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Prenatal Cardiac Function and Postnatal Cognitive Development: An Exploratory Study

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Fetal cardiac function was measured at 24, 30, and 36 weeks gestation and quantified in terms of heart rate, variability, and episodic accelerations. Children's representational capacity was evaluated at 27 months in terms of language and play. Thirty- and 36-week-old fetuses that displayed greater heart-rate variability and more episodic accelerations, and fetuses that exhibited a more precipitous increase in heart-rate variability and acceleration over gestation achieved higher levels of language competence. Thirty-six-week-old fetuses with higher heart-rate variability and accelerations, and steeper growth trajectories over gestation, achieved higher levels of symbolic play. Cardiac patterning during gestation may reflect an underlying neural substrate that persists through early childhood: Individual variation in rate of development could be stable, or efficient cardiac function could positively influence the underlying neural substrate to enhance cognitive performance.

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It is now well accepted among neurobehavioral developmental scientists that the transition from fetus to infant is accompanied by significant developmental continuities in neural development (e.g., Als, 1982; Joseph, 2000; Prechtl, 1984). Well into prenatal life several anatomical, brainstem, and sensory systems are so developed that they are approaching structural and functional maturation. Consequently, postnatal development in diverse spheres of function might profitably be considered against the backdrop of prenatal development. Our goal in this study was to ask whether select features of prenatal development help to explain select features of postnatal function.

Developmental scientists have long been interested in the period before birth as a forebear of subsequent development (e.g., Sontag, 1941; Sontag & Richards, 1938). However, empirical validation of whether features of prenatal development predict postnatal function has been impeded by the general inaccessibility of the fetus. Although significant advances in biotechnology have now opened a window to the intrauterine world, investigators have continued to face the challenge of measuring behavior without the aid of directly seeing, hearing, touching, or manipulating the subject of study. Few studies have attempted to document prenatal to postnatal consistencies, which may portend antenatal origins of individual differences in infants and children (e.g., DiPietro, Hodgson, Costigan, & Johnson, 1996; Groome et al., 1999; Madison, Madison, & Adubato, 1986; Shadmi, Homburg, & Insler, 1986; St. James Roberts & Menon-Johansson, 1999); to date, none has followed children past the first year of life.

Heart rate is the most commonly measured characteristic of fetal function, originating in clinical evaluation of fetal well-being. In general, fetal heart rate decreases during gestation, whereas measures of both continuous and episodic variability in heart rate increase; both processes have been attributed to increased parasympathetic innervation of the heart (Dalton, Dawes, & Patrick, 1983; Freeman, Garite, & Nageotte, 1991; Martin, 1978). Stability in heart rate and variability during gestation, a prerequisite for establishing potential individual differences, has been well established (DiPietro, Costigan, Pressman, & Doussard-Roosevelt, 2000; DiPietro, Hodgson, Costigan, & Johnson, 1996; Nijhuis et al., 1998). Within-individual stability from prenatal to postnatal life in measures of fetal heart rate or variability is now documented as well (DiPietro et al., 2000; Lewis, Wilson, Ban, & Baumel, 1970; Thomas, Haslum, MacGillivray, & Golding, 1989).

As with the fetus, cardiac measures have a long tradition of use as indicators of autonomic function in developmental research with infants and children by relating cardiac measures to child performance. For example, better contemporaneous heart rate variability (e.g., vagal regulatory capacity) has been associated with shorter visual fixation duration (Richards, 1985), efficient habituation (Bornstein & Suess, 2000), more advanced language and play (Suess & Bornstein, 2000), as well as higher Bayley scores (DeGangi, DiPietro, Greenspan, & Porges, 1991). Earlier heart-rate measures have also been successfully implemented in predicting performance at later ages (Doussard-Roosevelt, Porges, Scanlon, Alemi, & Scanlon, 1997; N. A. Fox & Porges, 1985).

To date, investigations relating prenatal heart rate to developmental outcomes after birth have relied on measures of heart rate that are episodic in nature and arise from obstetric practice. These measures, termed accelerations, represent excursions in heart rate that occur for a defined period of time and attain a specific magnitude around an estimated baseline. The presence of accelerations becomes a more prominent feature of fetal heart-rate patterns as gestation advances and forms the cornerstone of clinical assessment of fetal well-being (Ware & Devoe, 1994). Accelerative processes are believed to be vagal in nature (Martin, 1978) and mediated, in part, by coactivation with central processes that also generate spontaneous fetal movements (DiPietro, Hodgson, Costigan, Hilton, & Johnson, 1996; Timor-Tritsch, Dierker, Zador, Hertz, & Rosen, 1978). Accelerations during labor have been associated with neonatal neurobehavioral performance (Emory & Noonan, 1984) and developmental maturation in the first year of life (Painter, Depp, & O'Donoghue, 1978). Antenatal assessment, based on measures that include accelerations, has been associated with performance on the Bayley Mental Development Index at age 2 (Todd, Trudinger, Cole, & Cooney, 1992). However, interpretation of these studies as relevant to normally developing fetuses and infants is limited by the inclusion of at-risk pregnancies and preterm births.

The goal of this study was to determine whether a predictive relation between heart-rate measures and age-appropriate aspects of early childhood performance originates in the fetal period through a third-year postnatal follow-up of children first studied as fetuses (DiPietro, Costigan, Shupe, Pressman, & Johnson, 1998). Our outcome measures center on symbolic function, in specific language and pretense play, which constitute critical age-appropriate cognitive and representational skills in toddlers (Bornstein & Haynes, 1998; de Villiers & de Villiers, 1999; Edwards & Liu, 2002; Piaget, 1936/1952; Užgiris & Raeff, 1995). Typically developing children in this age range manifest rapidly advancing receptive and expressive verbal skills. Similarly, symbolic play is emerging as children more and more readily represent their own experiences as well as those of others in pretense. Many factors contribute to individual differences in language and play (e.g., Bornstein, Haynes, O'Reilly, & Painter, 1997; Bornstein, Haynes, & Painter, 1998; Bornstein & O'Reilly, 1993)—neurobiological status and cardiac efficiency among them (e.g., Sigman & Sena, 1993; Suess & Bornstein, 2000). Underlying individual variation in children's language and play development are the abilities to self-regulate and control physiological systems and activities that help to maintain optimal cognitive and learning states (Weiner, 1948). In turn, the ability to regulate cardiac function and state and respond to the environment are critical to physical, psychological, and social growth (Porges, 1996). Among the many structures and functions developing in toddlers, both language and play are expected to be positively influenced by efficient autonomic function. Both are also "scalable" dimensions of growth (in the sense that they are anchored in at least interval scales).

Guided by the existing literature regarding the use of cardiac activity as a metric for underlying neural development, we expected that higher levels of parasympathetic function, as evidenced by decreasing heart rate, increasing variability, and increasing accelerations, would be associated with better developmental performance during childhood. We incorporated both continuous measures of function (heart rate and variability) that are recognized by developmentalists as well as episodic measures (accelerations) that have been established in the obstetric literature. Just as during any other developmental period, there is individual variation in the rate of heart-rate development during gestation (Nijhuis et al., 1998). Therefore, we also expected that fetuses that developed at more rapid rates would also develop more rapidly as infants, showing higher levels of cognitive function at postnatal assessment. This investigation was undertaken to advance our understanding of pre- to postnatal development by evaluating multiple indexes of heart rate from midgestation to late gestation to predict multiple characteristics of child cognitive development (language and play) during the third year of life. Prominent among sources of error that may influence detecting and interpreting endogenous predictive validity in the child are exogenous influences. In this study, we controlled for maternal verbal intelligence and social desirability in responses.

METHOD

Participants

Fifty-two healthy, pregnant women and their singleton fetuses participated in the prenatal assessment phase of the study (see DiPietro et al., 1998). Pregnant women were enrolled if they had an unremarkable pregnancy history, were nonsmokers, and had good pregnancy dating based on the following: a pregnancy test within 2 weeks of a missed menstrual period or a first trimester obstetric or ultrasound examination. All children were term at birth, of normal birth weight, and discharged from the regular newborn nursery according to normal schedules.

Mothers and children who had been seen in pregnancy participated in this follow-up assessment at 27 months; the data reported here use a subsample of a larger sample of fetuses, some of whose fetal data have been previously reported (DiPietro et al., 1998). Seventeen dyads that participated in the prenatal phase did not participate in the postnatal assessment. Five had moved, 11 declined to participate, and 1 child was not being taught English, leaving 35 mother–child pairs in the final sample (16 girls and 19 boys). The follow-up rate from the prenatal to toddler period was 67%. However, there were no identifiable differences in either prenatal or postnatal variables between follow-up participants and nonparticipants: Children seen as toddlers did not differ from children not seen in fetal heart rate at 24, 30, or 36 weeks gestation, heart-rate variability, or heart-rate acceleration, all *t*s *ns*. All children, whether they were seen in the child study or not, were term at birth, of normal birth weight, and length of gestation, *t*s *ns*, and discharged from the regular newborn nursery according to normal schedules. Mothers of children seen as toddlers did not differ from mothers of children not seen in age or years of education, *t*s *ns*. There was no difference in family income between the 35 families seen in the follow-up assessment and the 17 families not seen.

Table 1 presents the child's age, the mother's age, the education of the parent at prenatal and postnatal assessment, family socioeconomic status (SES), and comparisons of these family demographic variables between girls and boys. At postnatal assessment, children were between 25 and 30 months of age. Girls did not differ from boys on any variable. Mothers averaged 30.2 years of age at the prenatal assessment and 33.5 years at the postnatal assessment. They all had completed high school; 25 had completed college, and of those 17 had completed university graduate programs. Years of education were somewhat higher for mothers with sons than for mothers with daughters at both prenatal and postnatal assessments, and so years of education was selected as a potential covariate in analyses of sex differences in fetal and child variables. At the time of the child postnatal assessment, 2 mothers reported that they were not working outside the home, and the 33 mothers who did report working averaged 33.5 hr per week (SD = 11.4). All fathers, except 1, had completed high school; 18 had completed college, and of those 10 had completed university graduate programs. Families were of middle to upper middle SES as measured by the Hollingshead (1975; see also Gottfried, 1985) Four-Factor Index of Social Status.

TABLE 1
Demographic Characteristics of the Sample

	Total Sample[a]		*Girls*[b]		*Boys*[c]		
	M	*SD*	*M*	*SD*	*M*	*SD*	*Girls Versus Boys*
Child's age in months							
At postnatal assessment	27.0	0.9	27.4	1.2	26.7	0.6	$t(20.8)^{d} = 1.94$, *ns*
Maternal age in years							
At prenatal assessment	30.2	3.1	30.4	3.5	30.1	2.8	$t(33) < 1$, *ns*
At postnatal assessment	33.5	3.2	34.0	3.6	33.1	2.9	$t(33) < 1$, *ns*
Maternal education in years							
At prenatal assessment	16.1	2.5	14.8	2.7	17.2	1.8	$t(25.3)^{d} = -3.05, p < .05$
At postnatal assessment	16.5	2.2	15.7	2.4	17.3	1.7	$t(25.9)^{d} = -2.21, p < .05$
Paternal education in years							
At prenatal assessment[e]	15.7	2.6	15.0	2.7	16.3	2.5	$t(29) = -1.37$, *ns*
At postnatal assessment	15.8	2.4	15.3	2.2	16.3	2.6	$t(33) = -1.24$, *ns*
Family SES[f] at postnatal assessment	51.5	10.4	48.4	10.7	54.1	9.7	$t(33) = -1.64$, *ns*

Note. SES = socioeconomic status.
[a]N = 35. [b]n = 16. [c]n = 19. [d]Modified degrees of freedom are reportd for the separate-variance t test. [e]Missing data resulted in the degrees of freedom for the t test = 29. [f]Hollingshead (1975) Four-Factor Index of Social Status.

Fetal Data Collection and Quantification

Details of the fetal data collection at 24, 30, and 36 weeks gestational age appear in work of DiPietro et al. (1998). To control for potential diurnal and prandial effects, fetuses were tested at the same time during each visit, either at 1:00 p.m. or 3:00 p.m., and women were instructed to eat 1.5 hr prior to testing, but not again before testing. Women were monitored in a left lateral recumbent position while resting quietly. Fetal heart-rate detection and quantification were based on standard Doppler cardiography and digitized on a computerized data collection system. Fetal heart-rate data were processed using a series of error rejection procedures, based on moving averages of acceptable values, which were applied to remove movement artifact. Data were interpolated to preserve temporal integrity, but interpolated data were not used in data analyses. A moving baseline was fit to the artifact-free data to provide a background from which to detect episodic changes. The data were epoched into fifty 1-min periods. Fetal heart-rate measures were calculated as: (a) heart rate, the mean of the fifty 1-min epochs; (b) heart-rate variability, computed as the standard deviation for each 1-min epoch, again averaged over the 50-min recording; and (c) heart-rate acceleration, the number of changes in heart rate that exceeded 15 beats per min above baseline for at least 15 sec during the 50-min recording.

Child Data Collection and Quantification

The child follow-up took place between 25 and 30 months of age, during one 2-hr home visit scheduled at a time convenient to mother and child. Children first played alone; then they participated in a structured play activity and a language assessment with a researcher. In the week before the home visit, mothers received in the mail and completed questionnaires, including one that evaluated child expressive vocabulary. During the home visit, mothers completed a sociodemographic questionnaire about the family, evaluated the quality of the play session, and were administered a measure of verbal intelligence. Following the home visit, further information about the child's communicative skill was obtained through a scheduled telephone interview. Mothers were also given additional questionnaires after the visit to return by mail; one assessed social desirability of maternal responses. Researchers and mothers alike were blind to fetal data and hypotheses of the study.

Language. Four measures of each child's language competency were obtained. One week prior to the home visit, mothers received the MacArthur Communicative Development Inventory (CDI; Fenson et al., 1993) by mail and were asked to complete it on the basis of their general knowledge of the child. The total number of words that the mother reported her child produced on the MacArthur

CDI was calculated and converted to an age-normed percentile score. During the home visit, a researcher administered the Comprehension Scale ‘A’ and the Expressive Language Scale of the Reynell Developmental Language Scales—Second Revision (RDLS; Reynell & Huntley, 1985). Children’s raw (total number of items passed) and standard language scores for comprehension and production were calculated from the RDLS, and standard scores were used in the analyses. The Vineland Adaptive Behavior Scales (VABS): Interview Edition Survey Form (Sparrow, Balla, & Cicchetti, 1984) Communication Domain, obtained by interview after the home visit, was used to assess mothers’ perceptions of child communication skills. The score for the Communication Domain is the sum of raw scores for the Expressive and Receptive subdomains converted to a standard score.

Play. Two measures for each child’s play were obtained. During the home visit, the child was videotaped while playing alone and then in elicited play with an experimenter. Two sets of standard, age-appropriate toys (doll, bear, blanket, doll bottle, tea set, pot, pan, spatula, fire truck with fire fighter, gas pump, drill, pliers, six colored wooden blocks, stacking barrels, and a toy camera) were used. These toys were selected to represent feminine, masculine, and gender-neutral categories (see, e.g., Caldera, Huston, & O’Brien, 1989) and allowed for a variety of different play behaviors, ranging from simple exploration to more complex symbolic play. During 10 min of solitary play, the mother was asked to sit near the child but to refrain from interacting with the child; she was given a family sociodemographic questionnaire to complete, making her less accessible to the child although still reassuringly nearby. Play was coded from videotapes in accordance with a mutually exclusive and exhaustive play category system that included eight levels (Levels 1–4: exploratory play, Levels 5–8: symbolic play) and a default (no-play) category derived from previous research (see Bornstein, Haynes, O’Reilly, et al., 1997). Reliability of play was based on sec-by-sec agreement. There were 600 sec in a play session, and κ assessments were based on whether coders agreed with the play level coded for each sec. Average κ for child symbolic play was .90. Four indexes of play were taken: the count of symbolic play bouts, the proportion of play bouts that were symbolic, the total duration of symbolic play, and the proportion of play duration that was symbolic. Because these indexes are consistently highly correlated (see Bornstein, Haynes, Legler, O’Reilly, & Painter, 1997; Bornstein, Haynes, O’Reilly, et al., 1997), their mean standard score was used as a summary index representing the amount of child-alone symbolic play.

Following child solitary play, the child participated in a structured symbolic play task based on the same eight-level play scale. This task involved a researcher eliciting increasingly sophisticated levels of play from the child. With the child seated at a table, the researcher presented object(s) to elicit, one at a time, play at Levels 5 through 8. At each level, the child was offered three opportunities to perform each behavior. An object was placed in front of the child, and the researcher asked, "What can you do with this?" The child was given 30 sec to demonstrate play at any level, if she or he did not, the researcher verbally solicited the behavior: "Can you give the bear a drink?" If the child did not perform the behavior after another 30 sec, the researcher demonstrated and then solicited the behavior again. Children were given 3 points if they responded spontaneously, 2 points if they responded after a verbal solicitation, 1 point if they responded after the demonstration, or 0 points if they did not respond at all. The scores for each play level were summed to create a total score, which ranges from 0 to 12.

During the home visit, the mother and the researcher independently evaluated the play sessions by marking a series of 8-point scales, randomly ordered with respect to valence. Their responses were then recoded so that 0 = *not at all* and 7 = *very much so.* Mothers reported that their children were in good health at the time of the observation ($M = 5.9$, $SD = 1.5$), and according to the researcher, children appeared alert ($M = 6.7$, $SD = 0.5$), happy ($M = 6.3$, $SD = 1.3$), and relaxed ($M = 6.1$, $SD = 1.5$). According to the researcher, children showed only moderate interest in the researcher ($M = 3.1$, $SD = 1.9$) and camera ($M = 2.9$, $SD = 1.5$), and mothers agreed, reporting that their child's interest in the camera ($M = 2.9$, $SD = 2.0$) and the observer were moderate ($M = 3.1$, $SD = 1.7$). Mothers reported that the toys were attractive to their children ($M = 5.2$, $SD = 1.5$), but that their child's play during the session was characteristic of their usual play with toys ($M = 5.3$, $SD = 1.5$). These reports suggest that the play data we obtained were typical of the children in general.

Covariates

In an attempt to focus on the predictive validity of fetal function, we assessed possible influences of several covariates, including infant birth weight and mothers' age, verbal intelligence, and tendency to respond in a socially desirable fashion vis-à-vis maternal report. The Peabody Picture Vocabulary Test–Revised (Dunn & Dunn, 1981), a reliable and valid measure of maternal verbal–perceptual vocabulary intelligence, was administered to the mother at the end of the home visit. The Social Desirability Scale (Crowne & Marlowe, 1960), used to assess a person's tendency to reply to questions in a socially desirable fashion, was used to estimate the degree to which maternal report may be contaminated in the MacArthur CDI and VABS–Communication Domain.

RESULTS

Analytic Strategy

Prior to any analysis, univariate distributions for all variables were evaluated for the whole group and by sex for normalcy and influential outliers (J. Fox, 1997).

Heart-rate variability at 36 weeks gestation was reexpressed using a $\log_{10}$ transformation to approximate normality and reduce outliers. However, because heart-rate variability was transformed only for the 36-week variable, untransformed variables were used in the repeated-measures analysis of variance (ANOVA) and the linear growth modeling. Transformed variables were used in correlational analyses; for clarity, untransformed means are presented in tables of descriptive statistics.

There were no significant interrelations between heart rate and variability (*r* range = .09–.17) or heart rate and accelerations (*r* range = .01–.28) at any gestational age. Heart rate variability and accelerations were correlated, *r*s = .56, .84, and .85 at 24, 30, and 36 weeks gestation, respectively, *p*s ≤ .001. However, both were retained as independent measures in the analysis because they represent conceptually distinct cardiac phenomena.

As noted in the description of the sample, significant differences emerged between mothers of girls and mothers of boys in their years of education at the prenatal and the postnatal assessments, and education level was significantly correlated with 30-week heart-rate variability, $r = .46$, $p < .01$, and acceleration, $r = .43$, $p < .05$. For these fetal variables, the sex difference was reexamined controlling for mothers' years of education. No difference in findings was detected.

There was no correlation between birth weight and any fetal heart measure (*r* range from .01–.14); the correlation between birth weight and the 27-month language aggregate was .09, *ns*, and between birth weight and the symbolic play aggregate it was –.10, *ns*. Thus, birth weight was not used as a covariate. The roles of maternal age, language, and socially desirable responding are discussed in the section on prediction of language.

Descriptive Statistics and Developmental Trends in Fetal Heart Measures

The means and standard deviations for fetal heart measures are presented in Table 2. Also displayed in Table 2 are the mean growth trajectories, β_{10}, from the unconditional models for two fetal heart measures: Only these measures showed significant variation among fetuses in their growth trajectories, and the slope coefficients were included in the final analyses examining predictive validity between fetal measures and child outcome measures. Linear growth modeling (LGM) was implemented by HLM 5 (Raudenbush, Bryk, Cheong, & Congdon, 2000); the LGMs reported in this article follow the model described in Bryk and Raudenbush (1992, pp. 134–140).

In repeated-measures ANOVAs of heart-rate level and variability with gestational age as a within-subjects variable, the same developmental patterns were detected as those reported in work by DiPietro et al. (1998), which included this

TABLE 2
Fetal Measures

Fetal Heart Measures	*M*	*SD*
Heart rate		
24 weeks	145.72	5.74
30 weeks	139.87	6.53
36 weeks	139.01	8.20
Heart-rate variability		
24 weeks	3.90	0.76
30 weeks	4.99	1.17
36 weeks	5.74	1.96
Growth trajectory 24–36 weeks	0.15	0.17
Heart-rate acceleration		
24 weeks	1.06	1.64
30 weeks	4.66	3.64
36 weeks	7.17	5.06
Growth trajectory 24–36 weeks	0.51	0.38

study sample. In general, from 24 to 36 weeks gestation, fetuses exhibited reduced heart rate and increased heart-rate variability. In addition to the measures reported by DiPietro et al. (1998), we also evaluated heart-rate acceleration, and the results of this repeated-measures ANOVA, as well as the developmental trends and growth trajectories for all fetal heart measures, are included here.

Fetal heart rate declined 0.56 beats per minute (bpm) each week from 24 to 36 weeks gestation, $t(34) = -6.16$, $p < .001$. Fetuses varied significantly in their mean heart rate at 24 weeks, $\chi^2(34, N = 35) = 82.76$, $p < .001$, and those with a higher heart rate at 24 weeks showed smaller declines in their heart rate over time ($r = .70$). However, fetuses did not vary significantly in their heart-rate decline, $\chi^2(34, N = 35) = 43.86$, *ns*.

Fetal heart-rate variability increased 0.15 bpm each week from 24 to 36 weeks gestation, $t(34) = 5.58$, $p < .001$. Fetuses varied significantly in their heart-rate variability at 24 weeks, $\chi^2(34, N = 35) = 53.34$, $p < .05$. There was no relation between heart-rate variability at 24 weeks and increase in growth trajectory over time ($r = -.01$). Fetuses varied significantly in the trajectories of heart-rate variability, $\chi^2(34, N = 35) = 136.00$, $p < .001$.

Fetal heart-rate acceleration increased significantly during the period of gestation studied, $F(2, 33) = 35.30$, $p < .001$. Accelerations increased from 24 to 30, from 30 to 36, and from 24 to 36 weeks, as indicated by the repeated-measures ANOVAs, $F(1, 34) = 39.50$, 12.52, and 64.33, respectively, ps $\leq .001$. Each week, fetal heart-rate acceleration increased 0.51 times per 50-min of recording from 24 to 36 weeks gestation, $t(34) = 8.14$, $p < .001$. Although fetuses did not vary in their heart-rate accelerations at 24 weeks, $\chi^2(34, N = 35) = 27.05$, *ns*, they varied significantly in the trajectories of heart-rate accleration, $\chi^2(34, N = 35) = 75.92$, $p < .001$.

Descriptive Statistics for Children's Cognitive Development

Table 3 shows the means and standard deviations for measures of child language and symbolic play. As expected, the four child language measures were highly positively correlated, *r*s = .51 to .82, *p*s < .001, justifying the use of their mean standard score as a comprehensive language aggregate score. The mean RDLS Comprehension score approximated 1 *SD* above the normed average, and the Expressive score approximated the normed average (Reynell & Huntley, 1985). The mean number of words that mothers reported their children used was at the 27-month normed average on the MacArthur CDI (Fenson et al., 1993). The Vineland Communicative subdomain score fell less than 1 *SD* above the mean reported in a standardized sample of 27-month-olds (Sparrow et al., 1984). Even though the correlation between child-alone symbolic play and elicited symbolic play was not significant ($r = .25$, *ns*), because of their conceptual relatedness, a play aggregate score was computed as the mean standard score of these two measures.

Predictive Validity Between Fetal Measures and Child Measures

Table 4 presents zero-order correlations of fetal measures at the three gestational ages and the growth trajectories of heart-rate variability and acceleration with child outcome measures of language and play at 27 months.

TABLE 3
Child Measures

	M	*SD*
Language aggregate score	0.03	3.51
Reynell[a]—Comprehension	1.27	1.15
Reynell[a]—Expressive	0.22	0.60
MacArthur[b]—Vocabulary	0.49	0.25
Production		
Vineland[a]—Communication	107.57	14.59
Play aggregate score	0.01	0.76
Child alone–symbolic play	0.00	0.92
Elicited symbolic play	8.22	3.07

[a]Standard score. [b]Percentile score.

TABLE 4
Predictive Relations Between Fetal Heart Measures and Child Language and Play at 27 Months

Fetal Heart Measure	*Language Aggregate Score*	*Play Aggregate Score*
Heart rate		
24 weeks	.05	.50**
30 weeks	–.02	.37*
36 weeks	–.14	.33
Heart-rate variability		
24 weeks	.32	–.19
30 weeks	.42* (.34)[a]	.21
36 weeks	.38* (.33)[b,c]	.34*
Growth trajectory 24–36 weeks	.31*	.38*
Heart-rate acceleration		
24 weeks	.17	–.10
30 weeks	.43* (.33)[a]	.12
36 weeks	.47** (.40*)[b]	.38*
Growth trajectory 24–36 weeks	.46** (.41**)[b]	.47**

Note. One-tailed tests were used for directional hypotheses regarding fetal growth trajectories. All others were two-tailed tests. N varied from 32 to 35, resulting in varying degrees of freedom for analyses.
[a]Partial correlation controls for maternal verbal intelligence. [b]Correlation of the residual of child language measure controlling for maternal verbal intelligence with the fetal variable. [c]$p = .057$.
$^{*}p \le .05$. $^{**}p \le .01$.

Prediction of language. Bartlett's test of sphericity was significant, $\chi^2(11, N = 35) = 922.16$, $p < .001$, rejecting the hypothesis that all the correlations, tested simultaneously, did not statistically differ from zero. Fetal heart-rate variability and acceleration at the two older ages and the rising growth trajectories of heart-rate variability and acceleration were positively related to the child language aggregate score: Fetuses with higher heart-rate variability and more accelerations at 30 and 36 weeks gestation, and who exhibited a more precipitous increase in heart-rate variability and acceleration over gestation, demonstrated higher levels of language competence at 27 months postnatal age. Post hoc analysis of the components of this aggregate score revealed that each heart-rate measure was related to essentially all language component scores, including those generated by experimenter and by maternal report. The few nonsignificant correlations, mostly between heart-rate variability and the RDLS, were all in the same direction, with *r*s ranging from .24 to .31, suggesting that the small sample size (post hoc power ranged from .40 to .57) may have contributed to a failure to detect relations in the population.

It would be premature to draw conclusions regarding the predictive validity of fetal cardiac function to 27-month child language without considering the potential role of the mediating variables, such as the child's mother. Maternal age correlated only with heart-rate acceleration at 30 weeks, $r = .41$, $p < .05$; the part correlation between the language aggregate score and heart-rate acceleration at 30 weeks from which maternal age was partialled was .37, $p < .05$. Concurrent associations between maternal verbal intelligence and child language were significant for the language aggregate score, sharing 12% of variance; maternal verbal intelligence was also positively related to 30-week heart-rate variability and acceleration, sharing 15% and 17% of variance, respectively. (Mothers' tendency to make socially desirable responses did not correlate with maternal language reports and so was excluded as a potential covariate.) Accordingly, we reanalyzed significant zero-order correlations, taking into consideration the covariance of maternal verbal intelligence. The partial correlations or the correlations between the residual of the postnatal and the prenatal variable, after removing the covariance of maternal intelligence, are presented in parentheses after the zero-order correlations in Table 4. The same patterns of results, albeit with the relative magnitudes of correlation coefficients somewhat attenuated, obtained for the predictive relations between prenatal cardiac function and postnatal language after maternal contributions were taken into consideration

Prediction of play. Bartlett's test of sphericity was again significant, $\chi^2(11, N = 35) = 898.57$, $p < .001$. Heart rate at 24 and 30 weeks, heart-rate variability and acceleration at 36 weeks, and the rising trajectories of heart-rate variability and accleration were positively related to the play aggregate score: Fetuses that had higher heart rate at 24 and 30 weeks gestation, displayed greater heart-rate variability and acceleration at 36 weeks, and exhibited a more precipitous increase in heart-rate variability and acceleration over gestation scored higher on the aggregate of child-alone symbolic play and elicited symbolic play at 27 months postnatal age. The correlations between these fetal variables and the play component scores were all in the same direction, with *r*s ranging from .15 to .55. However, significant predictive relations were observed only for heart rate at 24 weeks on child-alone symbolic play, and for heart rate acceleration at 36 weeks and the rising growth trajectories of heart-rate variability and acceleration on child-elicited play.

DISCUSSION

Although at birth significant events lead us to believe that intrauterine and extrauterine life are discontinuous, considerable stability also characterizes development between the fetus and the child. Recently, DiPietro et al. (2000), based on the parent sample of children who participated in this follow-up study, established that there is significant stability in fetal heart-rate measures in the gestational period investigated (rs range from .56–.73 for heart rate and .30–.68 for variability), as well as stability between prenatal and postnatal cardiac measures (e.g., r for 36-week fetal heart rate and infant heart rate at 1 year = .40; fetal to infant variability = .47). The purpose of this study was to explore predictive validity of fetal development across the "great divide of birth." Our results confirm that, from a developmental perspective, this divide may be more impressive in appearance than in reality and that cross-domain associations exist. We found that prenatal measures of fetal cardiac function predicted postnatal measures of child representational ability, language, and symbolic play. We measured language by experimenter assessment and by maternal report, and we measured spontaneous symbolic play and also assessed a "zone of proximal development" (Vygotsky, 1978) in child play by examining, from their basal performance, how far children could be "stretched" in their symbolic-play capacity. In general, fetuses with greater heart-rate variability and more accelerations at 30 and 36 weeks gestation, and fetuses that exhibited a more precipitous increase in heart-rate variability and acceleration over gestation, grew into children who demonstrated higher levels of language competence at 27 months postnatal age even after controlling for maternal language ability. Fetuses that showed higher heart rate at 24 and 30 weeks, more heart-rate variability and accelerations at 36 weeks, and exhibited a more precipitous increase in heart-rate variability and acceleration over gestation also achieved higher scores in symbolic play at 27 months postnatal age. These findings point to provocative stabilities in development from the prenatal period over the longest time studied to date; they are similar in two distinct (if related) spheres of cognitive accomplishment in early childhood; and they are consistent with endogenous stability independent of exogenous factors inherent in the postnatal rearing environment.

We analyzed developmental trends as well as individual variation in fetal heart function. Fetuses showed developmental trends over the three ages in heart rate: Normatively, mean heart rate decreased over the 24- to 36-week gestational age range tested, whereas heart-rate variability and accelerations increased. If fetuses show individual variability in heart rate, and the normative developmental function in fetuses is to increase in heart-rate variability and acceleration, it could be that fetuses that are advanced in their development in these two realms of cardiac function within the normal range, or that are developing at more rapid rates, are fetuses whose autonomic functioning in general or cardiac functioning in particular is more advanced. It could also be that these fetuses are simply "ahead of the curve" in general development. We predicted that those fetuses would also show advanced postnatal function.

Although heart rate predicted play at younger fetal ages, measures of variability and acceleration in fetal heart rate and their growth trajectories were more successful and systematic at predicting developmental outcomes. This is consistent with the clinical perspective that variability is more informative of fetal well-being than mean rate, so long as rate is within a normal range (Dawes, Houghton, Redman, & Visser, 1982; Odendaal, 1990; Street, Dawes, Moulden, & Redman, 1991; Yeh, Forsythe, & Hon, 1973). Variability is generally accepted to indicate parasympathetic influences: Higher parasympathetic tone *in utero* suggests higher parasympathetic vagal tone in the individual, which results in better performance. So, too, in developmental research, variability in infant heart rate has been the basis of findings relating cardiac patterns to performance, ranging from simple measures of variability to more complex measures of respiratory sinus arrhythmia (Bernston et al., 1997). The measures of variability and acceleration used in this study were correlated; we included both to examine whether they predict outcomes differently. The continuous measure of variability, based on standard deviation within a time domain, reflects small, short-term changes around baseline, both above and below. In contrast, accelerations are large, longer term excursions above baseline. Both are considered to be influenced by development of vagal regulation, although knowledge regarding the distinction between the processes underlying each is by no means clear. From an empirical standpoint, our results indicate that both seem to be related to long-term outcomes in roughly the same manner, and both may be indexing the same developmental process.

Differences in predictive validity were observed over gestation. For measures of variability, associations with language and play outcomes became more robust at later gestational ages, and growth trajectories were predictive. Because the normative developmental function during the fetal period is to increase heart-rate variability and accelerations, it is logical that both greater variability in heart rate as well as faster attainment of this variability indicates greater autonomic regulatory control. However, heart rate per se behaved differently from heart-rate variability and acceleration; no relation with language was found, and the associations with play declined in magnitude over gestation. It is possible that the association with play is mediated not by the developmental level of the child, but by an unmeasured attribute, such as child temperament. In any case, any predictive associations between fetal heart rate and postnatal developmental outcomes will require greater elaboration and confirmation before understanding can be achieved.

The existing evidence for prenatal to postnatal stability tends to be “complete” (see Kagan, 1971; Wohlwill, 1973), such as data related to motor activity (Groome et al., 1999), heart rate (DiPietro et al., 2000), and behavioral state (Groome, Swiber, Atterbury, Bentz, & Holland, 1997). That individual differences in fetal cardiac function predict individual differences in child language and play, independent of the role of mother, provides important evidence of possible prenatal-to-postnatal “heterotypic” stability (Bornstein, 2002; Bornstein & Sigman, 1986; Kagan, 1971). Several possible explanations for these stability results suggest themselves. First, it could be that individual differences in general development are stable from fetus to child, so that fetuses that are in the upper end of the distribution in terms of development on fetal measures are in the upper end of the distribution in terms of development on child measures. In fact, the normative developmental trend is for variability and acceleration to increase over gestation, and those fetuses that were more advanced at 30 and 36 weeks and that were developing faster in gestation grew into children who scored better on age-appropriate measures of representation in their third year of postnatal life.

Alternatively, stability could reflect consistent individual differences in specific nervous system functions. Individual differences in fetal cardiac growth implicates some stability of nervous system function and might set the occasion for faster learning after birth. Notably, heart-rate variability (e.g., good vagal regulatory capacity) is associated with more advanced language and play in toddlers (e.g., Suess & Bornstein, 2000). Both the development of fetal heart-rate variability in gestation and the onset of episodic accelerations in the third trimester have been attributed to increasing parasympathetic control (Dalton et al., 1983). The capacity of the fetus likely reflects reflexive brainstem activities, and by the seventh to eighth week of gestation the major structures of the medulla, including the vagus nerve, have been established (Gilles, Leviton, & Dooling, 1983; Sidman & Rakic, 1982). When faced with environmental challenge, the "vagal brake" is released, thereby allowing activation of the sympathetic system, increased metabolic output, and mobilization of resources (Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996). This function of the vagal system is measured by changes in vagal tone, an index of heart-rate variability. Suppression of vagal tone is associated with advanced cognitive performance (visual fixation in Richards, 1985; habituation in Bornstein & Suess, 2000; higher Bayley MDI and PDI scores in DeGangi et al., 1991). Children who show vagal change similar to the group mean should demonstrate better language and play skills to the extent that the group response represents appropriate physiological self-regulation that facilitates mental (language and symbolic-play) development. Underlying the development of language and play must be the child's characteristic capacity to self-regulate those physiological systems that facilitate attentional and cognitive processing and social-communicative interaction. It might be, then, that children's cognitive performance reflects efficient cardiac function and growth, which provide physiological and metabolic support to meet attentional and cognitive task demands.

The patterns of results reported here, however consistent, derive from a small and selected sample and require replication in larger and more heterogeneous samples. Nonetheless, the predictive analyses supported the expectations set out. The predictive validity of fetal cardiac function for childhood cognitive performance obtained over and above both antecedent and contemporary influences of maternal verbal abilities and social desirability of responsiveness. These analyses suggest that the predictive validities we observed may be endogenous: In terms of autonomic function, fetuses that are more developed, or developing along the normative trajectory but at more advanced rates, appear to be those that perform better as children in their cognitive functioning. In a systems view, multiple factors contribute to the developmental origins, status, and trajectory of all structures, functions, and psychological processes. In this exploratory study, we have identified individual differences factors that already appear in fetuses, that are not systematically reflective of host or other contextual variables, but that demonstrably help to shape human functioning after birth.

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