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Regular Article

Social motivation in infancy is associated with familial recurrence of ASD

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Abstract

Pre-diagnostic deficits in social motivation are hypothesized to contribute to autism spectrum disorder (ASD), a heritable neurodevelopmental condition. We evaluated psychometric properties of a social motivation index (SMI) using parent-report item-level data from 597 participants in a prospective cohort of infant siblings at high and low familial risk for ASD. We tested whether lower SMI scores at 6, 12, and 24 months were associated with a 24-month ASD diagnosis and whether social motivation's course differed relative to familial ASD liability. The SMI displayed good internal consistency and temporal stability. Children diagnosed with ASD displayed lower mean SMI T-scores at all ages and a decrease in mean T-scores across age. Lower group-level 6-month scores corresponded with higher familial ASD liability. Among high-risk infants, strong decline in SMI T-scores was associated with 10-fold odds of diagnosis. Infant social motivation is quantifiable by parental report, differentiates children with versus without later ASD by age 6 months, and tracks with familial ASD liability, consistent with a diagnostic and susceptibility marker of ASD. Early decrements and decline in social motivation indicate increased likelihood of ASD, highlighting social motivation's importance to risk assessment and clarification of the ontogeny of ASD.

Keywords: autism spectrum disorder; infancy; measurement; social motivation

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Early detection of autism spectrum disorder (ASD) is a major objective of clinical developmental research, given ASD's lifelong impact and the established association between early intervention and improved outcomes (Estes, Munson, et al., 2015; Fuller and Kaiser, 2020; Shi et al., 2021). Prospective infant sibling studies have shown that consolidation of core ASD symptoms of social communication impairment and restricted and repetitive behaviors and interests (RRBs) is often preceded by diverse signs of atypical development, such as motor and attention deficits, which are not unique to ASD (Elsabbagh & Johnson, 2016; Sacrey et al., 2015). Assessments indexing initial manifestations of core ASD symptom domains could clarify how diverse pre-diagnostic features converge on ASD, which is vital for a more complete clinical science of its ontogeny and characterization of early ASD risk.

Social motivation, defined as the disposition to orient to social stimuli, to seek, want, and like social contact, and to maintain social interactions (Chevallier et al., 2012), has been implicated in the development and presentation of core autistic features. Low social motivation is hypothesized to contribute to social communication deficits and may also reinforce non-social, object-oriented fixations associated with RRBs. Like ASD, social motivation is heritable (Marrus et al., 2020; Sung et al., 2005), and quantitative differences in social motivation track with familial ASD liability (Uljarević et al., 2021). Brain systems underpinning social motivation include components of social and reward neurocircuitry (Chevallier et al., 2012), both of which have shown differences in ASD (Clements et al., 2018; Sato & Uono, 2019), including during early childhood (Abrams et al., 2013; Guo et al., 2021). Through its alignment with ASD's defining characteristics, and hypothesized relationship to ASD outcomes and its underlying biology, social motivation represents a candidate quantitative marker for both ASD susceptibility and diagnosis. Currently, however, the field lacks dimensional measures of social motivation in infants, a prerequisite for characterizing its role in the emergence of ASD, with ramifications for advancing early risk assessment and targeted intervention.

In typical development, behavioral expressions of social motivation are observed from early infancy. For example, newborns direct attention to social stimuli such as human faces

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(Rosa Salva et al., 2011) and biological versus scrambled motion (Simion et al., 2008). Predictable social smiling with exposure to faces and interactions (Emde & Harmon, 1972), present by three months of age, as well as subsequent smiling with early communicative gestures (Messinger & Fogel, 1998) both provide face-valid evidence for infants' liking of social experiences. Within the first year, infants also spontaneously demonstrate the ability to initiate social contact with caregivers, novel adults, and other infants (Hay et al., 1983; Ross & Goldman, 1977; Schaffer & Emerson, 1964). Typical behaviors during this period, such as interactive play (Markova, 2018), reciprocal babbling (Albert et al., 2018), and bids to re-engage an interactive partner (Tremblay-Leveau & Nadel, 1996) foster ongoing interaction and relationships. By affording a repertoire of social experiences, social motivation is hypothesized to stimulate social learning, while disrupted social motivation is hypothesized to constrain development of social communication, culminating in ASD (Chevallier et al., 2012).

Consistent with this hypothesis, literature on pre-diagnostic signs of ASD provides evidence of reduced social motivation before core social communication symptoms. Retrospective approaches using blinded coding of home videos found that within the first year, infants later diagnosed with ASD showed lower social initiative, looking at others, and response to interpersonal overtures compared to typically developing infants and infants with global delays (Palomo et al., 2006; Saint-Georges et al., 2010). In prospective studies, decreased social function among children with later ASD has been most consistently observed after the first year (Sacrey et al., 2015), although reduction in specific behaviors reflecting aspects of social motivation, such as social smiling (Ozonoff et al., 2010), response to name (Miller et al., 2017), back-and-forth vocalizations (Sacrey et al., 2021), and fixation on social versus non-social stimuli (Jones & Klin, 2013) have been reported earlier. The diversity in quality and context of social motivation-related behaviors suggests that a broad construct encompassing naturalistic social orienting, seeking, liking, wanting, and maintaining could capture sufficient dimensional variation to quantify social motivation as a potential indicator of ASD susceptibility in infancy.

Although comprehensive, quantitative infant assessments of social motivation have not yet been developed, recent parent-report instruments (Marrus et al., 2020; Phillips et al., 2019), and eye-tracking measures (Vernetti et al., 2018) support the ability to measure social motivation in toddlerhood. Parent-report instruments assessing clinically informative behaviors across day-to-day contexts have shown lower social motivation scores in children with ASD (Phillips et al., 2019) and associations between social motivation and quantitative ASD traits (Marrus et al., 2020). These findings suggest that a parent-report measure for infants may provide a translatable approach to index individual differences in social motivation and enhance ASD screening and characterization of ASD's emergence during development.

To determine whether measurable differences in infant social motivation precede ASD diagnosis, as well as differentiate toddlers with and without ASD, we leveraged existing parent-report data from the Infant Brain Imaging Study (IBIS) (Estes et al., 2015). This longitudinal, multisite study of infant siblings at high and low familial risk for ASD afforded a continuum of typical and atypical social development, while enriching for social deficits. The prospective family study design allowed investigation of relationships between infant social motivation and later ASD, as well as between social motivation and inherited ASD liability stratified according to familial risk in conjunction with presence or absence of an ASD diagnosis. As an initial test of a clinically feasible approach to index social motivation in infancy, we reviewed items on a series of parent-report measures querying aspects of social behavior consistent with displays of social motivation, including measures of temperament, adaptive function, social development, and communication in infants at ages 6, 12, and 24 months. We incorporated those items with strong face validity for social motivation into a composite social motivation index (SMI) for each study time point. Following examination of the SMI's psychometric properties, we tested the hypothesis that lower social motivation could distinguish children with ASD both prior to and at the time of diagnosis. We additionally tested the hypothesis that lower social motivation scores would be observed with greater levels of familial ASD liability.

Method

Participants

The IBIS is a prospective, multisite study of infant siblings at high and low familial risk of ASD, with assessments at 6, 12, and 24 months (Estes et al., 2015). High-risk (HR) infants have an older biological full-sibling with ASD, whereas comparison low-risk (LR) infant siblings have no first-degree relatives with ASD or intellectual disability. For these analyses, 597 participants had appropriate data for generating a score on the SMI ($n_6 = 374$, $n_{12} = 318$, $n_{24} = 396$). The LORIS data management platform (Das et al., 2016) served as the behavioral, clinical, and imaging hub for data collection, curation, preparation for analysis, and archiving. See supporting information for exclusion criteria.

At 24 months, an experienced psychologist or psychiatrist reviewed behavioral testing, including the Autism Diagnostic Observation Schedule (ADOS, Lord et al., 2000), to determine a clinical best estimate diagnosis of either autistic disorder or pervasive developmental disorder not otherwise specified using the DSM-IV-TR checklist (American Psychiatric Association, 2000). All families provided informed consent in accordance with each site's Institutional Review Board.

Derivation of a SMI

Data from the IBIS study battery, collected prospectively when infants were ages 6, 12, and 24 months, were reviewed for items querying social behavior in parent-report measures, as these provide clinically relevant and scalable assessment of individual differences in infancy, with ratings representing real-world behavior across time and contexts. Items were selected from validated developmental instruments, specifically, the Vineland Adaptive Behavior Scales, an adaptive function measure (Sparrow et al., 2005); the Infant Behavior Questionnaire-Revised, a temperament measure (Gartstein & Rothbart, 2003); the Macarthur-Bates Communicative Development Inventory, a language measure (Fenson et al., 2006); and the First Year Inventory, a screener for ASD risk (Watson et al., 2007). See supporting information for details on study instruments.

Candidate social motivation items were selected (NM) based on face validity for Chevallier et al.'s definition of social motivation (2012) as the disposition to orient to social stimuli, to seek social contact, to want and like social experiences, and to work to maintain social interactions. Items were chosen to index social motivation in aggregate across its key elements as manifested via a series of common, observable infant behaviors that included directing

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attention to others (orienting), initiating interaction (seeking), positive affect in social contexts (liking or wanting), or responses likely to sustain engagement (maintaining). Social motivation items were distinguished from items probing emotion recognition, instrumental requests, or physical play. To maximize variation in the representation of social motivation during early development, unique items from available study measures at each time point were included in separate 6-, 12-, and 24-month social motivation indices. Five items were reverse-coded so that for all items, higher scores indicated greater social motivation, and items and were weighted equally by re-scaling scores to range from 0 to 1 (Cohen et al., 1999). Duplicate item content was not present across instruments with the SMI for a given age.

In a preliminary review of candidate items, Cronbach's alpha, a well-established measure of internal reliability which quantifies the inter-relatedness across items (Cronbach, 1951), was calculated separately for each full series of SMI items identified at the 6, 12, and 24-month time points and again for cases when each item was singly removed. Items whose removal resulted in a higher alpha, indicating improved inter-relatedness among remaining items, were eliminated. As an additional validity check, a consensus of authors (JNC, KB, and LM) with expertise in ASD and/or infant development confirmed that remaining items showed good face validity for Chevallier and colleagues' definition of social motivation.

Next, finalized items (Table 1) were summed into separate 6-, 12-, and 24-month composites. To facilitate cross-age comparisons, these scores were standardized to T-scores with a mean = 50 and standard deviation = 10. T-scores were calculated as equal to the Z-score * 10 + 50, where the Z-score = (mean score-raw score)/(standard deviation). Analyzed participants ($n_6 = 374$, $n_{12} = 318$, $n_{24} = 396$) had complete item-level scores, excepting 38 whose 12-month scores were normalized to account for "not applicable" ratings on two items regarding social behavior while being held during feeding. Scores for one participant with notably low ratings across age were winsorized to T-score = 5. All analyses involved the same finalized 6-, 12-, and 24-month SMI item sets.

Statistical Analyses

Participant characteristics

Student's t-tests and chi-square tests evaluated group differences in continuous and categorical data, respectively. Effect sizes for continuous measures were Cohen's d, where $d \geq 0.8$ is large, $d \geq 0.5$ and < 0.8 is medium, and $d \leq 0.2$ is small. Effect sizes for comparisons of proportions were odds ratios or Cramer's V, where $V \geq 0.5$ is large, $0.2 < V < 0.5$ is medium, and $V \leq 0.2$ is small (Cohen, 1988).

Measurement properties of the SMI

Cronbach's alpha was calculated to index the inter-relatedness of SMI item sets at each age and across age. Values of alpha > 0.7 are considered acceptable, >0.8 are considered good, and >0.9 are considered excellent (Nunnally, 1978). We applied exploratory factor analysis to test the hypothesis that items across 6, 12, and 24 months loaded onto a single factor, using principal axis factoring and an oblimin rotation in SPSS. To allow for a sufficient ratio of participant number to items, items were pooled into 10 parcels, an established approach in measurement modeling (Stucky et al., 2012), consisting of composites of items with balanced distribution by instrument type and age of administration. We followed the EFA with a confirmatory factor analysis (CFA) to determine fit indices for a unitary factor structure (see supplement for details).

Spearman's correlations indexed rank-order cross-age stability and Pearson's correlations were computed for convergent and divergent validity. Zou's confidence interval method for the difference in correlations (Zou, 2007), which accounts for dependency between correlations, was used to compare correlations for variables involving primary tests of convergent and divergent validity.

To evaluate convergent validity, we utilized measures assessing social communicative performance, since social communication is theorized to be influenced by social motivation (Chevallier et al., 2012; Su et al., 2021) and since separate measures of infant social motivation were not present in IBIS. We anticipated correlations consistent with partially overlapping relationships of the SMI and these metrics. The Autism Observation Scale for Infants (AOSI), a direct assessment of ASD features (Zwaigenbaum et al., 2021, see supplement), or the ADOS were used as primary metrics to evaluate convergent validity for the SMI given the theorized relationship between decreased social motivation and increased signs of ASD. Secondary analyses of convergent validity included the Mullen Receptive (RL) and Expressive Language (EL) scales, which encompass aspects of communication.

For testing of divergent validity, we predicted lower correlations than those observed for testing of convergent validity. For a primary analysis of divergent validity, we selected the Mullen Fine Motor (FM) scale, as this measure entails a distinct domain of function that may be demonstrated independently from social interaction. In secondary analyses of divergent validity, we also obtained correlations for the Mullen Gross Motor (GM) and Visual Reception (VR) scales, two functions also not contingent on social interaction. These two latter behaviors were included since they have demonstrated associations with subsequent ASD outcome in infancy (Estes et al, 2015), and their relationships to ASD outcome were compared with those for social motivation as part of our analyses.

Relationship of social motivation to ASD diagnosis

To evaluate relationships between social motivation and ASD, binary logistic regressions were first performed for base models with diagnosis as the dependent variable and social motivation T-score as the independent variable. Full models included covariates of sex and cognition based on the Early Learning Composite (ELC) from the Mullen Scales of Early Learning (Mullen, 1995). The Hosmer-Lemeshow test indicated adequate fit ($p > .05$) for all models. Variance estimates were Nagelkerke's pseudo-R^2.

Parallel base models with independent variables of Mullen GM function and VR were also run to informally compare the relative effects observed across for these domains versus social motivation. These behaviors were selected for comparison because they have previously been identified as infant behavioral markers of ASD risk by age 6 months (Estes et al., 2015). A third series of models also evaluated whether additive contributions for ASD outcome were present for social motivation, GM, VR, and pre-diagnostic ASD-related behaviors measured by the AOSI.

Development of social motivation relative to familial ASD liability

Hierarchical linear modeling (HLM), an advanced regression technique accounting for shared variance in nested data, was applied to investigate the longitudinal relationships between familial liability for ASD and social motivation, controlling for sex. For the familial liability variable, children were classified into three risk-diagnostic groups denoting increasing levels of familial background for ASD (Marrus et al., 2018): LR− (low-risk children without ASD), HR−

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Table 1. Social motivation index item content

	Age (months)		
	6	12	24
Orienting-directing attention to social stimulus			
Orienting to caregiver voice or conversation	X	X	
Orienting to playful caregiver bid		X	
Avoidance of eye contact (reverse-coded)		X	
Response to name	X	X	
Watching peers		X	X
Seeking-initiation of interaction			
Initiation/attempted initiation of social contact	X	X	
Effort to get caregiver attention to share interest or play	X	X	
Proximity-seeking	X	X	
Demonstrating affection	X	X	
Showing objects to caregiver		X	X
Giving objects to caregiver		X	X
Play-seeking behavior with peers		X	X
Wanting/Liking-desire/enjoyment of social experiences			
Enjoyment of proximity to caregiver or others	X	X	
Enjoyment of playful facial expressions	X	X	
Positive affect while orienting to caregiver		X	
Positive affect with others' social approach	X	X	
Indifference with others' social approach (reverse-coded)	X	X	
Positive affect during interactive game	X	X	
Positive affect upon caregiver return	X	X	
Desire to please others			X
Maintaining-actions sustaining interaction			
Responsive social smile, babbling, or conversation	X	X	X
Playing interactive games	X	X	
Cooperative play			X
Sustaining proximity to caregiver	X	X	
Sharing			X
Turn-taking			X
Imitation of caregiver sounds or facial expressions	X	X	X
Imitation of early social gestures (e.g., clapping, waving)	X	X	
Spontaneously waving good-bye		X	X
Spontaneous helping			X

Note. Correspondence of concepts in social motivation items to Chevallier et al.'s definition (2012).

(high-risk children without ASD), and HR+ (high-risk children with ASD). SMI scores were hypothesized to be lowest for the HR+ group, given that decreased social motivation is observed in ASD. Scores for the HR− group were hypothesized to fall between the HR+ and LR− groups given prior evidence supporting the heritable nature of ASD symptoms and social motivation (Marrus et al., 2020). Categorical variables were dummy coded, with sex = male and familial liability = HR− siblings as reference groups. Age was centered at 6 months to test for early-arising group differences in social motivation. Longitudinal observations (6, 12, and 24 months) were nested within individuals, allowing intercepts to be modeled separately for each individual (i.e., as random effects). Interaction terms for risk-diagnostic variables with age evaluated behavioral course as a function of familial liability. Conditional R^2 described variance accounted for by effects within and between time points.

Relative decline in social motivation in HR children with versus without ASD

Chi-square testing evaluated whether the presence or absence of a strong individual-level decline in social motivation distinguished HR children with versus without ASD. Here, findings were

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Table 2. Participant characteristics

	6-month visit ($n = 374$)	12-month visit ($n = 318$)	24-month visit ($n = 396$)
Age (months)	6.62 (0.66)	12.47 (0.53)	24.6 (0.76)
	5.35–8.80	11.40–15.15	23.25–27.70
Sex (female/male; %male)	159/215 (57.5%)	127/191 (60%)	153/243 (61.4%)
Familial risk status (LR/HR; %HR)	137/237 (63.4%)	80/238 (74.8%)	121/275 (69.4%)
Diagnosis (no/yes ASD; %ASD)	257/46 (15.2%)	237/47 (16.5%)	330/58 (14.9%)
Ethnicity (no/yes Hispanic; %Hispanic)	283/17 (5.7%)	230/12 (5.0%)	276/12 (4.2%)
Race (*n*/%)			
White	260 (87.5%)	246 (90.8%)	292 (88.0%)
African American/Black	8 (2.7%)	2 (0.74%)	4 (1.2%)
Asian	4 (1.3%)	2 (0.74%)	5 (1.5%)
Multiracial	25 (8.4%)	21 (7.7%)	31 (9.3%)
Mullen early learning composite	100.13 (11.87)	101.50 (13.88)	102.05 (18.16)
	59–140	62–142	49–153

Note. Participants include infants at high (HR) and low familial risk (LR) of autism spectrum disorder (ASD). Three LR children met criteria for ASD. Ranges presented for continuous variables.

parameterized in terms of a categorically strong decline in social motivation, rather than continuous scores. This was due to our hypothesis that a large decrease in social motivation, but not necessarily a range of less substantial declines, particularly for above-average SMI scores, would be more consistently associated with a clinically significant reduction in social function and increased likelihood of ASD diagnosis. Strong decline was defined as a 15 point drop in SMI T-score, since this increment of 1.5 standard deviations is commensurate with developmental delay (Marrus et al., 2018) and thus a difference constituting clinical impact. Differences in SMI T-scores were calculated between the first year of life and 24 months, using the higher available SMI T-score at 6 or 12 months.

In addition to primary analyses using subjects with available SMI scores, models testing relationships between social motivation and ASD diagnosis were run following multiple imputation (Enders, 2017; Rubin, 1996). This procedure replaced missing SMI scores with predicted values based on available data, as missing data may bias reported relationships (see supplemental methods for details).

Results

Participant characteristics

SMI T-scores were generated for low-risk (LR) and HR participants at 6-, 12-, and 24-month visits (Table 2). Across visits, participants did not significantly differ in proportions by sex, ASD diagnosis, race, or ethnicity, or in mean general cognition on the ELC (see supplement for statistics). At the 12-month time point, a higher proportion of HR versus LR infants was observed in comparison to proportions at 6 and 24 months (Table 2, $\chi^2(2) = 10.64$, $p = .005$; $V = 0.01$).

Measurement properties of the SMI

At all ages, SMI T-scores displayed a continuous, unimodal distribution with slight negative skew ($skew_6 = -0.82$, standard error (SE) $= 0.13$; $skew_{12} = -1.63$, $SE = 0.14$; $skew_{24} = -0.41$, $SE = 0.12$) (Figure 1a–c). Items showed good internal reliability at each age ($\alpha_6 = .75$, $\alpha_{12} = .89$, $\alpha_{24} = .81$) and when pooled across age ($\alpha_{6\text{-}12\text{-}24} = .87$). An exploratory factor analysis using item parcels comprised of items from all three ages was consistent with a single factor accounting for 42% of the variance based on the inflection point of the scree plot and an eigenvalue >1. Item parcels exhibited moderate to high loadings onto this factor, where loadings ranged between 0.55 and 0.79 (see supplement for details). Fit indices obtained by CFA of a unitary social motivation factor were consistent with acceptable to good fit: CFI = 0.95, TFI = 0.93, RMSEA = 0.08, and SRMR = 0.43.

Composite SMI scores, in turn, showed good temporal stability across age: $\rho = 0.58$ ($p < .001$, 95% confidence interval (CI) [0.47, 0.67], $n = 194$) from 6–12 months, $\rho = 0.40$ ($p < .001$, 95% CI [0.27, 0.51], $n = 214$) from 12–24 months, and $\rho = 0.22$ ($p = .001$, 95% CI [0.09, 0.35], $n = 210$) from 6 to 24 months. These cross-age correlations were of comparable or greater magnitude to those for the Mullen ELC, a standardized measure of infant cognitive development: $\rho = 0.27$ ($p < .001$, 95% CI [0.18, 0.36]) from 6 to 12 months, $\rho = 0.43$ ($p < .001$, 95% CI [0.35, 0.50]) from 12–24 months, and $\rho = 0.17$ ($p < .001$, 95% CI [0.08, 0.27]) from 6 to 24 months. At 24 months, females scored higher than males, including when analyzing children without ASD to account for male predominance of cases ($t(327) = 2.62$, $p = .009$; $d = 0.29$).

In a primary test of convergent validity, SMI scores were negatively correlated (in the expected direction) with concurrent total scores on the AOSI: $r_{AOSI\text{-}6} = -.33$ ($p < .001$, $n = 361$) and $r_{AOSI\text{-}12} = -0.38$ ($p < .001$, $n = 306$), and 24-month ADOS calibrated severity score: $r_{ADOS\text{-}24} = -0.47$ ($p < .001$, $n = 373$). We secondarily evaluated convergent relationships between the SMI and Mullen Expressive (EL) and Receptive (RL) Language scales. The SMI showed mostly moderate magnitude correlations with these measures ($r_{EL\text{-}6} = .26$, $r_{EL\text{-}12} = .31$, and $r_{EL\text{-}24} = .30$; $r_{RL\text{-}6} = .36$, $r_{RL\text{-}12} = .24$, and $r_{RL\text{-}24} = .39$, all p's $< .001$). Correlations across the AOSI and language measures were consistent with partially overlapping variance with the SMI, with shared variance (R^2) up to 14.4% from 6 to 12 months and 22.1% at 24 months.

Conversely, a primary test of divergent validity with the Mullen FM scale showed weaker associations between concurrent SMI and FM scores than SMI and AOSI/ADOS scores at all ages

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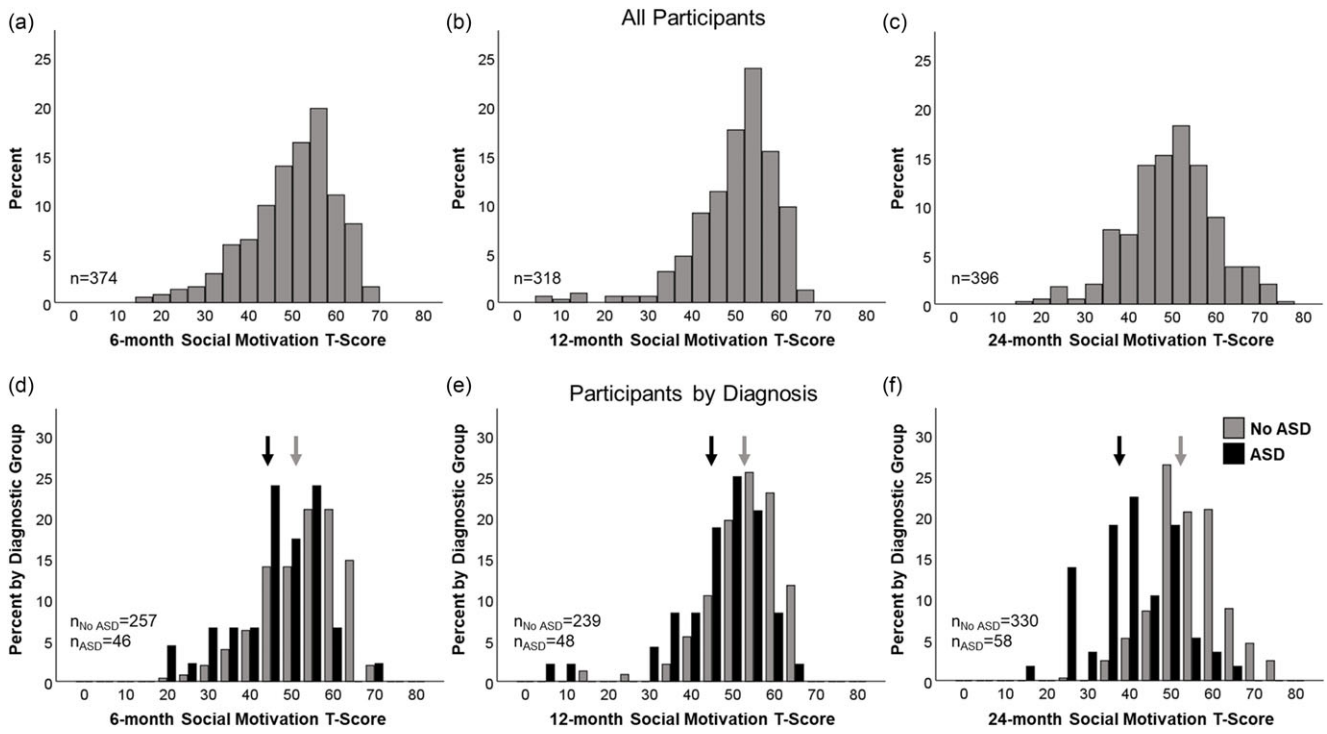

Figure 1. Social Motivation Score Distributions at 6, 12, and 24 Months Social Motivation Index T-score distributions (A-C) among all low- and high-risk participants. Bars (D-F) categorize participants by diagnosis. Gray and black arrows indicate group means for children without and with ASD.

($r_{FM\text{-}6} = .18$, $r_{FM\text{-}12} = .17$, and $r_{FM\text{-}24} = .22$, p's $< .01$, $n > 316$, see supplement for tests of significant differences from AOSI/ADOS correlations). In secondary tests of divergent validity, similarly low correlations were observed for Mullen GM scale [$r_{GM\text{-}6} = .21$ ($p < .001$), $r_{GM\text{-}12} = .11$ ($p = .052$) and $r_{GM\text{-}24} = .22$ ($p < .001$)] and VR scale [$r_{VR\text{-}6} = .18$, $r_{VR\text{-}12} = .16$, and $r_{VR\text{-}24} = .25$ (p's $< .01$)].

Relationship of social motivation to ASD diagnosis

Given the hypothesis that early deficits in social motivation contribute to later ASD, we examined in LR and HR infants whether children diagnosed with ASD at 24 months exhibited lower SMI scores at 6 and 12 months. At both ages, later-diagnosed infants displayed lower scores [means and standard deviations: $SMI_{6\text{-}noASD}$: 50.63 (9.54) versus $SMI_{6\text{-}ASD}$: 44.01 (11.27); $SMI_{12\text{-}noASD}$: 50.95 (8.74) versus $SMI_{12\text{-}ASD}$: 44.24 (11.25)]. These differences represented moderate effect sizes ($d_6 = 0.67$; $d_{12} = 0.73$, p's $< .001$; Table S1) comparable to differences observed for the AOSI ($d_6 = 0.37$; $d_{12} = 0.57$, p's $< .05$).

At 24 months, lower SMI scores in children with versus without ASD [$SMI_{24\text{-}ASD}$: 38.18 (10.34) versus $SMI_{24\text{-}noASD}$: 51.87 (8.39)] constituted a large effect size ($d = 1.57$, $p < .001$), with a larger downward shift and greater separation in SMI score distributions for children with versus without ASD (Figure 1d–f). Effect sizes (Table S1) and distributions (Fig S1) did not substantively change after removing children with significant cognitive delay, i.e., ELC < 70 (Marrus et al., 2018), from analysis.

Using binary logistic regression, we next evaluated the magnitude of the relationship between social motivation at each age and ASD diagnosis in LR and HR infants (Table 3). At all ages, base models without covariates were significant. Six- and 12-month SMI scores respectively explained 8.8% and 9.9% of the variance in ASD diagnosis. Concurrent 24-month SMI scores explained 39% of the variance in ASD diagnosis.

In full models (Table 3), where SMI scores were entered *after* accounting for effects of sex and cognition (using the concurrent ELC score), SMI scores remained significant predictors of ASD outcome at all ages. At 6 months, sex, but not cognition, was significantly related to ASD diagnosis, while at 12 and 24 months, sex, cognition, and social motivation contributed additively to ASD outcome. Similar findings were observed when confining analyses to HR infants (Table S2) and when accounting for missing data using multiple imputation (Table S3).

In the same sample, findings for social motivation were qualitatively compared to analogous base models for GM function and VR (Table S4). These behaviors offered an informal standard of comparison given that, in IBIS, both showed lower 6-month scores in HR+ (HR with ASD) versus LR- (low-risk without ASD) groups (Estes et al., 2015) while showing low correlations with the SMI, as detailed above. At all ages, GM and VR T-scores explained numerically less variance in ASD outcome than social motivation (≤4% at 6 and 12 months, ≤23% at 24 months).

A joint model including social motivation, GM, and VR, and ASD-related behaviors on the AOSI or ADOS, revealed that at age 6 months, only social motivation significantly predicted ASD outcome. Small additive contributions to ASD outcome were present for the SMI and AOSI at 12 months and additive contributions of all behaviors occurred at 24 months (Table S5).

Development of social motivation relative to familial ASD liability

Using HLM, we next tested whether social motivation across ages 6, 12, and 24 months varied as a function of familial ASD liability stratified by risk-diagnostic groups (i.e., LR-, HR-, and HR+). HR- siblings served as the reference group for comparison of LR− to HR− (low versus medium liability) and HR+ to HR− (high versus medium liability). A base model covaried for age and sex, followed

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Table 3. Relationship of social motivation index scores to ASD

	6-month Models		12-month Models		24-month Models	
	Base ($n = 303$)	Full ($n = 301$)	Base ($n = 287$)	Full ($n = 286$)	Base ($n = 388$)	Full ($n = 385$)
Constant	3.08	10.93	4.27	50.63*	359.87***	105,682.48***
SM	0.94 (0.91,0.97)***	0.95 (0.92,0.98)**	0.94 (0.91,0.97)***	0.96 (0.92,0.99)**	0.85 (0.81,0.88)***	0.88 (0.84,0.92)***
Sex		2.93 (1.36,6.32)**		2.33 (1.07,5.06)*		1.83 (0.76,4.43)
ELC		0.98 (0.95,1.01)		0.96 (0.94,0.99)**		0.92 (0.90,0.95)***
Model test	$\chi^2(1) = 15.70$***	$\chi^2(3) = 27.08$***	$\chi^2(1) = 17.37$***	$\chi^2(3) = 32.97$***	$\chi^2(1) = 97.62$***	$\chi^2(3) = 148.50$***
Total variance	0.088	0.15	0.099	0.18	0.39	0.56
SM variance	0.088	0.054	0.099	0.038	0.39	0.15
Sex variance		0.050		0.052		0.037
ELC variance		0.046		0.094		0.37

Note. Binary logistic regression models test the relationship of social motivation (SM) to autism spectrum disorder (ASD; No = 0, Yes = 1) in children at low and high familial risk. Base models examine sole contributions of SM. Full models first account for sex (Female = 0, Male = 1) and cognition (ELC = Early Learning Composite). Exponentiated β coefficients reported for SM, sex, and ELC index the relationship between independent variables and ASD outcome, which is calculated as the natural log of the odds for diagnosis (odds = probability of ASD/probability of no ASD). For sex, a categorical variable, βs indicate the male to female odds ratio of ASD; for continuous variables, $\beta < 1$ indicates that higher values correspond with lower odds of ASD. 95% confidence intervals in parentheses. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

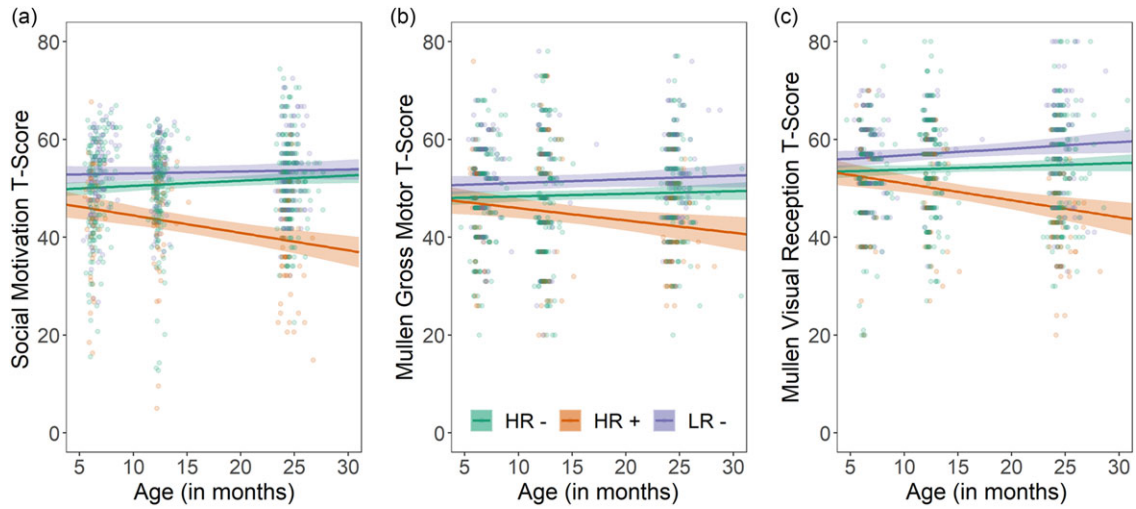

Figure 2. Social Motivation, Gross Motor Function, and Visual Reception Across Age Trajectories of social motivation (A), gross motor function (B), and visual reception (C) are shown for risk-diagnostic groups (LR−, HR−, HR+) based on hierarchical linear models incorporating sex, age (centered at 6 months), ASD familial liability, and interaction of liability with age. In order of increasing familial liability: LR− = low-risk negative, HR− = high-risk negative, HR+ = high-risk positive.

by a model including liability group, and a full model including interaction terms of age with liability group (Table S6).

The full model exhibited the lowest Akaike information criterion, supporting the best fit, and the highest conditional R^2 of 47% (Table S6). Main effects of familial liability – indicative of risk-diagnostic group differences at 6 months (i.e., center of age) – were observed. Specifically, 6-month SMI T-scores were significantly greater for LR− versus HR− children ($B = 2.79$, $p < .01$; $d = 0.18$) and for HR− versus HR+ children ($B = -4.19$, $p < .01$; $d = -0.21$), consistent with an association of decreasing social motivation with increasing familial ASD liability (Figure 2a). In contrast, analogous models for GM and VR (Figure 2b, c; Table S8) showed lower 6-month T-scores in HR- versus LR- groups only (GM: $B = 3.01$, $p < .05$, $d = 0.16$; VR: $B = 2.96$, $p < .01$, $d = 0.17$).

Familial liability by age interactions for social motivation were significant for the comparison of HR− and HR + groups ($B = -0.50$, $p < .001$, $d = -0.38$), reflecting declining SMI T-scores between 6 and 24 months in the HR+ group. This finding was also observed for GM and VR (Figure 2a–c, Table S6). Additional models testing interactions with sex failed to show significant interactions and resulted in worse model fit. Comparable findings were observed for datasets generated following multiple imputation (Table S7).

Relative decline in social motivation in HR children with versus without ASD

Given the finding of group-level decline in SMI T-scores for HR+ children, we conducted an exploratory analysis to evaluate the extent to which individual-level relative decline differentiated HR children with versus without ASD ($n_{HR+} = 42$; $n_{HR-} = 151$). HR children were classified by presence or absence of a strong decline in SMI T-scores (≥15 points) between the first year and 24 months (Fig S2). Strong decline occurred in 31% HR+ versus

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4% HR-negative children ($\chi^2(1) = 26.95$, $p < .001$), corresponding to an odds ratio = 10.83, 95% CI [3.81, 30.84] for ASD in HR children. A similar odds ratio was observed in analyses using multiple imputation (odds ratio = 9.85, 95% CI [3.38, 28.67]).

Among HR+ children, those with versus without a strong decline displayed lower 24-month SMI T-scores ($SMI_{decline} = 30.67 \pm 7.32$; $SMI_{other} = 41.82 \pm 10.96$; $t(40) = 3.34$, $p < .01$, $d = 1.11$) but no significant difference in 24-month ADOS or ELC scores (Table S6). The declining group's low 24-month SMI scores contrasted with unremarkable mean SMI T-scores (53.70 ± 6.31; sample mean = 50) observed in the first year of life.

Discussion

Here we demonstrate that individual differences in social motivation are quantifiable during infancy by parental report, an accessible assessment modality for clinical practice. The SMI showed temporal stability during a rapid developmental stage and as hypothesized, differentiated children with versus without ASD at 6, 12, and 24 months, an effect not attributable to cognition. Consistent with prior reports of heritability of social motivation, increasing levels of familial ASD liability (i.e., LR− < HR− < HR+) corresponded to decreasing levels of social motivation at 6 months, prior to ASD diagnosis. At the group level, SMI T-scores declined from infancy through toddlerhood in HR+ infants, whereas at the individual level, strong decline occurred in a subgroup of these children, illustrating heterogeneous developmental pathways in ASD. These findings collectively support a role for social motivation as a biobehavioral marker of ASD susceptibility and diagnosis, for which both lower levels in infancy and strong decline in toddlerhood are associated with development of ASD.

Social motivation is quantifiable during infancy

The SMI displayed a continuous, unimodal distribution across children with and without ASD, as well as good internal consistency and cross-age stability. Items in the SMI, when pooled across age, showed moderate to high loadings on a single factor, consistent with representation of interrelated aspects of social motivation from infancy through toddlerhood. Moderate correlations of the SMI with the AOSI and ADOS, assessments of ASD-related symptoms, as well as communication skills on MSEL language measures, were consistent with convergent validity, while the finding of <25% overlapping variance between these metrics and the SMI supported its ability to measure a unique social construct. Lower correlations with metrics of distinct motor and VR abilities, in turn, demonstrated divergent validity. These features support evidence for the SMI's quantification of a dimensional, trait-like construct.

In terms of participant characteristics associated with differences in social motivation, higher 24-month SMI scores in females versus males and lower scores in ASD-affected toddlers corroborated findings at older ages (Phillips et al., 2019) and supported downward extension in the measurement of this construct. Pre-diagnostic and concurrent associations of lower SMI scores with ASD persisted when accounting for cognition, confirming specificity of these relationships to social motivation. In models evaluating joint behavioral contributions of social motivation with GM, VR, and ASD-related features on the AOSI, social motivation showed the earliest relationship to ASD outcome at 6 months, whereas additive contributions of other behaviors and social motivation were found at 12 and 24 months. These findings suggest that the SMI, in quantifying a specific behavioral dimension hypothesized to underlie development of ASD, offers value-added for tracking the emergence of ASD, while contrasting with prior literature emphasizing that ASD-related alterations in social behavior arise during the second year (Sacrey et al., 2015). From the standpoint of clinical practice, a parent-report SMI, in comparison to semi-structured assessments such as the AOSI, would offer the advantage of obviating the need for trained assessors and additional scheduling, which could expedite evaluation for ASD and referral for intervention.

Six-month social motivation corresponds with familial ASD liability

Lower 6-month SMI scores distinguished groups according to increasing familial ASD liability. First, when considering family history of ASD among children without a diagnosis, 6-month-olds with a family history had lower scores than 6-month-olds without a family history (HR− < LR−). Next, when considering ASD diagnosis among children with a family history, 6-month-olds with subsequent ASD had lower scores than children without ASD (HR+ < HR−). This stepwise relationship of LR− < HR− < HR+ is consistent with previously reported heritability of social motivation (Marrus et al., 2020; Sung et al., 2005) and the potential for developmentally-sensitive genetic factors that influence vulnerability and/or resiliency to ASD (Elison, 2020).

In contrast to social motivation, 6-month GM and VR, which are not aspects of core ASD features, differentiated HR infants only by presence or absence of a family history of ASD and not by subsequent diagnosis. At all three ages, GM and VR also exhibited nominally lower associations with ASD outcome (Table S3). Collectively, these findings support the specificity of social motivation as an infant behavioral marker of ASD recurrence and familial genetic risk, underscoring the utility of tracking precursors of core features to elucidate origins of ASD.

Heterogeneity in emergence of social motivation deficits in ASD

HR infants with either lower SMI T-scores or a decline in SMI T-scores were more likely to develop ASD. The longitudinal decline from infancy through toddlerhood (Figure 2) paralleled widening cross-sectional ASD group differences in social motivation first observed at 6 months and demonstrated incremental development of core ASD symptoms. Individual courses, in turn, revealed variable social motivation profiles across age (Fig S2), with a subgroup of 31% of HR+ infants exhibiting moderate SMI T-scores followed by a strong decline, reminiscent of reports of regression in ASD. This decline was associated with 10-fold higher odds of ASD among HR children, a notable elevation for a population with 20% baseline recurrence (Ozonoff et al., 2011). Thus, surveillance of social motivation from early infancy may be especially informative for risk assessment in children with a family history of ASD.

Clinical implications of variation in social motivation in ASD

As hypothesized, group-level SMI scores were lower in ASD-diagnosed toddlers, although their downward-shifted score distribution partially overlapped the distribution for toddlers without ASD. This observation resembles findings for school-aged children with ASD (Neuhaus et al., 2021) and suggests that categorically low

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levels of social motivation are not necessary for all cases of ASD, as expected under a stringent interpretation of the social motivation hypothesis (Chevallier et al., 2012). Thus, toddlers with ASD likely exhibit individualized profiles of relative strengths and weaknesses in aspects of core symptom domains, which could correspond to differences in the balance of the drive versus ability to engage in social communication with others. This notion is consistent with accounts of variability in social motivation and its expression among individuals with ASD (Jaswal & Akhtar, 2018). In addition, our findings of additive relationships between social motivation, cognitive domains, and ASD symptom features to ASD outcome (Table 3; Table S4) align with models in which cumulative inherited liability implicating multiple developmental domains underlies ASD's ontogeny (Constantino et al., 2021; Elsabbagh & Johnson, 2016). Quantitative developmental assessment across an array of ASD phenotypes relevant to both core symptoms and co-occurring features may thus improve screening, clinical subtyping, and more personalized intervention from an early stage in development.

Strengths and Limitations

As a composite derived from pre-existing data, the SMI incorporated items queried at specific ages. This approach maximized our ability to detect clinically relevant variation in social motivation while accounting for infants' expanding behavioral repertoire during development. However, this strategy precluded item-level continuity and uniform representations of social motivation across age by the composite scores, and some relevant items were not assessed at all time points. In an extension of this work, we have developed an *a priori* SMI with balanced representation of elements of social motivation and analogous items across developmental stages. Together with more advanced psychometric approaches in large longitudinal samples, such efforts will further clarification of social motivation's behavioral architecture in early childhood.

SMI items were systematically vetted according to the established conceptualization of social motivation as a disposition to engage with others. However, the disposition to socially engage may by necessity entail some demonstration of social ability. The SMI, in prioritizing parental impressions of cumulative experiences with their child, was designed to provide an overarching, real-world representation of social motivation rather than to explicitly separate social motivation from social skill. Our findings of partially overlapping variance between the SMI and direct metrics involving social communication skills, as well as additive contributions of the SMI and AOSI to ASD outcome, suggest that the SMI does capture unique variation relative to measures of social skills. This differentiation is noteworthy given strong intercorrelations for aspects of social behavior (Frazier et al., 2014; Marrus et al., 2020) and the theorized contribution of social motivation to the development of social communication abilities (Chevallier et al., 2012; Su et al., 2021). An important future direction to disambiguate social motivation from social skill includes integrating informant-based measures of real-world behavior with quantitative task-based measurements, such as eye-tracking, that can objectively index behavior in a controlled context designed to parse elements of social motivation (e.g., Vernetti et al., 2018). Applying social motivation metrics to populations with evidence for dissociation between social motivation and social cognition, such as children with William's Syndrome (Klein-Tasman et al., 2010), represents another approach to advance quantification of this construct.

Finally, we note that although the IBIS sample afforded a large dataset, replication to evaluate the consistency of our findings is warranted. Future studies would benefit from more diverse samples due to ASD's known heterogeneity, the sample's small number of ASD-affected females (consistent with ASD's 4:1 sex ratio), and the multiplex nature of the sample's HR+ cases, whose development might not generalize across all forms of ASD.

Conclusion

To our knowledge, this work describes the first example of a quantitative, dimensional approach to index social motivation, a heritable aspect of core ASD features, in infancy. The ability of parent report to detect associations between infant social motivation and later ASD highlights a translatable opportunity for novel social motivation measures to advance early detection, individualize intervention, and resolve developmental mechanisms of ASD.

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