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Visual configural processing in adults born at extremely low birth weight

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Abstract

Being born at extremely low birth weight (ELBW; ≤1,000 g) is associated with enduring visual impairments. We tested for long-term, higher order visual processing problems in the oldest known prospectively followed cohort of ELBW survivors. Configural processing (spacing among features of an object) was examined in 62 adults born at ELBW (M_{age} = 31.9 years) and 82 adults born at normal birth weight (NBW; ≥2,500 g: M_{age} = 32.5 years). Pairs of human faces, monkey faces, or houses were presented in a delayed match-to-sample task, where non-matching stimuli differed only in the spacing of their features. Discrimination accuracy for each stimulus type was compared between birth weight groups, adjusting for neurosensory impairment, visual acuity, binocular fusion ability, IQ, and sex. Both groups were better able to discriminate human faces than monkey faces ($p < .001$). However, the ELBW group discriminated between human faces ($p < .001$), between monkey faces ($p < .001$), and to some degree, between houses ($p < .06$), more poorly than NBW control participants, suggesting a general deficit in perceptual processing. Human face discrimination was related to performance IQ (PIQ) across groups, but especially among ELBW survivors. Coding (a PIQ subtest) also predicted human face discrimination in ELBW survivors, consistent with previously reported links between visuo-perceptive difficulties and regional slowing of cortical activity in individuals born preterm. Correlations with Coding suggested ELBW survivors may have used a feature-matching approach to processing human faces. Future studies could examine brain-based anatomical and functional evidence for altered face processing, as well as the social and memory consequences of face-processing deficits in ELBW survivors.

KEYWORDS

extremely low birth weight, extremely preterm, face-processing, perceptual development, second-order relations

1 | INTRODUCTION

Extremely premature birth provides a unique model for studying the effects of suboptimal intrauterine environments and early visual experience on visual processing. Being born preterm has been associated with enduring visual problems, including lower acuity, refractive errors, and central visual impairments (e.g., O'Connor et al., 2004; Powls, Botting, Cooke, Stephenson, & Marlow, 1997; Repka, 2002), even in the absence of retinopathy of prematurity (Larsson, Rydberg, & Holmström, 2005) and brain lesions commonly associated with preterm birth (Jongmans et al., 1996). The visual system is known to partially adapt to premature visual stimulation (showing accelerated ocular tracking and binocularity in preterm neonates vs. full-term controls, Jandó et al., 2012; Ricci et al., 2008), but the development of higher order visual skills (e.g. representation of action goals, Chaminade, Leutcher, Millet, & Deruelle, 2013), visuo-perceptual learning (Narberhaus et al., 2009), and human face recognition, (Cassia, Kuefner, Picozzi, & Vescovo, 2009) may be impaired. As the risk of adverse visual (e.g. Repka, 2002) and other neurological outcomes (Kapellou et al., 2006; Krägeloh-Mann & Cans, 2009) is inversely correlated with gestational age at birth, infants born extremely preterm or at extremely low birth weight (ELBW; ≤1,000 g) may be especially vulnerable to higher order visual impairments.

Normally, adults are proficient at recognizing personally familiar and famous human faces, despite poor lighting, distance, an unusual vantage point, altered contextual features such as hairstyle or glasses (Le Grand, Mondloch, Maurer, & Brent, 2001, 2003; Maurer, Grand, & Mondloch, 2002; Maurer et al., 2007; Mondloch, Grand, & Maurer, 2002; Mondloch, Maurer, & Ahola, 2006), and even vertical distortion of the face (Hole, George, Eaves, & Rasek, 2002). Adults' ability to learn new faces is associated with sensitivity to subtle differences in facial features and their spacing, and also the ability to process a face as a gestalt (Maurer et al., 2002, 2007; Richler, Mack, Gauthier, & Palmeri, 2009). Sensitivity to feature spacing develops slowly, becoming adult-like only in early adolescence (Campbell, Walker, & Baron-Cohen, 1995; Mondloch et al., 2002, 2006; Robbins, Shergill, Maurer, & Lewis, 2011). Visual deprivation for as little as 2 months after birth leads to permanent face-specific deficits in feature spacing sensitivity (Le Grand, Mondloch, Maurer, & Brent, 2001, 2003), while leaving sensitivity to feature-spacing in other stimuli intact (Robbins, Nishimura, Mondloch, Lewis, & Maurer, 2010).

Here we examined the opposite phenomenon—when visual input begins early because of premature birth. Reviews of individuals born very preterm (gestational age <32 weeks; birthweight ≤1,500 g) report medium-to-large impairments in visuospatial perception (Geldof, Wassenaer, Kieviet, Kok, & Oosterlaan, 2012; Ortibus, Cock, & Lagae, 2011) and a tendency to rely on information about features rather than spacing when performing complex matching or visuomotor tasks (Chaminade et al., 2013; Santos, Duret, Mancini, Busuttil, & Deruelle, 2010). Even when performance outcomes equal those of controls, adults born preterm activate different, likely compensatory, neural networks (Narberhaus et al., 2009). We hypothesized that similar tendencies would occur in adults born at ELBW.

Long-term effects of preterm birth on face processing were investigated by comparing adults in their early thirties who were born at ELBW to a demographically matched group of individuals born at normal birth weight (NBW; ≥2,500 g). Participants completed a delayed match-to-sample task involving human faces, less familiar non-human (monkey) faces, and non-face objects (houses). Non-matching stimuli differed from targets only in feature spacing. This paradigm has been validated previously in typically developing children and adults (Mondloch et al., 2006) and also cataract-reversal patients (Robbins et al., 2010).

Adult ELBW survivors were expected to discriminate human faces more poorly than NBW controls. We examined whether this deficit was specific to human faces, as observed in cataract-reversal patients (Robbins et al., 2010), or generalized to other classes of stimuli. If visual integration deficits secondary to ELBW were specific to human face processing, then discrimination of monkey faces and houses in ELBW survivors would be normal. Alternatively, if preterm birth affected general perceptual mechanisms, then ELBW survivors would show performance deficits for all three stimulus categories.

Research Highlights

- Individuals born extremely preterm and/or at extremely low birth weight (ELBW; ≤1,000 g) are at risk for enduring visual impairments.
- We tested for higher order visual processing deficits in adult ELBW survivors (age 29–35), using stimuli that differed only in the spacing of their features: human faces, monkey faces, and houses.
- Discrimination of human and monkey faces (and to some extent, houses) was poorer in ELBW survivors than in adults born at normal birth weight (NBW; ≥2,500 g).
- The ELBW deficit in face discrimination may be underpinned by decrements in Performance IQ and cognitive processing speed, secondary to extremely preterm birth.

Hierarchical regression models were used to identify predictive factors that may influence or explain visual discrimination performance in ELBW adults. These included fundamental characteristics such as sex, age, basic visual functioning, the presence of neurosensory impairment (NSI), and intellectual ability. In previous studies of this cohort, ELBW survivors have reported more visual problems (Saigal et al., 2007, 2016), greater likelihood of NSI (Saigal et al., 2016), and lower IQ levels (Saigal, Szatmari, Rosenbaum, Campbell, & King, 1991) than NBW controls, so analyses were adjusted for these factors.

2 | METHODS

2.1 | Participants

From a cohort of 397 infants born at ELBW between 1977 and 1982 in central-west Ontario, Canada (Saigal, Rosenbaum, Hattersley, & Milner, 1989), 179 survived to hospital discharge (45%). At birth, the survivors had completed 23–36 weeks' gestation (*median* = 27 weeks) and weighed 500–1,000 g, (M = 837 g). Some children died subsequently, leaving 166 who survived to young adulthood. Of these, 142 survivors participated at the assessment at age 22–26. One hundred and two ELBW survivors were located and participated in the most recent assessment at age 29–35 (61% of 166). Of these, 30 ELBW survivors with birth weights <10th percentile for gestational age were classified as small for gestational age (SGA; Kramer et al., 2001). The remaining 72 were born at an appropriate weight for gestational age (AGA). Twenty-seven ELBW participants had neurosensory impairments

(NSI). All participants in the current assessment completed questionnaires, but a number of them declined to participate in a full day of laboratory testing, leaving 65 ELBW survivors who participated in laboratory testing. Visual discrimination task data were missing for three of these participants. In all, 62 ELBW survivors performed the visual discrimination task, including 22 born at SGA and 7 with NSI.

A group of 145 participants born at NBW (*M* = 3,373 g), was recruited from local school boards and added to the cohort when children in both birth weight groups were 8 years old (Saigal et al., 1991). At that time, NBW controls were group-matched with the surviving ELBW children on age, sex, ethnicity, and familial SES. From these, 133 participated at the assessment at age 22–26. Ninety-four NBW adults were located and participated in the most recent assessment at age 29–35 (65% of 145). As several NBW controls opted not to come into the laboratory, laboratory test data were available for 85. Visual discrimination task data were missing from three of these participants, leaving 82 controls who performed the task. None of these were born SGA, and only one had NSI.

2.2 | Visual discrimination task

2.2.1 | Visual stimuli

Gray-scale digitized photographs of female human faces (Mondloch et al., 2002, 2006), monkey faces (Mondloch et al., 2006), and houses (Robbins et al., 2011) were presented in the visual discrimination task (Figure 1). Human models wore a surgical cap that covered their ears and hair, had a neutral facial expression, and wore no jewelry, glasses, or makeup. Each face or house was presented in five versions—a prototype with average spacing among features, and four altered versions. In the altered versions, the eyes were moved up or down (from average) by 0.95 *SD*, or closer together or farther apart by 2.60 *SD*, and the mouth was simultaneously moved up or down by 1.06 *SD* (Mondloch et al., 2002). These variations are within normal limits for human faces (Farkas, 1981). Spacing variations for monkey faces were identical to those for human faces, in keeping with previous studies (Mondloch et al., 2006; Robbins et al., 2010). Houses were modified by repositioning the upper and lower windows. Because adults are less sensitive to spacing differences in houses, the absolute spacing variations for houses were four times as large as those for faces. House dimensions used here were determined in previous work by calibrating adults' accuracy for houses to match that of faces (77%) (Robbins, Shergill, Maurer, & Lewis, unpublished data; Robbins et al., 2010; Robbins et al., 2011). The average size of the human face stimuli presented on screen was 16 cm height × 11 cm width (9.1° × 6.3° from a testing distance of 100 cm). The average size of the monkey face stimuli was 19.5 cm height × 18.5 cm width (11.1° × 10.6°). The average size of the house stimuli was 18 cm height × 12.5 cm width (10.3° × 7.1°).

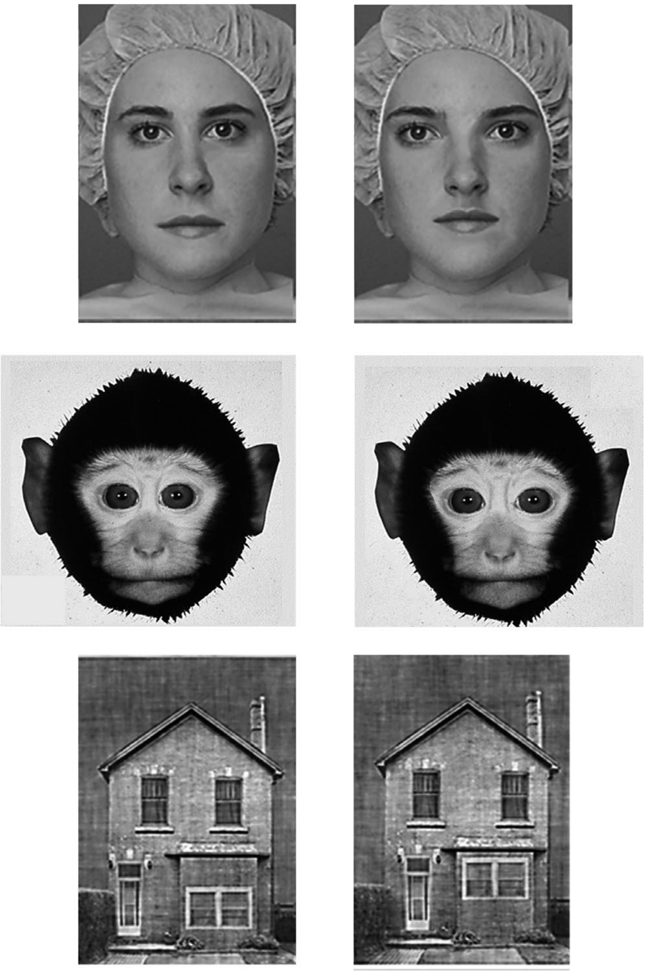


FIGURE 1 Examples of the spacing stimuli used in the visual discrimination task. Notes: The largest differences in spacing within each set of items are shown. Spatial frequency amplitude was matched across houses to ensure that participants could not exploit contrast differences to aid in recognition (Robbins et al., 2011)

Sensitivity to feature spacing (a type of configural processing) was examined in a delayed match-to-sample test (Mondloch et al., 2002) supplied by the Visual Development Laboratory at McMaster University. This experimental task was presented on a MacIntosh MacPro3.1 computer with Mac OSX Version 10.5.4, in SuperLab Pro 4.5. Stimuli were displayed on a 20" Dell Trinitron monitor (vertical refresh rate: 75 Hz; screen resolution: 1,024 × 768 pixels). Each block was preceded by a brief presentation of the five spacing arrangements for that category, so participants could see the range of variation across stimuli. For each trial, a fixation cross was displayed until the participant pressed the space bar. A test face (or house) appeared in the center of the computer screen for 1,000 ms, followed immediately by two images that remained on the screen until the participant responded. One image matched the test stimulus; the other differed in feature spacing. Participants were asked to indicate whether the matching stimulus was on the left or right side of the screen, as quickly and accurately as possible, by pressing a key. Each of five test stimuli was paired with every other stimulus twice, once with the match on the left and again on the right, to yield 40 trials per stimulus category. Stimuli were presented in blocks of human faces, houses, and monkey faces, in that order. Identification accuracy was assessed as the proportion of correctly identified faces or objects for each stimulus type.

2.2.2 | Procedure

Participants were tested individually in the laboratory, after providing written consent. The study protocol received clearance from the McMaster University Health Research Ethics Board. Monocular tests of linear visual acuity were administered using a Lighthouse Visual Acuity Chart (Lighthouse International) at 4 m. The best-corrected visual acuity for each eye was reported in relative distance for each participant (e.g. 20/20, 20/50). Higher scores in the denominator indicate poorer acuity. The Worth Four Light Test (Richmond Products) was administered to assess clinically normal binocular fusion (i.e., whether participants reported seeing 4/4 lights while wearing a red filter on one eye and a green filter on the other eye).

2.3 | Factors that may influence visual discrimination performance

2.3.1 | Vision perception

Monocular tests of visual acuity (Lighthouse Chart), and binocular fusion (Worth Four Light Test), were administered to assess fundamental aspects of visual perception. Binocular fusion was scored as the presence of normal versus abnormal fusion (suppression of one eye, diplopia (double vision), or alternating suppression of each eye).

2.3.2 | Intellectual ability

Ten subtests from the Wechsler Intelligence Scale for Children, Revised (WISC-R; Wechsler, 1974, had been administered at age 8 to assess verbal IQ (VIQ) and performance IQ (PIQ). Intelligence is thought to be an enduring personal trait (Fry & Hale, 2000), such that adult IQ measures correlate significantly with childhood measures in both individuals born at NBW (e.g. $r = .62–.70$), and those born very preterm ($r = .74$; Breeman, Jaekel, Baumann, Bartmann, & Wolke, 2015; Fagan, Holland, & Wheeler, 2007). Here, VIQ and PIQ scores were analyzed separately (vs. Full Scale IQ) in order to assess performance deficits in participants with normal verbal abilities, or the reverse.

2.4 | Statistical analyses

First, we examined the representativeness of sample participants versus non-participants in each birth weight group, using t tests or χ^2. Differences in sample characteristics between birth weight groups then were assessed using t tests or χ^2. Visual discrimination performance (the percentage of correct responses for each stimulus category) was calculated for each participant.

Means and standard deviations differed by stimulus category, therefore the percentage of correct responses for each stimulus type was entered in a 3 (stimulus category: human faces, monkey faces, houses) by 2 (birth weight group: ELBW, NBW) ANOVA. To identify factors predicting visual discrimination performance, accuracy was examined in separate hierarchical regression analyses for each stimulus category. Analyses were adjusted for birth weight group, sex, NSI (present/absent), visual acuity in the better eye, binocular fusion (normal/abnormal), and intellectual ability (PIQ, VIQ). Precise gestational ages at birth were unavailable for NBW controls. Analyses were not adjusted for differential effects of SGA status, as this factor was collinear with birth weight group ($r = .93$).

Continuous variables were centered prior to analysis. Covariates on the first step were followed by birth weight group on the second step, two-way interactions with birth weight group on the third step, and three-way interactions with group on the fourth step. Significant interactions were interpreted in follow-up analyses.

3 | RESULTS

Demographic data for 102 ELBW and 94 NBW participants and 77 and 51 non-participants, respectively, are presented in Table 1. (Demographic data for the cohort as a whole are available in Supplemental Table S1). In both birth weight groups, participants were somewhat higher-functioning than non-participants. ELBW participants had higher VIQ, $t(135) = 2.34$, $p < .03$, but lower familial socioeconomic status (SES), $t(154) = −3.23$, $p < .01$, than non-participants. They were also more likely to be female $\chi^2_{(179)} = 4.31$, $p < .04$, OR = 1.88 (95% CI = 1.03, 3.43), but did not differ from non-participants on other demographic variables, all $p > .05$. NBW participants had higher VIQ, $t(143) = 2.38$, $p < .02$, and PIQ, $t(140) = 2.03$, $p < .05$, but lower familial socioeconomic status (SES), $t(143) = −2.06$, $p < .05$, than non-participants. They were also more likely to be female, $\chi^2_{(145)} = 4.08$, $p < .05$, OR = 2.03 (95% CI = 1.02, 4.06) but did not differ from non-participants on other demographic variables, all $p > .24$.

In comparisons across birth weight groups, ELBW participants were more likely than NBW participants to report NSI, $\chi^2_{(196)} = 25.79$, $p < .001$, OR = 33.48 (95% CI = 4.45, 252.13), and less likely to demonstrate normal binocular fusion, $\chi^2_{(147)} = 20.78$, $p < .001$, OR = 0.14 (95% CI = 0.06, 0.35). ELBW control participants had lower levels of visual acuity, $t(147) = 3.31$, $p < .01$, VIQ, $t(183) = −4.99$, $p < .001$, and PIQ, $t(180) = −6.08$, $p < .001$, than NBW participants, and were slightly younger (32.1 vs. 32.5 years), $t(194) = −1.92$, $p < .06$. Sex distribution, $p > .90$, and familial SES, $p > .35$, were similar in ELBW and NBW participants. Individuals with NSIs were not specifically excluded from any analysis.

All participants demonstrated understanding of the match-to-sample task by achieving an average score >50% across the three domains. Since we were interested in examining performance variability within the full range of performance for each group and across groups, all scores were retained.

TABLE 1 Demographic information by group

	ELBW participants $n = 102$	NBW participants $n = 94$	ELBW non-participants $n = 77$	NBW non-participants $n = 51$	*p* Value ELBW versus NBW	*p* Value ELBW participants versus Non-participants	*p* Value NBW participants versus Non-participants
Birth Weight; g, *m (SD)*	832 (132)	3,407 (464)	844 (111)	3,309 (530)	<.001	.505	.251
Gestation; weeks; *median* (range)	27 (23–36)	Term	27 (23–36)	Term	<.001	.353	—
Male Sex; *n* (%)	41 (40)	37 (39)	43 (56)	29 (57)	.905	.038	.043
SGA; *n* (%)	30 (29)	0 (0)	13 (17)	0 (0)	<.001	.052	—
NSI; *n* (%)	27 (27)	1 (1)	24 (31)	2 (4)	<.001	.491	.248
Familial SES at age 8; *m (SD)*	3.1 (0.9)	3.0 (1.0)	3.6 (1.0)	3.3 (1.0)	.369	.002	.041
PIQ at age 8; *m (SD)*	94.8 (17.0)	108.2 (12.2)	92.4 (16.6)	104.0 (11.3)	<.001	.437	.045
VIQ at age 8; *m (SD)*	92.9 (15.1)	103.1 (12.7)	86.5 (15.3)	97.9 (12.9)	<.001	.021	.019
Current Age in years; *m* (range)	32.1 (29.0 to 35.9)	32.5 (30.0 to 34.9)	—	—	.057	—	—

Notes: Abbreviations: NSI, neurosensory impairment; PIQ, Performance IQ; SGA, small for gestational age; SES, socioeconomic status, where category 1 is high; VIQ, Verbal IQ. Data from the adult assessment (age 29–35) were available for 102/179 participants born at ELBW and 94/145 participants born at NBW. Data missing from the childhood assessment (age 8) resulted in lower *ns* for ELBW SES ($n = 97$), PIQ ($n = 89$), and VIQ ($n = 91$), and for NBW PIQ ($n = 93$). SGA and NSI status were determined at birth.

3.1 | Visual discrimination task performance

Sample-wide distributions of scores were normal for monkey faces and approximately normal for human faces and houses. (Table S2 and Figure S1). A house score was missing for one NBW control, and a human faces score was missing for another NBW control. A few participants in each group failed to complete the monkey task. However, proportions of participants without monkey face scores were the same for ELBW ($n = 6$) and NBW ($n = 9$) participants, $\chi^2_{(145)} = 0.05$, $p > 0.80$, OR = 1.14 (95% CI = 0.38, 3.38), suggesting the groups did not differ in motivation levels, persistence, or effort.

Results from the principal ANOVA are presented in Table 2. Mean accuracy across the three task domains was 75% ($SD = 10.3$) for ELBW participants and 82% ($SD = 8.1$) for NBW participants. ELBW survivors made fewer correct responses than NBW controls, $F(1, 126) = 20.27$, $p < .001$, $\eta^2 = .14$, with no interaction, $p > .19$. NBW control participants discriminated human faces, $t(142) = 4.06$, $p < .001$, monkey faces, $t(128) = 3.84$, $p < .001$, to a lesser extent, houses, $p < .06$, more accurately than did ELBW survivors (Table 2 and Figure 2). Accuracy also differed by stimulus category, $F(2, 252) = 160.63$ $p < .001$, $\eta^2 = 0.56$. Accuracy for houses was greater than for human faces, $p < 0.04$, which in turn was greater than for monkey faces, $p < .001$, in pairwise tests. Both main effects remained significant in a second ANOVA from which individuals with NSI were removed, $p < .001$. There was no interaction, $p > .17$.

3.2 | Hierarchical regression analyses

Results from hierarchical regression analyses for each visual stimulus category are presented in Table 3. To capture variability across the sample, scores from each stimulus category were analyzed separately.

3.2.1 | Human face discrimination

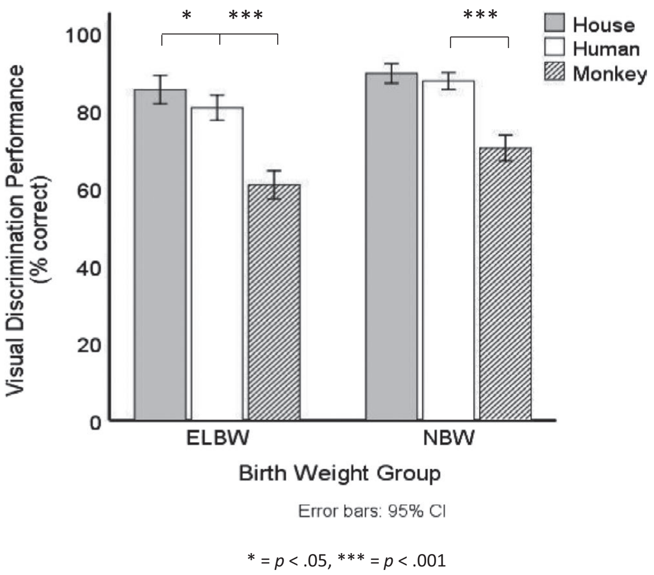
Together, the covariates from step 1 (IQ measures, visual acuity, fusion, NSI, and sex) were associated with human face discrimination, F-change $(6, 127) = 4.75$, $p < .001$. Within this step, higher PIQ ($B = 0.20$, $p < .02$) predicted significantly better discrimination of human faces. Discrimination was unrelated to visual acuity, $p > .65$. At step 2, birth weight group added significantly to the prediction, F-change $(1, 126) = 8.85$, $p < .01$. ELBW survivors discriminated between human faces more poorly than did NBW controls ($B = 5.84$, $p < .01$). Two-way interactions did not improve the prediction, $p > .55$, but together the three-way interactions added to predictions of human face discrimination, F-change $(4, 116) = 3.12$, $p < .02$. Within this step, PIQ interacted with group and either NSI, $p < .01$, or fusion, $p < .01$. The three-way interaction with VIQ and fusion (but not NSI, $p > .09$) also reached significance, $p > .03$. In all, this model accounted for 34% of the variance in discriminating human faces.

The three-way interactions were probed by repeating the same regression analysis separately for each birth weight group. Among ELBW survivors, PIQ (but not VIQ) accounted for significant variance

TABLE 2 Descriptive statistics for visual discrimination scores by group and stimulus class

	N	Median	Range	Mean (*SD*) % correct	Variance	Skewness (*SE*)
Sample						
Houses	144	90.00	45.0–100.0	87.38 (12.41)	154.05	−1.78 (0.20)
Human faces	144	85.00	45.0–100.0	84.27 (11.64)	135.48	−1.08 (0.20)
Monkey faces	130	67.50	37.5 – 97.5	66.08 (14.46)	209.10	−0.02 (0.21)
ELBW						
Houses	62	90.00	45.0–100.0	85.00 (14.24)†	202.66	−1.47 (0.30)
Human faces	62	82.50	45.0–97.5	79.80 (12.87)***	165.64	−0.69 (0.30)
Monkey faces	56	58.75	37.5–87.5	60.76 (13.32)**	177.48	0.34 (0.32)
NBW						
Houses	82	92.50	50.0–100.0	89.18 (10.57)†	111.74	−2.03 (0.27)
Human faces	82	90.00	50.0–100.0	87.65 (9.36)***	87.55	−1.35 (0.27)
Monkey faces	74	71.25	37.5–97.5	70.10 (14.06)**	197.68	−0.33 (0.28)

Notes: Group differences were identified by independent sample *t* tests.
$^{***}p < .001$, $^{**}p < .001$, $^{\dagger}p < .06$.



Error bars: 95% CI

* = *p* < .05, *** = *p* < .001

FIGURE 2 Visual discrimination performance for adult ELBW participants and NBW control participants by stimulus category. *N* = 128 (56 ELBW)

as a main effect (11%; $B = 0.36$, $p < .01$). PIQ also interacted with NSI ($B = 1.02$, $p < .02$) and marginally with fusion ($p < .08$) in predicting performance. This model accounted for 38% of the variance in discrimination of human faces.[1] Probing the two-way interactions further revealed an effect of PIQ on human face discrimination in ELBW survivors with normal fusion ($B = 0.41$, $p < .03$), and perhaps without NSI ($B = 0.26$, $p < .061$).

Among NBW controls, PIQ interacted with fusion ($B = −0.65$, $p = .05$) to predict human face discrimination, but no other predictors reached significance, all $p > .055$. The NBW model accounted for only 13% of the variance in human face discrimination. No predictors reached significance in NBW controls with normal fusion (all $p > .07$), but in NBW controls with abnormal fusion, acuity predicted human face discrimination ($B = 4.82$, $p < .04$).

3.2.2 | Monkey face discrimination

The covariate step also predicted monkey face discrimination, *F*-change (6, 115) = 2.20, $p < .05$. Within this step, only fusion ($B = −10.45$, $p < .01$), predicted performance. Birth weight group on step 2 added significantly to the prediction of monkey face discrimination, *F*-change (1, 114) = 11.04, $p < .01$, indicating that ELBW survivors discriminated monkey faces more poorly than did NBW controls ($B = 9.31$, $p < .01$). None of the interaction terms was significant, all $p > .18$. This model accounted for 22% of the variance.

3.2.3 | House discrimination

Only fusion was a significant predictor of house discrimination ($B = −6.23$, $p < .04$); all other $p > .12$. This model accounted for 12% of the variance in of house discrimination scores.

3.3 | Correlations between IQ subtests and visual discrimination performance

Independent sample *t* tests revealed that NBW participants had higher performance scores than ELBW participants on all the WISC-R subtests (all $p < .02$), except General Information and Vocabulary ($p > .07$; data not shown). To examine visual discrimination performance in relation to particular aspects of IQ, human, monkey, and house discrimination scores were submitted to post hoc correlational analyses with scores from each of the WISC-R subtests (PIQ, Coding, Block Design, Picture Completion, Picture Arrangement, and Object Assembly; VIQ, General Information, Verbal Similarities, Arithmetic, Vocabulary, and

TABLE 3 Hierarchical regression analysis summaries of human face, monkey face, and house discrimination performance on birth weight group, IQ scores, visual acuity in the better eye, fusion, neurosensory impairment (NSI), and sex

Variable	R^2	*F*Δ	*df*	*B*	*SE*	sr^2
Human faces *N* = 134 (55 ELBW)						
Step 1	.18	4.75***	6, 127			
PIQ				0.20*	0.08	.04
VIQ				−0.10	0.08	.01
Acuity				0.06	0.13	<.01
Fusion				−5.86*	2.56	.03
NSI				−5.37	4.17	.01
Sex				2.86	1.87	.02
Step 2	.24	8.85**	1, 126			
Birth weight group				5.84**	1.96	.05
Step 3	.27	0.82	6, 120			
PIQ × Group				−0.24	0.16	.03
VIQ × Group				0.07	0.17	<.01
Acuity × Group				−0.05	0.29	<.01
Fusion × Group				−0.46	5.47	<.01
NSI × Group				16.04	11.36	.01
Sex × Group				−1.17	3.73	<.01
Step 4	.34	3.12*	4, 116			
PIQ × NSI × Group				0.90**	0.34	.04
VIQ × NSI × Group				−0.55	0.33	.02
PIQ × Fusion × Group				−0.39**	0.15	.04
VIQ × Fusion × Group				0.36*	0.16	.03
Monkey Faces *N* = 122 (51 ELBW)						
Step 1	.10	2.20*	6, 115			
PIQ				0.16	0.12	.01
VIQ				−0.03	0.12	<.01
Acuity				0.28	0.18	.02
Fusion				−10.45**	3.70	.06
NSI				3.16	6.03	<.01
Sex				−1.20	2.67	<.01
Step 2	.18	11.04**	1, 114			
Birth weight group				9.31**	2.80	.08
Step 3	.20	0.32	6, 108			
PIQ × Group				−0.10	0.24	<.01
VIQ × Group				0.06	0.25	<.01
Acuity × Group				0.29	0.40	<.01
Fusion × Group				3.53	8.35	<.01
NSI × Group				9.57	15.74	<.01
Sex × Group				−2.88	5.31	<.01
Step 4	.22	0.65	4, 104			
PIQ × NSI × Group				0.67	0.50	.01
VIQ × NSI × Group				−0.58	0.52	.01
PIQ × Fusion × Group				−0.07	0.24	<.01
VIQ × Fusion × Group				0.23	0.27	.01

(Continues)

TABLE 3 (Continued)

Variable	R^2	$F\Delta$	df	B	SE	sr^2
Houses N = 134 (55 ELBW)						
Step 1	.07	1.63	6, 127			
PIQ				0.12	0.09	.01
VIQ				−0.03	0.10	<.01
Acuity				0.01	0.15	<.01
Fusion				−6.23*	2.97	.03
NSI				0.02	4.84	<.01
Sex				0.01	2.16	<.01
Step 2	.08	1.16	1, 126			
Birth weight group				2.52	2.34	.01
Step 3	.09	0.27	6, 120			
PIQ × Group				0.07	0.19	<.01
VIQ × Group				−0.12	0.20	<.01
Acuity × Group				0.16	0.35	<.01
Fusion × Group				5.55	6.62	.01
NSI × Group				1.34	13.74	<.01
Sex × Group				−1.47	4.52	<.01
Step 4	.12	1.00	4, 116			
PIQ × NSI × Group				0.45	0.43	.01
VIQ × NSI × Group				−0.43	0.41	.01
PIQ × Fusion × Group				−0.02	0.19	<.01
VIQ × Fusion × Group				0.31	0.20	.02

Abbreviations: PIQ, Performance IQ; VIQ, Verbal IQ; NSI, neurosensory impairment.
***$p < .001$, **$p < .01$, *$p < .05$.

Verbal Comprehension). In ELBW survivors, PIQ and each of the PIQ subtests were positively correlated with human face discrimination, all $p < .05$. (Table 4). Notably, the correlation between PIQ and human face discrimination scores was stronger in ELBW survivors than NBW controls, $Z = 2.04$, $p < .05$, two-tailed. (Figure 3a vs. 3b). Coding ability also tended to predict human face discrimination more closely in ELBW survivors, $Z = 1.38$, $p < .09$, one-tailed. (Figure 4a vs. 4b). Within the ELBW group, Coding was more closely associated with discrimination of human faces than with houses, $Z = 2.47$, $p < .02$, two-tailed (Figure 4a vs. 4c). In the control group, Coding was not associated with either human faces or houses ($Z = .24$). Among NBW controls, Object Assembly was positively correlated with human face discrimination ($p < .01$), and Block Design with discrimination of houses ($p < .03$). There were no associations with VIQ or any of the VIQ subtests in either group (all $p > .05$), except in the ELBW group, where Verbal Similarities predicted discrimination of houses ($p < .03$).

4 | DISCUSSION

Adult ELBW participants were less proficient than group-matched adults born at NBW in using feature spacing to discriminate between human faces and between monkey faces. This pattern of performance suggested an inability to distinguish between individual faces—whether human or monkey—on the basis of the spacing among their internal features. Together with marginally poorer ELBW discrimination of houses, the findings suggest that a general perceptual mechanism may have been affected by extremely preterm birth.

As a group, ELBW survivors possessed several a priori disadvantages—lower visual acuity, lower IQ scores, more neurosensory impairments and abnormal binocular fusion. Group differences in visual acuity accounted for little variance in face processing, consistent with the notion that human face discrimination involves higher order visual integration processes (Maurer et al., 2007; see also Le Grand, Mondloch, Maurer, & Brent, 2001; Le Grand, Mondloch, Maurer, & Brent, 2003). In contrast, PIQ predicted visual discrimination of human faces across groups, and particularly among ELBW participants with normal fusion and without NSI. Among the PIQ subtests, Coding ability strongly predicted discrimination of human faces but not houses in ELBW survivors, whereas in NBW controls, Coding was poorly associated with both human faces and houses. Given the propensity of individuals born preterm to rely on featural rather than spatial information for processing complex stimuli (Chaminade et al., 2013; Santos et al., 2010), ELBW survivors may have resorted to feature-matching to discriminate human faces. Like

TABLE 4 Zero-order correlations (*r*) between IQ measures and visual discrimination performance by group and task domain

	ELBW Score (*n*)			NBW Score (*n*)		
	Human	Monkey	House	Human	Monkey	House
PIQ	.49*** (59)	.30* (54)	.27* (59)	.17 (81)	.14 (73)	.14 (81)
Coding	.38** (56)	.27 (50)	−.07 (56)	.16 (81)	.01 (73)	.12 (81)
Block Design	.40** (60)	.16 (54)	.25 (60)	.20 (82)	.16 (74)	.24* (82)
Picture Arrangement	.30* (60)	.19 (54)	.40** (60)	−.03 (82)	.06 (74)	.06 (82)
Picture Completion	.26* (60)	.15 (54)	.14 (60)	.01 (82)	.09 (74)	−.04 (82)
Object Assembly	.43** (60)	.29* (54)	.25 (60)	.29** (82)	.20 (74)	.01 (82)
VIQ	.18 (60)	.10 (54)	.23 (60)	−.02 (82)	.04 (74)	−.03 (82)
Information	.17 (60)	.10 (54)	.25 (60)	−.08 (82)	.08 (74)	−.14 (82)
Similarities	.20 (60)	.17 (54)	.29* (60)	.06 (82)	−.05 (74)	.04 (82)
Arithmetic	.12 (60)	.23 (54)	.20 (60)	−.01 (82)	.16 (74)	.01 (82)
Vocabulary	.17 (60)	−.06 (54)	.13 (60)	.04 (82)	−.01 (74)	<.01 (82)
Comprehension	−.01 (59)	−.05 (53)	−.01 (59)	−.10 (82)	−.02 (74)	.02 (82)

***$p < .001$, **$p < .01$, *$p < .05$.

Coding, feature-matching requires rapid one-to-one matching of discrete stimuli. Evidence of group differences in the correlations linking Coding ability and discrimination of human faces suggests that processing speed may be more important for discriminating human faces than houses. Human faces are generally more salient than houses, and therefore more likely than houses to elicit complex cognitive computations, including feature-matching. Presumably, faces are salient for NBW controls as well, but control adults probably assessed human faces holistically, as gestalts (Maurer et al., 2002; Richler et al., 2009). The differential use of holistic processing versus feature-matching may explain the between-groups dissociation in correlations with Coding.

In contrast to Coding, Object Assembly scores predicted better discrimination of human faces in both birth weight groups. These correlations suggested that the abilities to visualize and perceptually construct common objects (in this case, faces) predicted human face discrimination equally well in both groups.

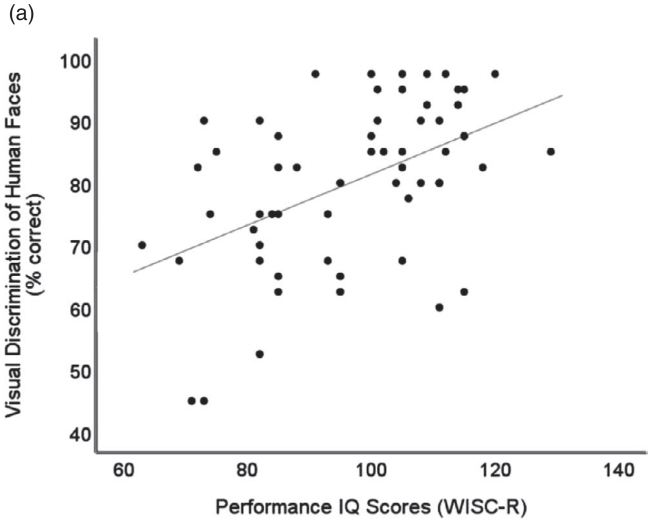
ELBW performance was also normative in at least one other important respect. Like their NBW counterparts, ELBW survivors were significantly more accurate at identifying human faces—stimuli with which they had had extensive experience—than monkey faces, which they had encountered only rarely (Mondloch et al., 2006; Robbins et al., 2010). Thus, both groups demonstrated superior discrimination of human faces over monkey faces (20%–25% differences; group difference, $p > .30$), and compared well to those of other, visually normal adults (9% difference) (Mondloch et al., 2006). Premature exposure to visual stimuli in infancy had not eliminated the benefits of a lifetime of experience with human faces.

This pattern of results is reminiscent of previous findings in 8-year-old children. Eight-year-olds typically make more errors than adults in discriminating human faces (Mondloch et al., 2006), monkey faces (Mondloch et al., 2006), and houses (Robbins et al., 2011), but still achieve higher accuracy for human faces than for the other two categories. Thus, both 8-year-olds (Kobayashi, Cassia, Kanazawa, Yamaguchi, & Kakigi, 2018; Pascalis, Haan, & Nelson, 2002) and adult ELBW survivors show evidence of perceptual narrowing in the absence of normal, adult-like performance.

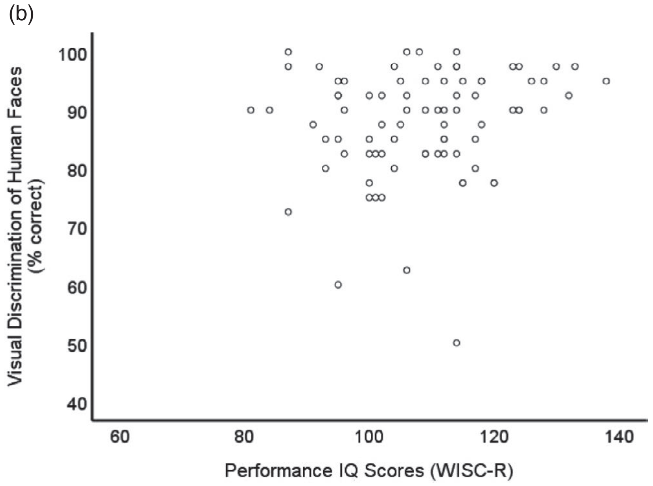
The face-processing literature has suggested that two factors may underlie adults' sensitivity to feature spacing: a domain-general discrimination mechanism that can be applied to monkey faces or houses as well as human faces (Mondloch et al., 2006; Robbins et al., 2010), and a domain-specific mechanism that depends on early visual experience, by which the neural architecture for processing human faces is set up or preserved (Le Grand et al., 2001, 2003). In congenital cataract patients, the domain-specific mechanism for discriminating human faces is impaired due to early visual deprivation, whereas the domain-general mechanism appears to develop well despite missed early visual experience (Mondloch et al., 2006; Robbins et al., 2010). Conversely, in ELBW survivors, the domain-specific sensitivity to human faces appears to be comparatively well-developed, whereas a more general discrimination mechanism is impaired with respect to faces (human and monkey, and to a lesser extent, houses). In adults aged 29–35, this more general impairment could not be a function of developmental stage (as in 8-year-olds). Instead, we propose that the general impairment may reflect differences in brain function that are secondary to extremely preterm birth.

4.1 | A potential role for processing speed in face discrimination

In later versions of the WISC, Coding ability is one of three subtests that contribute to a cognitive index of processing speed (e.g. WISC-III; Kezer & Arik, 2012). In several theoretical accounts of developing intelligence, processing speed is integral to



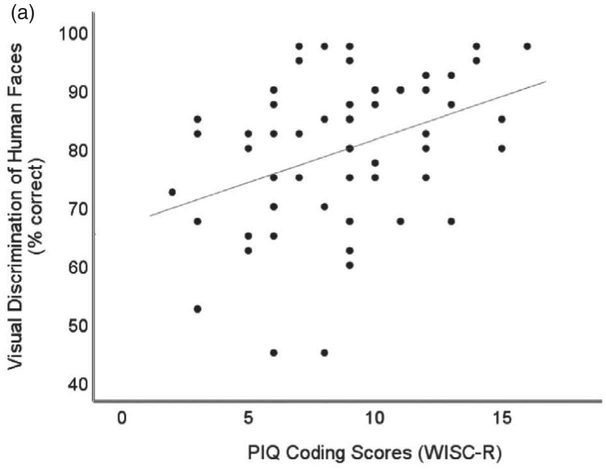
ELBW: *r*(59) = .485, *p* < .001



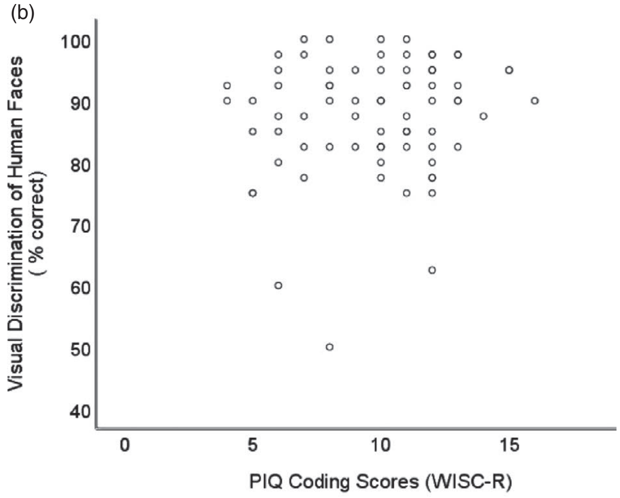
NBW: *r*(81) = .171, *p* > .12

Z = 2.04, *p* < .05, two-tailed

FIGURE 3 Associations between WISC-R PIQ scores and human face discrimination in (a) adults born at ELBW, and (b) adults born at NBW

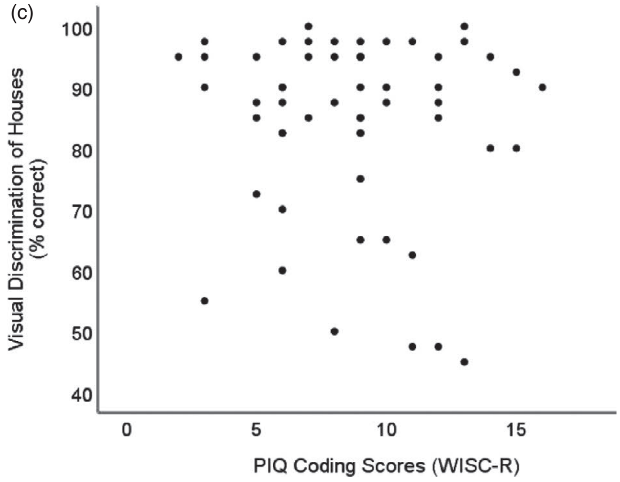


ELBW: *r*(56) = .384, *p* < .01



NBW: *r*(81) = .157, *p* > .16

Z = 1.38, *p* < .09, one-tailed



ELBW: *r*(56) = -.074, *p* > .55

Z = 2.47, *p* < .02, two-tailed

FIGURE 4 Associations between WISC-R PIQ Coding subtest scores and human face discrimination in (a) adults born at ELBW, and (b) adults born at NBW. (c) Association between WISC-R PIQ Coding subtest scores and discrimination of houses in adults born at ELBW

working memory capacity, and through working memory, to reasoning skills, (e.g. Fry & Hale, 1996; Kail, 2007; Kail & Salthouse, 1994; Nettelbeck & Burns, 2010). Relatively slower processing speeds result in slower cognitive operations, poorer synchronization among task components, and less efficient decision making (Nettelbeck & Burns, 2010).

Normal adult face-processing expertise entails being able to identify individual faces that are presented only briefly—"at a glance" (Maurer et al., 2007; Richler et al., 2009). In the present task, faces were presented for 1,000 ms. Since adults born at NBW were well able to identity human faces (88%–90% correct), these stimulus presentation times were wholly adequate for typically developing adults. However, processing speed is one of the cognitive domains most at risk in individuals born very preterm (Anderson & Doyle, 2003; Butcher et al., 2012; Doesburg, Moiseev, Herdman, Ribary, & Grunau, 2013). Specifically, visuo-perceptive difficulties in preterm survivors have been linked to regional slowing of cortical activity in visual perception areas and frontal brain regions (Doesburg et al., 2013). In turn, slower cognitive processing speeds are known to contribute to differential IQ scores in this population (Butcher et al., 2012; Rose, Feldman, Jankowski, & Rossem, 2011). Within the face-processing literature, poor visual discrimination of faces has been attributed to encoding inefficiency and memory limitations commensurate with immaturity (Mondloch, Dobson, Parsons, & Maurer, 2004). In the present adult sample, the source of encoding inefficiency could not have been chronological immaturity, but rather, may have been slow processing speed.

4.2 | A potential role for altered cortical development

Like any computationally demanding visual task (e.g. Braddick, Atkinson, & Wattam-Bell, 2003; Santos et al., 2010; Taylor, Jakobson, Maurer, & Lewis, 2009), visual discrimination of human faces is a multistage process that evokes neural activity well beyond extrastriate regions (Maurer et al., 2007). Proficient face discrimination depends in part on efficient cognitive computation and communication among brain regions. Researchers posit that premature transition to the extrauterine environment during a period of rapid brain growth is conducive to diffuse brain injuries that alter neural connectivity and brain development (Kapellou et al., 2006; Nosarti et al., 2008; Volpe, 2009). Indeed, previous studies of preterm groups have linked long-term impairments in visuospatial reasoning ability to subtle alterations in cortical development in this population (Narberhaus et al., 2008; Nosarti et al., 2008; Volpe, 2009). Because the detrimental effects of preterm birth on brain development increase with shorter gestation (Kapellou et al., 2006; Krägeloh-Mann & Cans, 2009), adults born at ELBW are likely to accrue greater risks to higher order perceptual abilities such as visuospatial processing and object recognition, relative to groups born less premature (Narberhaus et al., 2009). Therefore, we hypothesize that altered cortical development in adult ELBW survivors may contribute to lower processing speed and PIQ in this group, with adverse effects on rapid discrimination of human faces, and potentially, other forms of complex visual processing.

4.3 | Strengths and limitations

This study is the first known to report differential discrimination of human faces in a prospectively followed adult ELBW cohort from a geographically defined region. Although well-established visual tests do not typically measure perception of faces, objects, scenes, or motion (Geldof et al., 2012; Ortibus et al., 2011), it is difficult to appreciate the nature of visual perceptive deficits in special populations without these kinds of tests. Our study of visual discrimination in ELBW survivors partially addresses this literature gap. In future studies, researchers could examine the implications of generalized perceptual discrimination deficits to face-learning, and to recognition of individual faces with which the person has extensive experience.

We acknowledge that our sample was limited by the original cohort size, high mortality, and three decades of attrition. Attrition is a common problem in longitudinal studies, particularly ones that extend across four decades. Despite these issues, the sample was large enough to reveal consistent differences between birth weight groups in task performance, IQ scores, visual acuity, and binocular fusion, as well as differential associations among these variables. Replication in larger cohorts or collaborative studies would be helpful for sorting out a variety of influences on visual integration deficits following extremely preterm birth.

A second limitation was the time span between the exposure of interest (preterm birth) and the measurement of adult outcomes. As well, the only available measures of IQ were derived from childhood tests. Nonetheless, intelligence is assumed to be an enduring individual trait (Fry & Hale, 2000), and the face-processing deficits reported here are unlikely to appear, de novo, in adulthood. These deficits align with a continuum of decrements affecting preterm populations beginning in early life: differences in higher order visuospatial processing have been documented in infants (Frie, Padilla, Ådén, Lagercrantz, & Bartocci, 2016; Rose, Feldman, & Jankowski, 2009), children (Butcher et al., 2012; Doesburg et al., 2013; Santos et al., 2010; Taylor et al., 2009), adolescents (Rose et al., 2011) and adults (Chaminade et al., 2013) born very preterm, suggesting that the effects of preterm birth on visuospatial processing encompass the whole developmental trajectory.

Finally, these data do not address the issue of deliberate strategies used during task performance. A speed-accuracy trade-off in ELBW participants cannot be ruled out, as response times were not available. This possibility is unlikely, though, as lower PIQ in preterm survivors has been associated with both reduced accuracy and slower response speeds in other visuospatial tasks (Butcher et al., 2012). To date, this task has successfully discriminated between adults and children (Mondloch et al., 2006; Robbins et al., 2011) and between cataract-reversal patients and normal controls (Mondloch et al., 2006; Robbins et al., 2010). However, differential response times during face processing should be tested in future studies to determine whether faces elicit group differences in cognitive or scanning strategies.

A puzzle in the interpretation is the abnormal performance of ELBW survivors for monkey faces, given near-normal discrimination for houses (suggesting normal sensitivity to spacing) and the expected superior performance for human over monkey faces (suggesting normal experience-dependent sensitivity). Poorer discrimination of both monkey faces and human faces suggests a deficit that is closely related to face processing, regardless of whether the faces represent an experienced category or not. One possibility is that monkey faces, unlike houses, are recognized as faces and hence trigger specialized face-processing mechanisms (Taubert, 2009). Future studies using neural markers specific to faces would be useful in evaluating this possibility (e.g. the N170/N250 ERP complex, or brain imaging of fusiform and frontal brain regions). The marginal group difference reported for houses also should be re-examined in a larger sample.

5 | CONCLUSIONS

Like NBW control adults, adult ELBW survivors were better able to discriminate human faces than monkey faces, suggesting ELBW survivors were not impaired in abilities that depended on extensive experience with human faces. Overall, however, they were significantly less accurate than NBW control adults in discriminating between individual human faces and between individual monkey faces on the basis of the spacing among their features. This general deficit in face discrimination may be underpinned by decrements in PIQ and cognitive processing speed that are secondary to extremely preterm birth. Documenting functional and anatomical evidence of altered brain development in ELBW survivors may shed additional light on the etiology of face-processing difficulties and other high-level visual processing problems following preterm birth. The social and memory consequences of face-processing deficits also merit investigation in future studies.

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DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ENDNOTE

[1] *Analyses with IQ and Birth Weight*: To avoid reliance on an over-fitted model, additional regression analyses of task performance were performed with only the IQ measures and birth weight group as predictors. (Supplemental Table S3). In this analysis, birth weight group, PIQ, and the PIQ by group interaction explained significant variance in human face discrimination performance, all $p < .05$, together accounting for 26% of the variance in discrimination of human faces. In follow-up analyses by group, PIQ accounted for 23% of the variance in human face discrimination in ELBW survivors ($B = 0.50$, $SE = 0.12$, $p < .001$), but only 4% of the variance in NBW controls ($B = 0.17$, $SE = 0.09$, $p > .06$). VIQ did not reach significance in either group (all $p > .20$). These analyses demonstrate that associations between PIQ and human face discrimination performance did not depend primarily on characteristics of the sample. Parallel analyses of monkey face and house discrimination revealed similar main effects of birth weight group and PIQ (all $p < .05$), but no interactions (all $p > .45$).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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