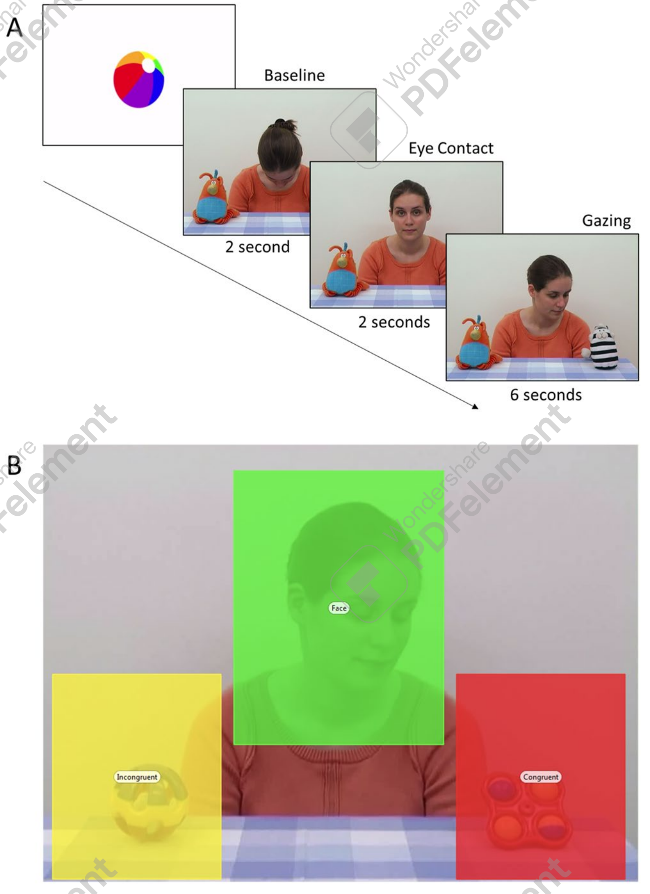

FIGURE 1 (a) Each video displayed a White, female adult with brown hair pulled back, sitting behind a desk with two objects at each side (Senju & Csibra, 2008). Each video trial started with an attention getter (colorful, dynamic ball in the screen's center), followed by three phases: Baseline (2 s), Eye Contact (2 s), and Gazing phase (6 s). (b) Screenshot from one trial in the eye tracking video stimulus, with areas of interest drawn around the model's face, the incongruent (control) object, and the congruent (target) object.

2.3 | Procedure

When the infants were awake and calm, they sat on a caregiver's lap, 60 cm from the monitor. The caregiver was instructed not to speak or point to the screen during testing and wore opaque glasses. Infants were calibrated with a 9-point procedure. Individual calibration points were repeated until acceptable, following recommended guidelines (Zeng et al., in press). At each visit (2, 4, 6, 8, and 14 months) infants watched 6 gaze following video trials. This task took 5–10 min. At the end of the first visit, caregivers completed a demographic survey. Parents were compensated $50 per visit.

2.4 | Planned data analyses

We conducted all analyses in RStudio (version 1.3.1073; R version 4.0.2). Mixed effects models were analyzed with the *lme4* and *lmerTest* package (Bates et al., 2015; Kuznetsova et al., 2017), using restricted maximum likelihood estimation for preliminary analyses to determine the emerging age of gaze following. We conducted structural equation modeling (SEM) analyses using the *lavaan* package (Rosseel et al., 2020). To minimize the influence of missing data (47.9%), we estimated parameters in the path models using full information maximum likelihood. We evaluated SEM model fit based on five fit indices (criteria for good model fit are included in parentheses; Hooper et al., 2008): the χ^2 statistic (good fit: $p > .05$), CFI (comparative fit index; good fit: ≥0.95), TLI (tucker-lewis index; good fit ≥0.95), RMSEA (root mean square error of approximation; good fit ≤0.06), and SRMR (standardized root mean squared residual; good fit ≤0.08).

2.4.1 | Latent gaze following factor

Measures

During the Gazing Phase (i.e., actress looking to the object), we calculated three indices of gaze following performance for each infant at each age (Astor et al., 2020; Hernik & Broesch, 2019; Ishikawa & Itakura, 2019; Senju & Csibra, 2008): (1) total looking time at the target object AOI divided by the total looking time at the target and control object AOIs, averaging across all usable trials (Object Look Proportion; a usable trial: at least one 100-ms fixation on either object during the Gazing Phase); (2) Number of trials in which the first look was to the target object AOI minus the number of trials in which the first look was to the control object AOI (First Object Look Score; a usable trial: at least one look on either object during the Gazing Phase); and (3) Number of trials in which the first face-to-object saccade was from the face to the target object AOI minus the number of trials in which first face-to-object saccade was from the face to the control object AOI (First Object Saccade Score; a usable trial: at least one face-to-object saccade during the Gazing Phase). A saccade (Video S2) required the starting location of the eye movement to be on the face while a look (Video S1) did not specify the starting location.

Measurement model

We examined whether the observed measures—Object Look Proportion, First Object Look Score, First Object Saccade Score—were reliable indicators of the latent construct of gaze following performance (Latent Gaze Following Factor) with confirmatory factor analysis (CFA). Our initial measurement model included the Latent Gaze Following Factor at each age (2, 4, 6, 8, and 14 months). The metric of each latent factor was determined by standardizing them. We also examined whether the model fit would significantly change if we constrained the factor loadings of the same observed measures on the latent factor at different ages to be equal (to show invariance of these measures on the latent factor). Within the final measurement model of Gaze Following, we used the standardized covariances between the Latent Gaze Following Factor at each age to examine its developmental stability.

2.4.2 | Latent social motivation factor

Measures

We measured each infant's level of social motivation *prior* to gaze following during the Eye Contact Phase with three measures: (1) total looking time at the face AOI during the Eye Contact Phase, averaged across usable trials (Eye Contact Duration; a usable trial: at least one 100-ms fixation on the screen during Eye Contact Phase); (2) latency from the start of the Eye Contact Phase (i.e., the start of the moment when the actress first started to lift her head) to the time the infant first fixated at the face

AOI during the Eye Contact Phase (Eye Contact Speed), computed by averaging across usable trials (a usable trial: at least one 100-ms fixation on the face during Eye Contact Phase) and multiplying by −1 (reverse coding) so that greater values (less negative values) indicated faster looking to the face and greater motivation, consistent with our other social motivation measures (see Supplementary Methods in Supporting Information S1 for details); (3) pupil dilation during the Eye Contact Phase prior to the model's head turn, averaged across usable trials (Pupil Dilation During Eye Contact; a usable trial: at least one 100-ms fixation on the face during Eye Contact Phase).

Given that the task was a free-viewing task with a fixed, brief time range of 2-s simulated eye contact period, infants could look wherever they wanted, either at the screen or off the screen. To capture infants' relative interest in the social stimulus compared to all of the nonsocial distractors (including those both on-screen, i.e., objects, or off-screen, e.g., table, wall), we used total looking time to the face to capture infants' differing levels of social orienting (Telford et al., 2016). However, there are other ways to operationally define social orienting. To complement this approach and to match the operationalization of social orienting in other studies (Chevallier et al., 2015; Elias & White, 2020), we also used proportion of looking time to the face out of the total looking time to the screen in our post hoc analysis (see Post Hoc Exploratory Analyses and Supplementary Results in Supporting Information S1).

We extracted the pupil diameters from Tobii Studio, which controlled for the distance from the eyes to the screen (Tobii, 2016). The pupil diameters were preprocessed to exclude speed and trend-line deviation outliers, interpolate missing data, and remove noise and artifacts with low-pass frequency filtering (Kret & Sjak-Shie, 2018). We calculated baseline pupil diameters by averaging each infant's pupil diameters when they fixated on the screen in the Baseline Phase (i.e., when the model looked down). We then measured average pupil diameters when the infants fixated on the Face AOI in the Eye Contact Phase. Pupil Dilations were corrected for baseline pupil diameters by subtracting the baselines from the average pupil diameters for each infant at every age across all trials (Gredebäck & Melinder, 2011; Hepach & Westermann, 2016).

Measurement model

Given that the measures of social motivation may reflect multiple, complex, simultaneous psychophysiological processes which may introduce confounds (Aslin, 2007; Wang, 2011), we used CFA to extract common variance from multiple measures, which can mitigate such confounds and provide convergent validity (DiStefano & Hess, 2005). We examined whether Eye Contact Duration, Eye Contact Speed, and Pupil Dilation During Eye Contact were indicators of the same latent factor, theorized as Social Motivation. Our initial measurement model included the Latent Social Motivation Factor at each age (2, 4, 6, 8, and 14 months). We also examined whether the model fit would change if we constrained the factor loadings of the same observed indicators on the latent factor at different ages to be equal (to show measurement invariance of these indicators on the latent factor). The metric of each latent factor was determined by standardizing them. Within the final measurement model of Social Motivation, we used the standardized covariances between the Latent Social Motivation Factor at each age to examine its developmental stability.

2.4.3 | Early infant social motivation predicts later gaze following

Longitudinal panel model

Building upon the two measurement models of Gaze Following and Social Motivation, we then examined whether the Latent Social Motivation Factor at earlier ages predicted the Latent Gaze Following Factor at later ages with a longitudinal panel model. At each age, we also included the concurrent effect of the Latent Social Motivation Factor on the Latent Gaze Following Factor. All paths from

Latent Social Motivation Factor to Latent Gaze Following Factor, including both the concurrent and predictive paths, were constrained to be equal, based on the assumption that the reward value associated with social motivation in the learning process of gaze following remained stable with age (Carlson & Triesch, 2004; Ishikawa et al., 2020).

To maximize data inclusion, we included all available data in our analyses and used full information maximum likelihood estimation in all of our measurement and longitudinal panel models in the presence of missing data (Jeličić et al., 2009).

2.5 | Post hoc exploratory analyses

In addition to the planned analyses, we examined the measurement model of Latent Social Motivation and the longitudinal panel model using modified measures of social orienting including the proportion of looking time to the face (out of total looking time to the screen; Eye Contact Proportion) and the Corrected Eye Contact Speed to control for the infants' baseline orienting speed (i.e., the latency to a nonsocial attention getter preceding each trial). We calculated the median score across trials for both the baseline orienting speed and the Eye Contact Speed for each infant at each age to reduce noise associated with potential differences in infants' first screen look locations when the video actress started lifting her head.using.

We also explored whether the infants looked back to their social partner after looking at the object to which they both attended (face-object-face gaze alternation), which is theorized to indicate infants' joint attention skills in live interactions (Hansen et al., 2018; Mundy et al., 2003, 2007). We examined how this gaze alternation developed from 2 to 14 months of age with a 2 (AOIs: target object vs. control object) × 5 (ages: 2, 4, 6, 8, and 14 months) mixed effects analysis of variance in a multilevel framework (Level-1: Age; Level-2: Infant). To explore its relationship with social motivation, we conducted correlations between this gaze alternation measure and Latent Social Motivation at each age (see Supplementary Analysis 2 in Supporting Information S1).

3 | RESULTS

3.1 | Latent gaze following factor

The age at which gaze following emerges varies widely depending on the operational definition of gaze following (planned analysis; see Supplementary Analysis 1 in Supporting Information S1); therefore, to provide a more complete assessment, we incorporated multiple measures of gaze following. Table 2 summarizes the number of infants contributing data and the number of usable trials. All three measures of gaze following were positively correlated with each other at each age (Table S4). The CFA result indicated that the measurement model of gaze following including 2, 4, 6, 8, and 14 months did not fit the data well. A final measurement model of gaze following (Figure 2) was fit to the data at 6, 8, and 14 months. Without constraints on factor loadings, the model exhibited good fit, $\chi^2(24) = 18.68$, $p = .769$, RMSEA < 0.001, CFI $= 1.00$, TLI $= 1.04$, SRMR $= 0.07$ (see Supplementary Materials in Supporting Information S1 for details of model building). All three observed indicators (i.e., Object Look Proportion, First Object Saccade Score, First Object Look Score) were positively and statistically significantly loaded on the Latent Gaze Following Factor at each age (see Table 3 for factor loadings). Hence, the latent factor reliably captured the common variance related to individual differences in gaze following underlying these three observed measures from 6 to 14 months of age.

We examined the developmental stability of gaze following using the standardized covariances between the Latent Gaze Following Factor at 6, 8, and 14 months in the final measurement model. The standardized covariances for the Latent Gaze Following Factor across age ranged from 0.10 to

TABLE 2 Sample sizes, the mean and range number of usable trials, means, and SDs for each gaze following measure at each age: Object Look Proportion, First Object Look Score, and First Object Saccade Score.

Age (months)	Object Look Proportion *N*	*M* (range) trials	*M* (*SD*)	First Object Look Score *N*	*M* (range) trials	*M* (*SD*)	First Object Saccade Score *N*	*M* (range) trials	*M* (*SD*)
2	28	2.11 (1–5)	0.55 (0.41)	28	2.11 (1–5)	0.32 (1.19)	8	2.00 (1–5)	0.50 (1.07)
4	43	2.56 (1–6)	0.54 (0.37)	43	2.56 (1–6)	0.28 (1.44)	33	1.94 (1–5)	0.55 (0.97)
6	56	3.34 (1–6)	0.60 (0.30)	56	3.34 (1–6)	0.55 (1.92)	49	2.63 (1–6)	0.63 (1.60)
8	46	4.48 (2–6)	0.56 (0.23)	46	4.48 (2–6)	0.57 (1.98)	46	3.54 (1–6)	0.59 (1.83)
14	40	5.28 (1–6)	0.65 (0.16)	40	5.28 (1–6)	1.73 (2.17)	40	4.50 (1–6)	2.25 (2.42)

Note: Given that there were 6 trials for each infant at each age, the First Object Look Score and the First Object Saccade Score ranged from −6 to 6. Targets refer to the correct objects (i.e., the objects the woman in the video was looking at).

Abbreviations: *M*, mean; *N*, the number of infants who contributed usable data to each measure at each age; *SD*, standard deviation; Trials, mean/range number of usable trials per infant for each age.

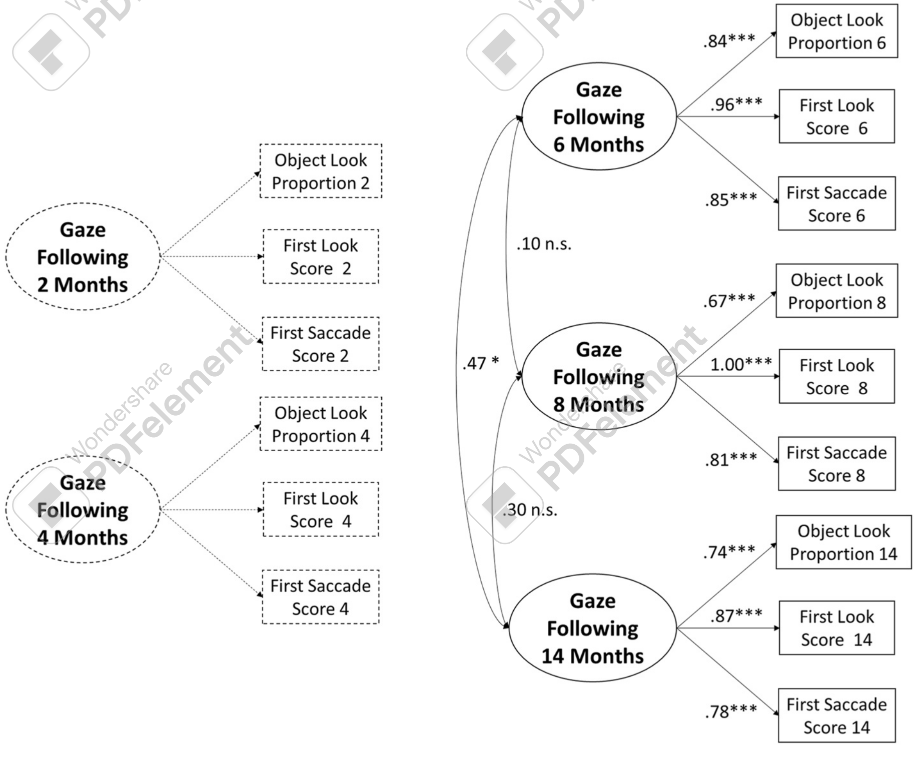

FIGURE 2 Path diagram for the measurement model of gaze following. Data at 2 and 4 months (dashed) were included in the initial model but excluded in the final model due to poor model fit. Standardized parameter estimates and significance of the final model (including 6, 8, and 14 months) were shown next to each solid path. Large ovals represent latent variables; rectangles represent indicators of each latent variable. n.s., not significant; *$p < .05$; ***$p < .001$.

0.47 and was statistically significant between 6 and 14 months ($r = .47$, $p = .015$), but not statistically significant between 8 and 14 months ($r = .30$, $p = .077$), nor between 6 and 8 months ($r = .10$, $p = .610$). These results suggest modest developmental stability of early gaze following between 6 and 14 months of age (Figure 3).

TABLE 3 Factor loadings of the measurement model of latent gaze following.

Age (months)	Factors	*b*	*SE*	*p*	95% CI (lower)	95% CI (upper)	*β*
6	*Gaze following by*						
	Object Look Proportion	0.25	0.03	<.001	0.19	0.32	.84
	First Object Look Score	1.84	0.21	<.001	1.44	2.24	.96
	First Object Saccade Score	1.37	0.20	<.001	0.99	1.75	.85
8	*Gaze following by*						
	Object Look Proportion	0.15	0.03	<.001	0.09	0.21	.67
	First Object Look Score	1.96	0.23	<.001	1.50	2.42	1.00
	First Object Saccade Score	1.47	0.23	<.001	1.01	1.93	.81
14	*Gaze following by*						
	Object Look Proportion	0.12	0.02	<.001	0.07	0.16	.74
	First Object Look Score	1.86	0.29	<.001	1.29	2.43	.87
	First Object Saccade Score	1.85	0.34	<.001	1.20	2.51	.78

Abbreviations: *b*, unstandardized coefficient; CI, confidence intervals; *SE*, standard errors; *β*, standardized coefficient.

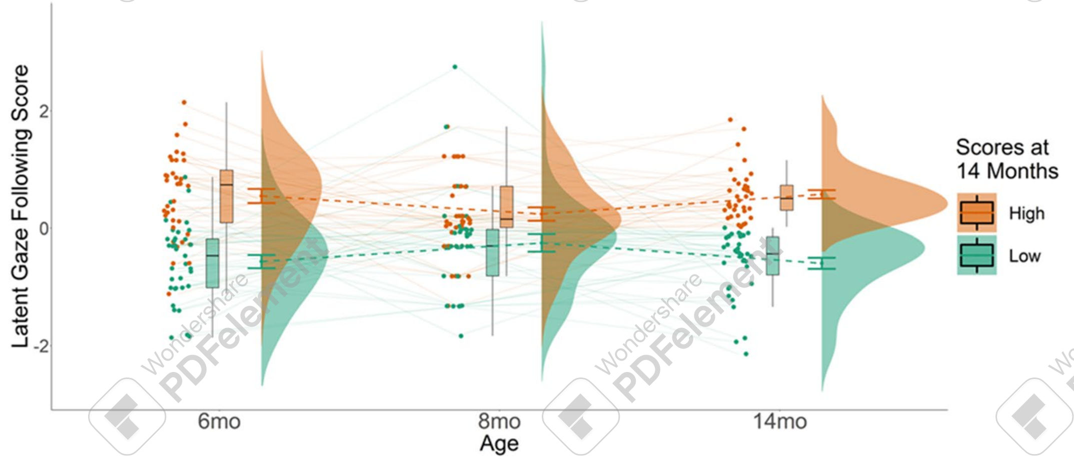

FIGURE 3 Raincloud plots show the change of Latent Gaze Following Scores from 6 to 14 months. Only for the purpose of data visualization, individual Latent Gaze Following Scores at each age were estimated from the measurement model of Gaze Following using the *lavPredict* function in the *lavaan* package (Rosseel et al., 2020). Infants are median-split into Low ($n = 35$; green) and High ($n = 36$; orange) groups based on their Latent Gaze Following Score at 14 months. Boxplots: Lines within the boxplots indicate the medians. Hinges of the boxplots show the first (bottom) and third (top) quartiles. The whiskers extend up to 1.5 × interquartile range (distance between top and bottom hinges), above and below the hinges. Dots to the left of the boxplots show the Latent Gaze Following Scores for individual infants. Density plots to the right of the boxplots show the distributions of the Latent Gaze Following Scores. Dots and error bars on the left edge of the density plots show the means and standard errors.

3.2 | Latent social motivation factor

Descriptive statistics for each social motivation measure and correlations among them are in Table 4 and Table S5, respectively. The result of CFA indicated that the measurement model of social motivation including 2, 4, 6, 8, and 14 months did not fit the data well. A final model was fit to the data

TABLE 4 Sample sizes, the mean and range number of usable trials, means, and SDs for each social motivation measure at each age: eye contact duration, eye contact speed, and pupil dilation in the eye contact phase.

	Eye contact duration (seconds)			Eye contact speed (seconds)[a]			Pupil dilation (mm)		
Age (months)	*N*	*M* (range) trials	*M* (*SD*)	*N*	*M* (range) trials	*M* (*SD*)	*N*	*M* (range) trials	*M* (*SD*)
2	42	4.29 (1–6)	0.71 (0.62)	34	3.50 (1–6)	−0.29 (0.28)	24	2.79 (1–6)	0.06 (0.13)
4	48	5.23 (1–6)	1.28 (0.59)	47	5.15 (1–6)	−0.46 (0.38)	38	4.11 (1–6)	0.11 (0.12)
6	59	5.68 (3–6)	1.27 (0.45)	59	5.41 (2–6)	−0.49 (0.28)	53	4.11 (1–6)	0.10 (0.17)
8	48	5.75 (2–6)	1.28 (0.42)	48	5.60 (2–6)	−0.41 (0.26)	44	4.18 (1–6)	0.08 (0.12)
14	40	5.63 (1–6)	1.15 (0.37)	40	5.33 (1–6)	−0.50 (0.28)	39	3.56 (1–6)	0.04 (0.11)

Abbreviations: *M*, mean; *N*, the number of infants who contributed usable data to each measure at each age; *SD*, standard deviation; trials, mean/range number of usable trials per infant for each age.

[a]Eye Contact Speed is the latency to the face AOI during eye contact phase multiplied by −1 (reverse coding the score) so that greater values (less negative values) indicate faster looking to the face, making it a positive indicator, consistent with the other two social motivation measures.

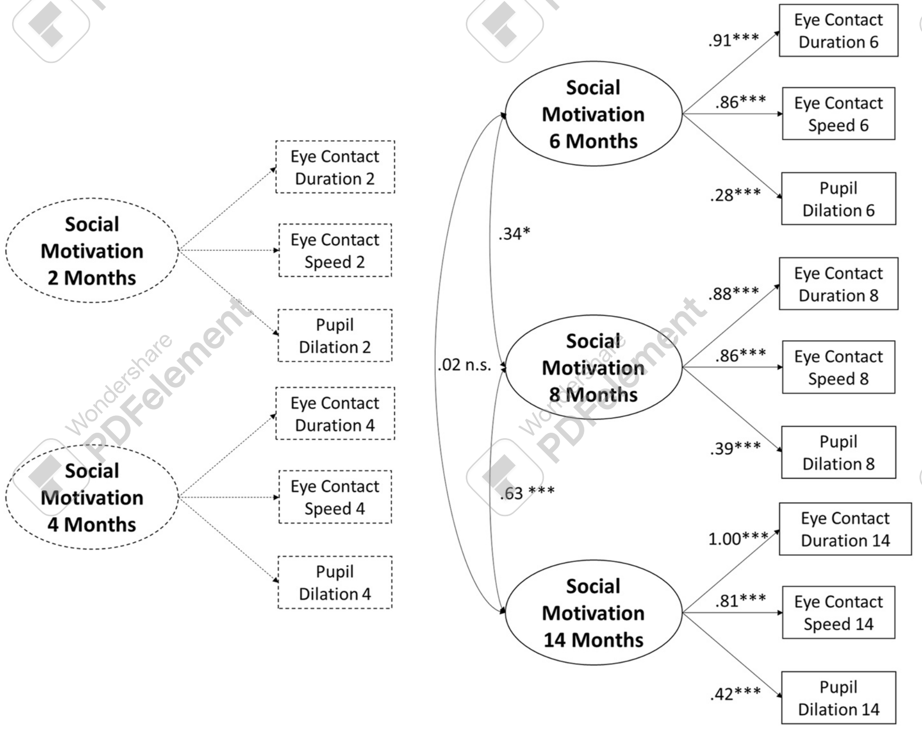

FIGURE 4 Path diagram for the measurement model of social motivation. Data at 2 and 4 months (dashed) were included in the initial model but excluded in the final model due to poor model fit. Standardized parameter estimates and significance of the final model (including 6, 8, and 14 months) were shown next to each solid path. Large ovals represent latent variables; rectangles represent indicators of each latent variable. n.s., not significant; $^{*}p < .05$; $^{***}p < .001$.

at 6, 8, and 14 months (Figure 4). With constrained invariant factor loadings across different ages, the model yielded good model fit, $\chi^2(29) = 35.56$, $p = .187$, RMSEA = 0.06, CFI = 0.96, TLI = 0.96, SRMR = 0.15. The final model also included correlations of residuals between Pupil Dilation at 6 and

TABLE 5 Factor loadings of the measurement model of latent social motivation.

Age (months)	Factors	*b*	*SE*	*p*	95% CI (lower)	95% CI (upper)	*β*
6	*Social motivation by*						
	Eye contact duration	0.38	0.03	<.001	0.32	0.44	.91
	Eye contact speed	0.23	0.02	<.001	0.19	0.27	.86
	Pupil dilation	0.05	0.01	<.001	0.02	0.07	.28
8	*Social motivation by*						
	Eye contact duration	0.38	0.03	<.001	0.32	0.44	.88
	Eye contact speed	0.23	0.02	<.001	0.19	0.27	.86
	Pupil dilation	0.05	0.01	<.001	0.02	0.07	.39
14	*Social motivation by*						
	Eye contact duration	0.38	0.03	<.001	0.32	0.44	1.00
	Eye contact speed	0.23	0.02	<.001	0.19	0.27	.81
	Pupil dilation	0.05	0.01	<.001	0.02	0.07	.42

Note: Higher values for Eye Contact Speed indicate faster speeds (shorter latencies) and lower values indicate slower speeds (longer latencies); therefore, higher values for all three measures indicate greater levels of social motivation.

Abbreviations: *b*, unstandardized coefficient; CI, confidence intervals; *SE*, standard errors; *β*, standardized coefficient.

8 months ($r = .45$, $p = .008$), and between Eye Contact Duration at 6 and 8 months ($r = .57$, $p = .070$). All three observed indicators, Eye Contact Duration, Eye Contact Speed, and Pupil Dilation during the eye contact phase, positively and significantly loaded on the Latent Social Motivation Factor at 6, 8, and 14 months of age (see Table 5 for factor loadings). Therefore, these three observed measures were valid indicators of the same underlying social motivation construct.

We examined the developmental stability of social motivation using the standardized covariances between the Latent Social Motivation Factor at 6, 8, and 14 months in the final measurement model. The standardized covariance of Latent Social Motivation Factor exhibited statistically significant correlations for the Latent Social Motivation Factor between 6 and 8 months ($r = .34$, $p = .028$) and between 8 and 14 months ($r = .63$, $p < .001$), but not between 6 and 14 months ($r = .02$, $p = .899$). These results suggest short-term developmental stability of social motivation between 6 and 14 months of age (Figure 5).

Interestingly, we also found that the face-object-face gaze alternation during the Gazing Phase was positively correlated with Latent Social Motivation, which provided further validation of our latent measure of social motivation (see Supplementary Analysis 2 in Supporting Information S1).

3.3 | Early infant social motivation predicts later gaze following

Building upon the measurement models of Social Motivation and Gaze Following, we examined whether Social Motivation at 6 and 8 months predicted later Gaze Following at 8 and 14 months in a longitudinal panel model (Figure 6). The final model, including correlations among residuals of observed indicators (Table 6; see Supplementary Materials in Supporting Information S1 for model fit of the initial model without modification), had a relatively good model fit for the data, $\chi^2(126) = 144.29$, $p = .127$, RMSEA = 0.05, 90% confidence interval (CI) = [0.00, 0.08], CFI = 0.96, TLI = 0.95, SRMR = 0.12.

As in the measurement models, factor loading of all observed indicators were statistically significant and positive on the latent factor. Standardized factor loadings and path estimates for the final

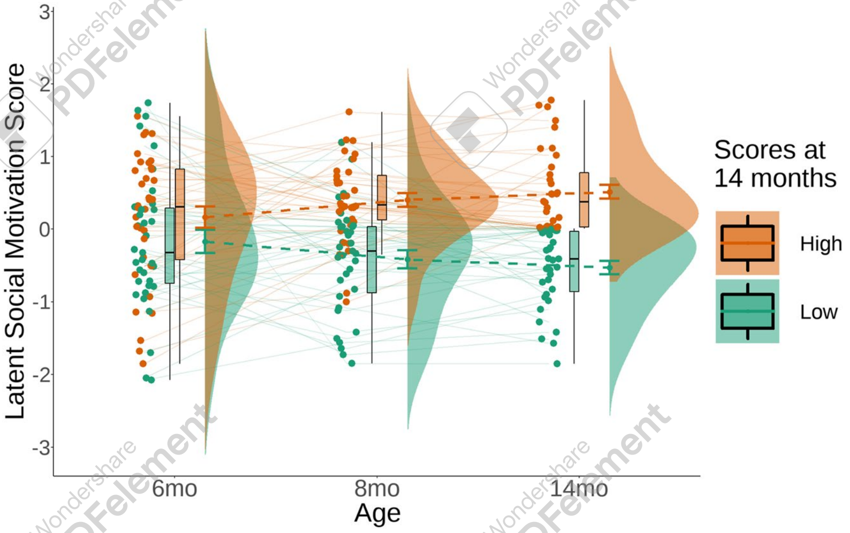

FIGURE 5 Raincloud plots show the change of Latent Social Motivation Scores from 6 to 14 months. Only for the purpose of data visualization, individual latent Social Motivation scores at each age were estimated from the measurement model of Social Motivation using the *lavPredict* function in the *lavaan* package (Rosseel et al., 2020). Infants are median-split into Low ($n = 35$; green) and High ($n = 36$; orange) groups based on their Latent Social Motivation Score at 14 months. Boxplots: Lines within the boxplots indicate the medians. Hinges of the boxplots show the first (bottom) and third (top) quartiles. The whiskers extend up to 1.5 × interquartile range (distance between top and bottom hinges), above and below the hinges. Dots to the left of the boxplots show the Latent Social Motivation Scores for individual infants. Density plots to the right of the boxplots show the distributions of the Latent Social Motivation Scores. Dots and error bars on the left edge of the density plots show the means and standard errors.

longitudinal panel model are displayed in Figure 6. Social Motivation predicted Gaze Following at the same age: at 6 months, $b = 0.20$, $SE = 0.06$, 95% CI = [0.08, 0.33], $\beta = .20$, 8 months, $b = 0.20$, $SE = 0.06$, 95% CI = [0.08, 0.33], $\beta = .20$, and 14 months, $b = 0.20$, $SE = 0.06$, 95% CI = [0.08, 0.33], $\beta = .18$. Further, Social Motivation at 6 months significantly and positively predicted Gaze Following at 8 months, $b = 0.20$, $SE = 0.06$, 95% CI = [0.08, 0.33], $\beta = .19$, and at 14 months, $b = 0.20$, $SE = 0.06$, 95% CI = [0.08, 0.33], $\beta = .15$. Similarly, Social Motivation at 8 months positively predicted Gaze Following at 14 months, $b = 0.20$, $SE = 0.06$, 95% CI = [0.08, 0.33], $\beta = .16$. Together, Latent Social Motivation positively predicted the concurrent level (i.e., at the same age) and the development of Latent Gaze Following between 6 and 14 months (Figure 7).

We also examined the measurement model for Latent Social Motivation and the longitudinal panel model using the modified measures of social orienting (i.e., Eye Contact Proportion and median Corrected Eye Contact Speed). The findings remained consistent, which suggest that, in this context, our total looking time measure might be similar to our proportion of looking time measure. This consistency also suggests that baseline orienting speed and starting fixation location on the screen were unlikely to have been confounds in our Latent Social Motivation measure (see Supplementary Results in Supporting Information S1).

4 | DISCUSSION

We found support for our hypothesis that infants with higher levels of social motivation had higher levels of subsequent gaze following. Infants displayed stable individual differences in gaze following

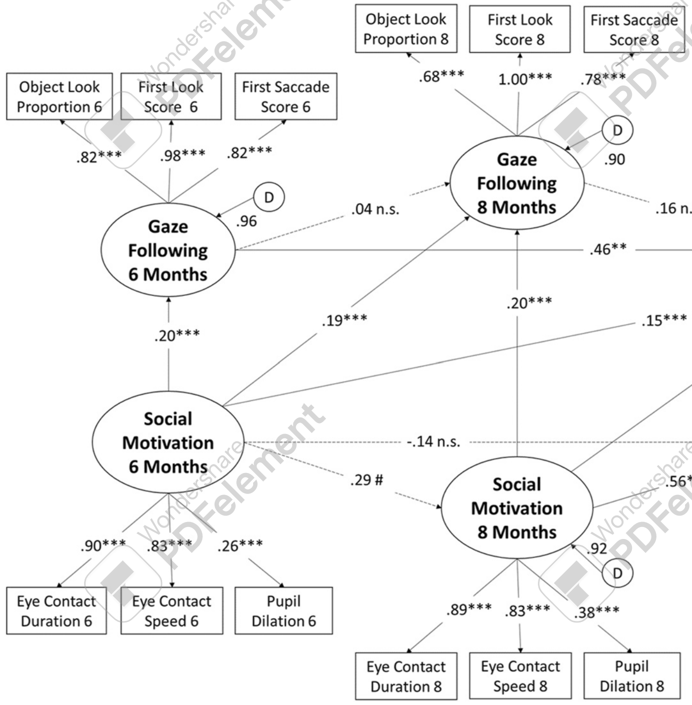

FIGURE 6 Standardized parameter estimates and significance of the final model. Large ovals represent latent variables; rectangles represent indicators of each latent variable; and small circles labeled D represent residual variance in the latent factors. R^2 for the latent variables were 0.04 for Gaze Following at 6 months, 0.10 for Gaze Following at 8 months, 0.44 for Gaze Following at 14 months, 0.08 for Social Motivation at 8 months, and 0.28 for Social Motivation at 14 months. Dash lines represent paths that were not significant. Correlations among residual variances of observed indicators that were added to the model were shown in Table 6. n.s., not significant; $^{\#}p = .072$; $^{**}p < .01$; $^{***}p < .001$.

TABLE 6 Correlations among residuals of observed indicators incorporated in the final longitudinal panel model.

Correlation	*r*	*p*
Pupil dilation 6 months–pupil dilation 8 months	.41	.016*
Eye contact duration 6 months–eye contact duration 8 months	.68	.014*
Eye contact duration 6 months–pupil dilation 14 months	−.30	.043*
First Object Look Score 6 months–First Object Saccade Score 8 months	.82	.016*
First Object Saccade Score 6 months–PUPIL dilation 6 months	−.45	<.001*
First Object Saccade Score 6 months–pupil dilation 8 months	−.35	.006*
First Object Saccade Score 6 months–pupil dilation 14 months	.71	<.001*
First Object Saccade Score 6 months–eye contact Speed 8 months	−.43	.001*
First Object Saccade Score 8 months–eye contact duration 8 months	.29	.103
Target Look Proportion 8 months–eye contact duration 8 months	.41	.024*

Note: These correlations were suggested by Modification Indices to improve model fit of the structural model of Latent Social Motivation predicting Latent Gaze Following (see Supplementary Materials in Supporting Information S1).

*ps < .05.

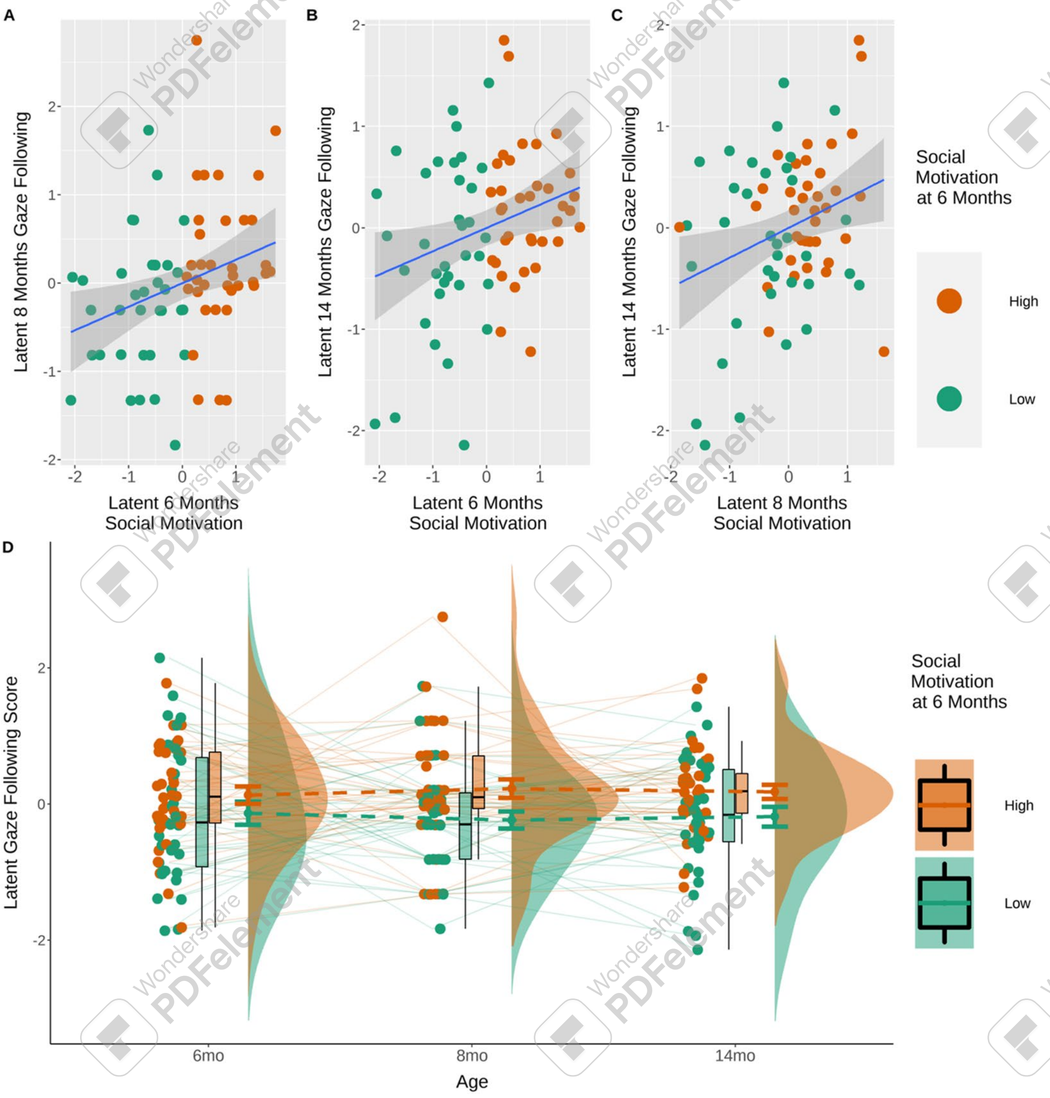

FIGURE 7 *Top*: The scatter plots illustrate the relationships between (a) Latent Social Motivation Scores at 6 months and Latent Gaze Following at 8 months ($\beta = .37$, $p = .006$), (b) Latent Social Motivation Scores at 6 months and Latent Gaze Following at 14 months ($\beta = .31$, $p = .006$), (c) Latent Social Motivation Scores at 8 months and Latent Gaze Following at 14 months ($\beta = .34$, $p = .006$). The blue lines represent the regression lines, and the shaded areas show the standard errors. *Bottom*: (d) Raincloud plots show the change of Latent Gaze Following Scores from 6 to 14 months as a function of infants' Latent Social Motivation Scores at 6 months. Infants were median-split into Low ($n = 35$; green) and High ($n = 36$; orange) groups based on their Latent Social Motivation Score at 6 months. Boxplots: Lines within the boxplots indicate the medians. Hinges of the boxplots show the first (bottom) and third (top) quartiles. The whiskers extend up to 1.5 × interquartile range (distance between top and bottom hinges), above and below the hinges. Dots to the left of the boxplots show the Latent Gaze Following Scores for individual infants. Density plots to the right of the boxplots show the distributions of the Latent Gaze Following Scores. Dots and error bars on the left edge of the density plots show the means and standard errors.

and social motivation from 6 to 14 months, with earlier levels of social motivation at 6 and 8 months predicting later levels of gaze following at 8 and 14 months. Together, our findings suggest that gaze following is a stable individual difference by 6 months of age, with developmentally stable social motivational underpinnings, supporting the potential role of social motivation in the development of gaze following in early infancy.

4.1 | Developmental stability of latent gaze following factor

The measurement model of latent gaze following–which included all three measures of gaze following–fit the data well at 6, 8, and 14 months, suggesting that we indexed reliable individual differences in infants' gaze following ability starting at the age of 6 months, but not at 2 and 4 months. Our design may have lacked the sensitivity to detect individual differences at these very early ages.

We detected overall (group level) gaze following at various ages depending on which measure we used. Specifically, group-level gaze following emerged at 4 months when using infants' first face-to-object saccades, at 6 months when using infants' total looking durations, and at 14 months when using infants' first looks (see Supplementary Analysis 1 in Supporting Information S1 for further discussion), similar to previous reports (Astor & Gredebäck, 2019; Gredebäck et al., 2008). In early infancy, different measures may vary in their sensitivity to capture infants' early cognitive skills and may introduce confounds that dampen construct validity (Kagan et al., 2002). These findings underscore the need for integrating convergent eye tracking measures to better measure gaze following acquisition in early infancy (Astor et al., 2020; Ishikawa & Itakura, 2019; Senju & Csibra, 2008).

Using the latent factor, we found an early emerging stability of gaze following which grew more stable with age. Individual differences in the latent measure of gaze following abilities were not associated between 6 and 8 months, only marginally associated between 8 and 14 months, and positively, moderately associated between 6 and 14 months. These findings suggest short-term periods of instability and fluctuations with age as these abilities emerge, but also a moderate level of long-term developmental stability between 6 and 14 months. Likewise, others report infants' gaze following skills are somewhat developmentally stable at early ages, but this stability appears to be relatively small (e.g., $r = .20$ from 6 to 10 months; Astor et al., 2020; $\rho = .37$ from 8 to 12 months; Schietecatte et al., 2012). Interestingly, another study failed to detect stable individual differences in a variety of social cognitive skills in the first year (Redshaw et al., 2020). Together, these findings indicate rapid changes to social cognitive skills in early infancy may make it difficult to consistently detect stable individual differences. Nonetheless, the current results replicated the early emerging stability of gaze following by 6 months using a noise-robust measure of gaze following.

4.2 | Developmental stability of latent social motivation factor

The measurement model of latent social motivation–which included all three measures of social motivation–fit the data well at 6, 8, and 14 months. These results suggest that we indexed reliable individual differences in infants' social motivation ability starting at the age of 6 months, but not at 2 and 4 months. Infants with higher levels of social motivation at 6 and 8 months also had higher levels of social motivation at 14 months. These findings suggest that social motivation may be moderately stable over early infancy in typically developing infants, consistent with previous reports of developmental stability in infants at risk for low social engagement (Costa & Figueiredo, 2011; Koegel et al., 2014). The current study is the first to report moderate developmental stability of social motivation measured with convergent behavioral and physiological measures of social stimuli.

Even though social attention and pupil dilation to social stimuli are widely-used measures of social motivation (Chevallier et al., 2015; Sepeta et al., 2012), using these measures alone can be problematic given their complex underlying psychophysiological processes (Aslin, 2007; Wang, 2011). For example, in addition to reflecting social reward processing, an increase in pupil dilation may additionally be driven by interest and information processing demands (Wang, 2011). Therefore, to address this issue, we extracted the common variance underlying multiple indicators to convergently measure social motivation.

Moreover, Chevallier et al. (2012) theorized that social motivation consists of three components: social orienting, social maintenance, and social reward processing. We included social orienting and social reward processing, which were accessible during brief, non-contingent, simulated social interactions using eye tracking. Nonetheless, studies need to explore additional aspects of social motivation (e.g., social maintenance over an extended time period, positive emotions during interactions) to understand their role in the development of gaze following. By including a wider variety of measures, future studies may improve the sensitivity and validity in capturing individual differences in infants' social motivation.

4.3 | Early infant social motivation predicts later gaze following

We found support for the social reinforcement learning hypothesis, which predicts that infants' social motivation levels are positively associated with their gaze following skills (Bottini, 2018; Chevallier et al., 2012). Social motivation at 6 months predicted gaze following at 8 and 14 months, and social motivation at 8 months predicted gaze following at 14 months. Moreover, we also find that social motivation predicts gaze following at the same age, which is consistent with a previous report that 9-month-olds' heart rate during simulated mutual gaze positively is positively associated with their gaze following seconds later (Ishikawa & Itakura, 2019). Heart rate elevation and pupil dilation, both indicating increase in physiological arousal, while observing social stimuli, may be useful indicators of social motivation (Bradshaw & Abney, 2021). Computational models of gaze following development have successfully simulated the social reinforcement learning processes, suggesting the existence of a social motivation factor (Carlson & Triesch, 2004; Ishikawa et al., 2020). Similarly, a recent study in human infants reported that infants show increasing attentiveness to others' social interactions from 7- to 14-month of age, which develop in parallel to improvements in their joint attention during parent-infant free-play interactions (Thiele et al., 2021). Likewise, our eye tracking measures of social orienting and social reward processing appear to be indicators of a latent social motivation factor that predicts the development of gaze following.

Our findings provide empirical and developmental evidence that social motivation plays a key role in the development of gaze following. One possible explanation is that higher levels of social motivation drive infants to look more at, and engage more with, others, which provides increased opportunities for learning and practicing their gaze following skills (see Senju & Johnson, 2009 for a review). Additionally, gaze following leads to joint-attentional communication and interaction between infants and their social partners regarding the objects to which they jointly attend (Senju & Csibra, 2008; Striano & Rochat, 2000). Given that infants actively seek and show positive emotions during joint attention (Clearfield et al., 2008; Venezia et al., 2004), such experiences may be more rewarding to the infants with higher social motivation and better reinforce their future gaze following behaviors.

There is also a need to explore the development of gaze following in a broader developmental context, including individual differences in more general sensory, motor, and cognitive development (e.g., information processing speed: Rose et al., 2012; orienting speed: Colombo et al., 1995; de Barbaro et al., 2011). For example, joint attention enhances infants' information encoding and learning of the objects that their social partners are interested in Cleveland et al. (2007). Previous studies suggest that infants' intrinsic learning desire shapes their social behaviors (Begus & Southgate, 2018). Thus, infants who have a greater desire to learn about what their social partners are looking at may be more likely to gaze follow. However, future studies are needed to investigate how infants' social motivation levels are related to their curiosity about social partners' interests.

4.4 | Limitations and future directions

Differences between video stimuli and live interactions may influence the manifestation and measurement of infants' social responses (Diener et al., 2008). The current study simulates a mutual gaze experience using video stimuli, which may deviate from a real-life eye contact experience. However, as far as we can tell, our infant participants are likely to perceive mutual gaze from the videos. Compared to video recordings, infants are more interested, and show more positive affect to, live peek-a-boo games (Diener et al., 2008). Eye-tracking is a valid approach to measure children's social behaviors (de Klerk et al., 2018; McClure et al., 2020). For example, 18-month-olds' gaze following ability–measured with the same paradigm as the current study–positively correlated with their responding to joint attention in a live interactive assessment (Navab et al., 2012). Eye-tracking and live-interaction measures of gaze following are complementary, each with unique strengths. While using pre-recorded video stimuli provides stringent experimental control, naturalistic live interactions are more reflective of the "messy" real world and may better elicit infants' social behaviors (Deák, 2015). In addition, testing gaze following in a complex environment with various objects may better reflect infants' ability to follow others' gaze in real life. Replicating the current findings with live models, particularly with eye tracking (Nyström et al., 2019; Thorup et al., 2016), offers strengths of both approaches.

Here, we focused on healthy, typically developing infants. However, gaze following is shaped by infants' early social experiences (Brooks et al., 2020; Senju et al., 2015; Simpson et al., 2016), and is commonly impaired in autism spectrum disorder (Thorup et al., 2016). The current study provides insights for understanding individual differences in early social motivation and gaze following, which may allow us to identify early risk factors of social disruptions using eye tracking (Isaksen & Holth, 2009; Thorup et al., 2016). Future studies might compare associations between measures of social motivation and gaze following in typically and atypically developing infants, as these may be fruitful targets to identify perturbations to these skills (Koegel et al., 2014).

While it appears that the development of gaze following in infants is universal, not limited to English-speaking (Byers-Heinlein et al., 2021) or Western cultures (Hernik & Broesch, 2019), there are few studies of infants living outside of North America/Western Europe (Singh et al., 2021); therefore, there may be geographical/cultural differences that have yet to be discovered. While our U.S-based sample was linguistically, racially, and ethnically diverse, we acknowledge that caution is warranted when considering the generalizability of our findings to other cultures. For example, compared to Western cultures, where gaze cue is a primary approach to initiate social interactions, caregivers in non-Western communities (e.g., Ni-Vanuatu) are more likely to use physical contacts to initiate joint triadic interactions with their children (Little et al., 2016). Thus, it is hypothesized that infants in these cultures may have fewer opportunities to learn and practice gaze following skills than their Western peers, which in turn may lead to different developmental patterns of gaze following (Little et al., 2016). However, this hypothesis needs to be more fully tested to better understand the role of experience in shaping infants' gaze following development. More cross-culture studies in gaze following are essential to our understanding of its developmental mechanisms (Hernik & Broesch, 2019).

5 | CONCLUSIONS

The present study considered the longitudinal developmental trajectory of individual differences in behavioral and physiological responses associated with the development of gaze following. Using

CFA, we combined behavioral and physiological measures to reveal the underlying constructs of social motivation and gaze following with high reliability and validity. Unlike prior studies, we found moderate developmental stability of social motivation. Furthermore, these stable individual differences in social motivation from 6 to 14 months positively predicted the development of gaze following, suggesting that social engagement may promote gaze following development. Infants' social motivation may be a target for future interventions to improve infants' gaze following skills.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest with regard to the funding source for this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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