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The Development of Regulatory Functions From Birth to 5 Years: Insights From Premature Infants

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This study examined physiological, emotional, and attentional regulatory functions as predictors of self-regulation in 125 infants followed 7 times from birth to 5 years. Physiological regulation was assessed by neonatal vagal tone and sleep–wake cyclicity; emotion regulation by response to stress at 3, 6, and 12 months; and attention regulation by focused attention and delayed response in the 2nd year. Executive functions, behavior adaptation, and self-restraint were measured at 5 years. Regulatory functions showed stability across time, measures, and levels. Structural modeling demonstrated both mediated paths from physiological to self-regulation through emotional and attentional processes and direct continuity between vagal tone and each level of regulation. Results support the coherence of the regulation construct and are consistent with neurobiological models on self and consciousness.

Regulation—a term still awaiting a comprehensive definition—has emerged in recent years as a central construct in the conceptualization of developmental progress. Several attempts to provide a definition for *regulation* have been made, each emphasizing a different angle in the understanding of regulatory processes. According to Posner and Rothbart (1998), regulation describes the ongoing interplay between mechanisms of excitation and those of inhibition that operate at each level from cell to behavior to mental representations. Calkins and Fox (2002) address the integration of processes at the physiological, emotional, attentional, and cognitive levels as the framework for the study of regulatory functions. From the position of affective neuroscience, regulation describes the complex and hierarchical relations between the three core brain systems, brainstem, limbic, and cortical, that cohere to organize behavioral output (Tucker, Derryberry, & Luu, 2000) or enable consciousness (Damasio, 2003). Finally, researchers on early relationships (Fogel, 1993) emphasize the coregulatory component in the development of regulatory functions and underscore the extreme dependence of the infant on its regulatory context and the openness of regulatory functions to external influences.

Apart from the struggle to reach an adequate definition that is wide enough to integrate multiple viewpoints yet specific enough as to not render the construct meaningless, several underlying assumptions are shared by all positions. First, authors agree that the term *regulation* implies, by definition, a systems perspective. *Regulation* refers to the organizational features of the system that integrate and hierarchically order functioning in its multiple components and enable their coherence into a single functional unit. Second, regulation requires the inclusion of time as an indispensable parameter of the system (Edelman, 1989; van Geert, 1994). *Regulation* describes the mechanisms that enable the various components to synchronize in time and the interplay between autoregulated and coregulated processes. Finally, given that complexity in dynamic systems increases over time, that systems self-organize from subcomponents and context, and that the system's evolvement is not predetermined but emergent (Thelen & Smith, 1994), the construct of *regulation* must include a developmental perspective. Such a developmental viewpoint must take into account the notion of plasticity, the system's openness to contextual influences, and the innate malleability of regulatory functions. Similarly, a developmental perspective must chart the paths by which lower level physiological systems support the emergence of higher order mechanisms of cognitive control.

Neuropsychological models on brain maturation (MacLean, 1990; Panksepp, 1998; Tucker et al.,

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2000) propose an evolutionary, vertical-integrative view on the development of regulatory capacities. Regulatory functions, according to this view, are processed along three core brain systems: brain stem, limbic, and cortical systems. Higher systems integrate, elaborate, fine-tune, and serve an inhibitory function for hierarchically lower systems. Converging evidence for the vertical-integrative perspective emerges from functional, neurochemical, and imaging studies that indicate that functioning across a wide range of tasks and systems involves hierarchical and synchronous functioning at the brain stem, limbic, and cortical levels in both humans and primates (Caldji, Diorio, & Meaney, 2000; Damasio, 2003; Heim & Nemeroff, 2001; Insel, 2007; Swain, Lorberbaum, Kose, & Strathearn, 2007). These studies show that higher order abilities involving cortical activity require simultaneous processing and modulation at various locations along the neuroaxis. Theoretically, the vertical-integrative view refutes the long-held schism between cognitive and emotional processes (Damasio, 1994) and underscores the role of brain stem systems implicated in homeostasis, motivation, and time-keeping processes in the development of self-regulatory functions (Llineas, 2001; Porges, 2003).

A developmental hierarchical-integrative perspective complements the simultaneous approach taken in these studies and highlights the sequential development of regulatory functions across development. Such approach includes both the *hierarchical* bottom-up component—that physiological, emotional, attentional, and self-regulatory functions develop on top of each other (Edelman, 2004)—and the *integrative* component—that brain stem, limbic, and cortical systems synchronize to execute a regulatory goal (Tucker et al., 2000). With the maturation of new skills, higher order regulatory processes are enabled, each carrying a different set of regulatory goals. Thus, if during the neonatal period the regulatory goal is to maintain physiological homeostasis and organism–environment exchange, the goal of emotion regulation processes in the first year of life is to handle external or internal stresses and manage emotional input. During the 2nd year, the goal of attention regulatory processes is to maintain on-task focus and goal-directed behavior, goals enabled by the important strides in social, linguistic, and motor capacities during that stage. With the development of the self during the preschool years, regulatory processes draw on the capacity of the self to reflect, and their goal is to feed back and enrich the self, internalize a cultural and moral code for its definition, construct a personal history, execute complex actions, and consolidate the brain's ''value systems'' memory (Edelman, 2004). A developmental hierarchical-integrative perspective implies that processes at each level integrate functioning at lower levels and, thus, even minor disruptions to lower levels may lead to dysfunctions in higher systems, as has long been suggested for the developmental sequelae of neonatal brain-stem-related dysfunctions (Luria, 1973). Yet, although the term *regulation* is considered central to developmental thought, a comprehensive longitudinal study that begins at birth and assesses physiological, emotional, and attentional processes as precursors to the emergence of self-regulatory skills has not been conducted.

Physiological Regulation in the Neonatal Period: Brain-Stem-Mediated Oscillators

According to the hierarchical-integrative perspective, regulatory capacities develop on the basis of brain-stem-related functions consolidating in the late fetal and early neonatal period. Sleep–wake cyclicity and cardiac vagal tone, two brain-stem-controlled oscillators, mature during the third trimester of pregnancy in preterm and full-term infants (Groome, Loizou, Holland, Smith, & Hoff, 1999; Mirmiran & Lunshof, 1996). The circadian time-keeping system, which monitors the biological clock, is located in a small region of the hypothalamus, the suprachiasmatic nucleus, and this master pacemaker integrates oscillators spread over the mammalian brain (Antle, Foley, Foley, & Silver, 2007). Noradrenergic neurons originating in the locus ceruleus, a brain stem nucleus implicated in arousal regulation, regulate sleep–wake cyclicity through indirect projections to the superchiasmatic nucleus (Gonzalez & Aston-Jones, 2006). The organization of the biological clock provides a framework for the fine-grained regulation of attention (Dahl, 1996). Sleep–wake cyclicity in the neonatal period was found to predict emotion regulation in the first months of life (Feldman, Eidelman, Sirota, & Weller, 2002; Feldman, Weller, Sirota, & Eidelman, 2002) and cognitive development up to 4 years of age in full-term and preterm infants (Anders, Keener, & Kraemer, 1985; Beckwith & Parmelee, 1986).

Cardiac vagal tone, measuring the effects of respiration on heart-rate variability as mediated by the parasympathetic system, is another brain-stem-controlled pacemaker that supports regulatory functions. According to Porges (1995) polyvagal theory, vagal tone reflects the mammalian brain stem organization and provides the foundation for complex behaviors such as emotional detection and social engagement (Porges, 2003). Fetal heart rate variability, emerging at 32–34 weeks gestational age (GA), is the earliest expression of parasympathetic control and plays a role in the development of inhibitory structures (Groome et al., 1999). When the trajectories of the biological clock and vagal tone were assessed weekly from midpregnancy to term, the maturation of the sleep–wake cycle was found to precede that of the vagal tone by 2 weeks, and both oscillators matured during the period corresponding to the third trimester of pregnancy (Feldman, 2006), a critical period for the development of physiological regulatory systems (Levitt, 2003). Neonatal vagal tone has been shown to predict regulatory outcomes, including parent–infant coregulation (Feldman & Eidelman, 2007), cognitive development (Doussard-Roosevelt, Porges, Scanlon, Alemi, & Scanlon, 1997), regulation of negative emotions (Huffman et al., 1998), and fewer behavior problems at 6 years (Doussard-Roosevelt, McClenny, & Porges, 2001). It is important to note that both the biological clock and cardiac pacemaker are open to environmental influences, such as maternal hormones (Seron-Ferre et al., 2002), variations in the intrauterine environment (Moore-Ede, Sulzman, & Fuller, 1992), and early maternal care (Feldman & Eidelman, 2003). As such, these oscillators highlight two basic aspects in the construct of regulation— the continuous interchange between first- and higher-order systems and the online integration of internal processes and environmental inputs.

Emotion Regulation Across the 1st Year

Perhaps the most researched subcomponent of regulation is ''emotion regulation,'' a concept that has been multiply defined and studied across the life span. Research on emotion regulation during the 1st year of life has typically examined infants' response to external perturbations and the strategies infants use to reachieve a steady state following stress or frustration. Such research enables the study of regulation at the stage when infants are just learning to detect and express emotions but are not yet capable of employing higher order mechanisms of control that require a sense of self. For instance, during the Behavior Response Paradigm (BRP; Garcia-Coll et al., 1988), a procedure in which infants face a series of increasingly aversive stimuli, premature infants born at lower biological risk expressed fewer negative emotions and more regulatory behaviors. Infants' regulation of distress within the parent–child relationship has been extensively studied using the ''still-face'' paradigm (Adamson & Frick, 2003; Weinberg & Tronick, 1996) or its more stressful variation—the ''arm-restraint'' procedure, where mothers hold the infant's arms in addition to maintaining a still face. Studies using these paradigms, mainly with full-term infants, showed a developmental progression in the use of regulatory tactics. For instance, the use of diversion strategies, such as reorienting, nonnegative communications, and avoidant behaviors, increased from 5 to 10 months during the arm restraint (Braungart-Rieker & Stifter, 1996) and averting behavior increased from 2 to 4 to 6 months (Moore, Cohn, & Campbell, 2001). Consistent with the hierarchical-integrative model, sleep–wake cyclicity and vagal tone in neonates were found to predict emotion regulation on the BRP at 3 months (Feldman, Eidelman, et al., 2002; Feldman, Weller, et al., 2002 Huffman et al., 1998) and these skills, in turn, predicted cognitive and attention outcomes at 1 and 2 years (Feldman, 2004). Similarly, regulatory behaviors during the ''still-face'' were predicted by vagal tone (Bazhenova, Plonskaia, & Porges, 2001; Moore & Calkins, 2004), no smiling and no crying on the ''still face'' differentially predicted externalizing and internalizing problems at 18 months (Moore et al., 2001), and affect regulation during the arm-restraint procedure predicted compliance at 18 months (Stifter, Spinrad, & Braungart-Rieker, 1999), pointing to the role of first-year emotion regulatory behaviors in shaping higher order regulatory capacities in later childhood.

Infants' affective reaction to maternal separation has generally been researched from the attachment perspective using the Strange Situation paradigm. Similar to the BRP and still-face, infants' regulatory behaviors during maternal separation were associated with cardiac vagal tone (Oosterman & Schuengel, 2007). Longitudinally, more effective regulatory behaviors during separation–reunion were predicted by mother–infant co-regulation during the first year in full-term infants (Kochanska & Coy, 2002) and were predictive of better behavior adaptation at 2 years in preterms (Feldman & Eidelman, 2004). Overall, these findings support the hierarchical-integrative model and show that infants' emotion regulation strategies are supported by brain-stem-mediated functions, especially vagal tone, and facilitate, in turn, higher forms of self-control.

Attention Regulation During the 2nd Year

During the 2nd year of life, the attention system undergoes significant reorganization, and toddlers acquire the ability to allocate attention to different sources, maintain attention to a task in the face of distractions, and keep a task in memory. Thus, infants become capable of hierarchically organizing attention according to importance and actively keeping focused attention to a task until completion (Posner & Rothbart, 1998, 2000). The 2nd year marks a transition for the attention system as it shifts from the information-processing oriented system of infancy to the executive attention system in the preschool stage (Davis, Bruce, & Gunnar, 2002). Such changes parallel the maturation of the prefrontal cortex during the 2nd year that enables the development of focused attention, delayed response, and effortful control (Diamond, 2002).

Consistent with the hierarchical-integrative model, toddlers' attention regulation skills draw on both emotion regulation and physiological regulation processes. Attention direction, shifting, and maintenance assist children in handling emotional distress, and the emergence of emotional detection promotes focused attention (Bruner, 1984; Posner & Rothbart, 2000). Attention typically cycles between split-second states of excitation and inhibition, and associations have been demonstrated between physiological oscillators and attention processes (Feldman & Mayes, 1999). Research in full-term infants suggests that cardiac vagal tone provides the basis for attention in infants and toddlers (Arditi, Feldman, & Eidelman, 2006; Suess, Porges, & Plude, 1994), and sleep–wake rhythms have been associated with attention problems and lower neurocognitive functions in both preterm and full-term children (Pearl, Efron, & Stein, 2002; Sadeh, Gruber, & Raviv, 2003).

Self-Regulation in the Preschool Years: Behavior Adaptation, Executive Functions, and Self-Restraint

Self-regulatory capacities begin to mature during the preschool years. The discussion of self-regulation presupposes the existence of a rudimentary self structure whose locus is experienced as internal and is perceived as continuous across time and context. Neurobiological models on self and consciousness (Damasio, 2003; Edelman, 2004) highlight the reliance of the self on first-order brain stem and subcortical structures that provide ongoing assessment of the internal milieu, upon which a more coherent cognitive-affective self schema can be constructed. Developmental accounts on self-regulation (Feldman, 2007b; Kopp, 1982) suggest that regulatory structures of the self are grounded in bodily experiences and draw on the organization of motor patterns and action tendencies that are transformed through carefully matched parent–infant coregulatory experiences into self-control skills during the toddler years. These self-control abilities, which still require external monitoring, are then internalized into self-initiated mechanisms of regulation in the behavioral and cognitive domains.

Self-regulatory abilities in the preschool years have been examined in relation to three sets of competencies. The most researched aspect is behavior adaptation, indexed by externalizing and internalizing symptoms, which considers the child's global adaptation to society, general well-being, and organization of behavior. Relevant to the present study is research showing links between externalizing and internalizing symptoms and dimensions of the hierarchical-integrative model: cardiac vagal tone in the neonatal period (Doussard-Roosevelt et al., 2001), emotion regulation (Hill, Degnan, Calkins, & Keane, 2006), and attention (Oberlander et al., 2007).

A second aspect of regulation receiving empirical attention in the preschool years is neuro-cognitive skills, in particular executive functions that require the suppression of prepotent response in the service of a goal-directed action (Diamond, 2002). Executive functions in 5-year-olds reflect the maturation of the prefrontal cortex and consider skills that enable response inhibition, attention shifting, planning, and effortful control (Zelazo, 2004). Consistent with the hierarchical-integrative model, executive functions in preschoolers have been associated with vagal tone (Blair & Peters, 2003), sleep patterns (Gottlieb et al., 2004), emotion and attention regulation (Blair & Peters, 2003), and fewer externalizing symptoms (Oberlander et al., 2007).

Finally, a third line addresses the development of moral internalization, conscience, and self-restraint in response to the demands of socialization agents (Hoffman, 2000). The emergence of self-restraint in the preschool years is based on early parent–infant co-regulation on the one hand (Feldman, Greenbaum, & Yirmiya, 1999) and on inborn dispositions for inhibitory control on the other (Kochanska, Murray, & Coy, 1997), pointing to the dual origins of self-regulation. Both effortful control (Kochanska & Knaack, 2003) and lower externalizing symptoms (Kerr, Lopez, Olson, & Sameroff, 2004) have been shown to predict moral internalizations, suggesting that one path to self-restraint is the combined contributions of global behavior adaptation and intact executive functions. It is thus likely that these interrelated aspects of self-regulation at 5 years—behavior adaptation, executive functions, and self-restraint—develop on the basis of regulatory processes across early childhood at the neonatal, infant, and toddler stages.

The Current Study

In light of the above, the present study followed a group of premature infants at seven time points from birth to 5 years and examined the emergence of regulatory functions as they progress from physiological to emotional to attentional to self-regulatory processes. Premature infants were chosen for the study of regulatory functions because of their well-documented difficulties in physiological and behavioral regulation (Minde, 2000) and in light of the developmental psychopathology perspective that suggests that high-risk conditions afford a useful window into general development (Cicchetti & Cohen, 1995). Consistent with the hierarchical-integrative model, four core systems were studied: brain-stem-supported physiological oscillators in the neonatal period (the biological clock and cardiac pacemaker); limbic-mediated emotion regulation skills at 3, 6, and 12 months; attention regulation capacities at 12 and 24 months; and mechanisms of cortical control implicated in self-regulation at 5 years: executive functions, behavior adaptation, and self-restraint.

Three main goals guided the study. The first was to describe the expression of multiple regulatory processes from birth to 5 years in a population prone to regulatory difficulties. For each level, differences between infants born at higher and lower medical risk were tested to address the contribution of initial conditions to the development of regulatory functions as children grow and environmental inputs become increasingly important in shaping regulatory outcomes. It was of interest whether differences between infants born at high and low medical risk to low-risk families would increase or decrease with age. The second goal was to describe the longitudinal pattern of associations between levels of regulation. Links between levels were expected, and it was hypothesized that the physiological, emotional, and attentional levels would predict, both independently and in combination, the three aspects of self-regulation at 5 years.

The third goal was to test causal paths in the emergence of self-regulation using structural modeling. According to the hierarchical-integrative model, each level of regulation supports the next one, and, thus, the most parsimonious model should chart links between each level and the next. Yet, theoretical accounts on developmental continuity suggest that continuity from infancy typically involves both direct and mediated paths (Carlson, Sroufe, & Egeland, 2004; Feldman, 2007a), and the model itself proposes links between early brain-stem-mediated dysfunctions and disruptions to prefrontal cortex skills (Luria, 1973). In light of the reported relations between vagal tone in preterm neonates and all levels of regulation—infants' emotion regulation, toddlers' attention regulation, and preschoolers' behavior adaptation—direct links were expected between vagal tone and attention regulation and behavior adaptation. Consistent with the notion that the biological clock provides a framework for attention (Dahl, 1996), direct links were also charted between sleep–wake cyclicity and attention regulation. It was expected that a model containing both direct and mediated paths would provide a more comprehensive framework to the central question tested in this study: How do children acquire self-regulatory skills across the first years of life?

Method

Participants

Mothers giving birth to preterm infants (birth-weight > 1,750 g) in a tertiary-level Neonatal Intensive Care Unit in Israel and who met the study's inclusion criteria were approached to participate in a follow-up. Infants' birth -weight ranged from 530 g to 1746 g (M = 1448.9 g, SD = 466.02 g) and GA was between 25 and 35 weeks (M = 31.46 weeks, SD = 3.04 weeks). Infants were excluded from the study if they had intraventricular hemorrhage Grades III or IV or suffered from perinatal asphyxia, metabolic, or genetic diseases. All children came from two-parent Israeli-Jewish families and all families were considered middle class (Harlap, Davis, Grower, & Prywes, 1977). Mothers were, on average, 27.96 years old (SD = 5.34) and completed 14.37 years of education (SD = 2.68). Fathers were, on average, 30.28 years old (SD = 5.71) with 13.97 years of education (SD = 3.02). Of an initial cohort of 158 premature infants, 125 completed the 5-year assessment, and attrition was mainly due to inability to locate families. Children not seen at 5 years did not differ from the participating children on medical or demographic conditions. The final sample included 46% girls. The study was approved by the Institution Review Board, and all participants signed an informed consent.

Procedure and Measures

Children were observed seven times between birth and 5 years: at 32 weeks GA (at 33–34 weeks for those born after 32 weeks GA); at term age (37 weeks GA); at 3, 6, 12, and 24 months (corrected to full gestation); and at 5 years (*M* = 5.32 years, *SD* = 0.60). At 32 and 37 weeks GA a 4-hr state observation was conducted and a 10-min sample of electrocardiogram (ECG) was collected within the same 24-hr period. Emotion regulation was assessed at 3, 6, and 12 months during stressful procedures. Attention regulation was assessed at 12 and 24 months during cognitive testing and at 24 months with a delayed response task (Diamond & Doar, 1989). At 5 years, executive functions were tested with the Developmental Neuropsychological Assessment (NEPSY; Korkman, Kirk, & Kemp, 1998), mothers completed the Child Behavior Checklist (Achenbach & Edelbrock, 1983), and self-restraint was examined during a temptation situation.

Neonatal Stage: Physiological Regulation

State observation at 32 and 37 weeks GA. During 4 consecutive evening hours (7–11 p.m.) trained coders observed the infant's state in 10-s epochs and entered the data into a computerized program. States were defined according to Brazelton (1973) and included the following: quiet sleep, active sleep, sleep–wake transition, unfocused wakefulness, alert wakefulness, and fuss-cry (for details, see Feldman, 2006). Observations took place between feedings, and arrangements were made to diminish interruptions. In cases of unexpected interruptions, if the observation included 3 hr or more, the data were sufficient to detect sleep–wake cyclicity, as the sleep–wake cycle in neonates lasts between 60 and 70 min (Stern, Parmelee, & Harris, 1973), and this occurred in 18% of the cases. If the observation included < 3 hr, it was terminated and resumed when the infant returned to a calm state, and this occurred in 7% of the cases. Coders were trained to 85% reliability using a training tape in real time, using a hidden beeper that beeped every 10 s. Reliability of each coder (eight students of psychology) was measured against the program manager, who was trained by the chief neonatologist. Reliability on 30 infants at different ages averaged 92%, $\kappa = .85$, and reliability remained the same during the last hour of the observation.

The time series of sleep–wake states, each consisting of 1,440 data points, was analyzed with spectral analysis according to Gottman (1981). Linear trends were removed, and then the residualized time series was analyzed with a Blackman–Tukey Fourier analysis using a Tukey–Hanning smoothing function. Fourier analyses decompose the time series into separate cycles, superimposed on a constant, and each cycle is defined by its power (amplitude) and frequency. Sleep–wake cyclicity was indexed by the amplitude of the basic cycle, the tallest ''spike'' in the periodogram. High amplitudes imply that more variance in infant states is accounted for by rhythmic oscillations of sleep and wakefulness. The amplitude of the basic cycle on the spectral density function of infant sleep and cardiac data (in seconds squared per hertz) has been used as a predictor of infant maturity during the neonatal period and has been shown to predict more optimal outcomes (Diambra & Menna-Barreto, 2004).

Cardiac vagal tone (Vna) at 32 and 37 weeks GA. Approximately 10 min of heart rate were recorded during quiet sleep from the cardiac monitor using a special A/D adaptor that registered the R waves and computed the R-R interval (heart period in milliseconds). Vna was quantified from the ECG output using Porges (1985) MXEdit system by an assistant trained to reliability at Porges' laboratory. After editing to remove artifacts, the system converts heart period data into time-based data sampled in 200-ms epochs, determines the periodicities of heart rate with a 21-point moving polynomial, filters the time series to extract the heart period within the frequency band of spontaneous breathing of neonates, and calculates the vagal tone index.

Infant medical risk. The CRIB (International Neonatal Network, 1993) is an objective quantitative measure of neonatal risk for preterm infants that evaluates birthweight, GA, minimum and maximum fraction of inspired oxygen, minimum base excess during the first 12 hr, and the presence of congenital malformations. Scores are summed to create the total CRIB score, and higher scores represent a greater risk. The CRIB scores were divided into high- and low-risk groups using the median split. CRIB scores averaged 0.29 in the low-risk group (*SD* = 0.45, range = 0–1) compared to 4.55 in the high-risk group (*SD* = 2.88, range = 2–13). Birth weights were 1367.2 g (*SD* = 436.8) for the low-risk and 1098.4 g (*SD* = 320.7) for the high-risk group, GA was 31.6 weeks for the high-risk group (*SD* = 1.9) and 29.3 (*SD* = 2.3) for the low-risk group. Significantly more infants in the low-risk group had maximum base excess in the first 12 hr in the optimal range of >−7.00 mmol/L compared to the high-risk group, $\chi^2 = 35.22$, $p < .01$, and minimum and maximum appropriate FiO_2 in the first 12 hr were in the more optimal range of 0.00 to 40.00 in the low- compared to the high-risk group, $\chi^2 = 27.93$, 36.14, $p < .01$, respectively. Validation for using the CRIB for developmental research is indicated by the lower performance of the high-risk group on the Neonatal Behavior Assessment Scale (Brazelton, 1973) upon discharge, indicating poorer neurobehavioral maturation, and the concordance between groups created by the CRIB and those created by the Neuro-Behavioral Risk Score (NBRS; Brazy, Eckerman, Oehler, Goldstein, & O'Rand, 1991), a comprehensive index of medical risk for premature infants based on the entire hospitalization period.

First Year: Emotion Regulation

Three months. Emotion regulation was assessed with the BRP (Garcia-Coll et al., 1988). Infants are presented with 17 stimuli in various modalities (sound, light). Each stimulus is presented for 20 s, with a 10-s break between stimuli. Stimuli are organized in increasing intrusiveness, from simple unimodal stimuli (bell sound, flashlight) to aversive, multimodal stimuli (fast-moving car, flashing lights, and loud noise). Infants sat in an infant seat, and a trained examiner presented the stimuli in a predetermined order. Microanalytic coding was conducted using a computerized system and considered five categories of behavior (Gaze, Affect, Vocalizations, Gross and Fine Motor, and Regulatory Behavior), each including a set of behaviors. Codes in the regulatory behavior category were based on previous research and included distancing (e.g., arching), clear gaze aversion from stimulus, autonomic activity (deep or quick breathing and related motor activity; Bazhenova et al., 2001), and self-soothing behavior (e.g., hand to mouth, playing with strap of chair), which were summed into an Emotion Regulation composite. The negative affect code from the Affect category was indicated when the infant showed fuss or cry behavior with negative facial expression. This negative emotionality code was examined in relation to the Emotion Regulation composite. Two coders coded the BRP while the tape was running in real time, shifting to slow motion to determine short events. Reliability was examined for 30 infants and exceeded 88% on all categories. Mean reliability was 93%, κ = .81.

Six months. Stress reactivity was examined during an arm-restraint paradigm (Stifter & Braungart, 1995). Mothers were asked to interact with the infant for 3 min and then to hold the infant's arm in addition to maintaining still face for 2 min. Free face-to-face play was then resumed for additional 2 min. Microcoding was conducted for four categories (Gaze, Affect, Vocalizations, and Regulatory Behavior). Infant regulatory behaviors were similar to 3 months with additional behaviors that become available at this age. These included autonomic behaviors, clear gaze aversion from mother's face, distancing (turning around, arching), self-soothing behavior, object manipulation, and diversion tactics (reorienting, nonnegative communications, avoidant behaviors; Braungart-Rieker & Stifter, 1996) and these were summed to create the Emotion Regulation composite. Similar to 3 months, the infant negative affect code from the Affect category was examined in relation to the Emotion Regulation composite. Two coders, blind to previous information, coded the arm-restraint episode while the tape was running in real time, shifting to slow motion to determine short events. Reliability was examined for 32 infants and exceeded 86% on all categories. Mean reliability was 92%, κ = .79.

Twelve months. At the end of the 12-month visit, mothers and infants participated in a separation–reunion episode. Mothers left the room and infants remained with a stranger for 3 min. Mothers then returned, and 3 min of mother–child reunion were videotaped. Microcoding was conducted separately for the separation and reunion episodes. The separation codes included four categories: Gaze, Affect, Vocalizations, and Activity. Reliability, computed on 28 interactions, exceeded 87% in all categories. Reliability averaged 92%, κ = .81 (range = .70–.86). Two composites were created for the separation codes on the basis of a principal components factor analysis (Feldman & Eidelman, 2004): Emotion Regulation and Negative Affect. The first factor loaded on neutral affect (.89), no vocalizations (.83), active play (.75), and toy manipulation (.71), and these were averaged into the Emotion Regulation construct during maternal separation (α = .73). The second factor loaded positively on negative affect (.91) and negatively on positive affect (−.68) and the negative affect code was used to index negative emotionality at 12 months and was examined in relation to the Emotion Regulation construct.

Second Year: Attention Regulation

Focused attention at 12 and 24 months. Focused attention was assessed during cognitive testing at 12 and 24 months on the Bayley Scale for Infant

Development–Second Edition (Bayley, 1993). Item-by-item coding of the videotaped session was conducted by coders who were blind to the test results and coded each item on a scale from 1 to 5 for on-task focused attention, level of interest, orientation to object, orientation to person, impulsivity, frustration tolerance, negative affect, and positive affect. A principal components factor analysis identified two factors with an eigenvalue above 2, and similar factors emerged at 12 and 24 months. The first factor loaded positively on focused attention (.88), maintaining interest (.84), and orientation to object (.81), and negatively on negative affect (−.73); had an eigenvalue of 3.19; and explained 42.2% of the variance. The average of items with positive loading was used to index attention regulation capacities and was termed *Focused Attention*. Focused Attention had low associations with the Bayley (1993) MDI scores at 12 months, $r = .20$, $p < .05$, and 24 months, $r = .22$, $p < .05$, and correlations emerged between delayed response and MDI scores at 24 months, $r = .19$, $p < .05$.

Delayed response at 24 months. Infants observed an experimenter randomly hiding an attractive object under one of two cups located in the right or left sides of the infant and were then asked to retrieve the toy after a 20-s delay. Performance on this task has shown to depend on the maturation of the prefrontal cortex in humans and monkeys. Infants were tested for 12 trials and the final score was the number of successful retrievals (Diamond & Doar, 1989). Focused attention and delayed response at 24 months showed a medium-level correlation, $r = .50$, $p < .01$, suggesting that these attention regulation measures tap a distinct, albeit related, skill from general cognitive abilities, associated with the capacity to maintain attention to a task in the face of distractions. The delayed response task is an index of working memory capacity, an important component of attention regulation and a precursor of executive functions (Diamond, 2002).

Five Years: Self Regulation

Executive functions. The NEPSY (Korkman et al., 1998) is a standardized test for neuropsychological abilities in children. The executive functions domain, used here, assesses the ability to inhibit impulsive responding, selectively attend to auditory and visual information, and the ability to plan, adapt, and maintain and change set. The executive function domain includes four subtests. *Tower* assesses planning, monitoring, self-regulation, and problem solving. The child moves three colored balls to target positions on three pegs quickly in the prescribed number of moves according to a set of rules. Part A of the *Auditory Attention and Response Set* assesses the capacity to attend selectively to simple auditory stimuli during a monotonous task. The child listens to 180 words on audiotape and responds only to the target word *red* by putting a red foam square in a box. Part B assesses the ability to shift set, maintain a complex mental set, and regulate response according to matching and contrasting auditory stimuli. The child is asked to respond to contrasting stimuli, changing the set from Part A (putting a yellow square when hearing *red* and vice versa), as well as hold a novel matching set (putting a blue square when hearing *blue*), which serves as a distractor. The first item of *Visual Attention* assesses the ability to attend to a visual stimulus and locate target stimuli (cats) quickly in a random array. The second item tests complex selective visual attention—the child locates and compares two target faces quickly in a linear array. The task assesses speed and accuracy of visual scanning, attention to details, and impulsivity. *Knock and Tap* examines self-regulation and the ability to inhibit impulses evoked by motor–visual stimuli that conflict with verbal direction (inhibition of dominant response). The child is taught a pattern of motor responses (‘‘When I tap you knock’’ and vice versa) and has to inhibit the impulse to imitate the examiner’s actions. Having learned that set, the child is required to learn a new set, shift sets, and inhibit the previously learned motor response.

Behavior problems. Behavior adaptation was indexed by the existence of fewer behavior problems as measured by the Child Behavior Checklist (CBCL; Achenbach & Edelbrock, 1983). Mothers completed the CBCL, a self-report measure of child behavior problems that includes 113 items each rated on a 3-point scale. Items are clustered into three scores: total behavior score, internalizing score, and externalizing score. The CBCL is the most widely used instrument for behavior problems in children with established reliability and validity.

Self-restraint. Children received an attractively wrapped gift. The tester then left the room for 3 min, put the gift on a table next to the child, and asked the child not to touch the gift until she returned. Microcoding considered five behaviors: no touch, peek with no reaching, hand reach, touch, and open gift wrap. Two coders, blind to previous information, coded the episode. Reliability was examined for 28 children and exceeded 90% on all categories. Mean reliability was 96%, $\kappa = .92$. Two composites were created: The combined proportions of no touch and peek (compliance) and the latency to the first touch (resisting temptation), and their standardized scores were averaged into a Self-Restraint score. On all variables, scores greater than 3 *SD* above or below the mean were considered outliers and excluded from analysis.

Results

Results are reported in four sections. In the first, descriptive statistics are presented and differences between infants born at high and low medical risk are assessed. The second section presents correlations between composite measures of physiological, emotional, and attentional regulation—aggregated to index the different levels of regulation—and the three aspects of self-regulation: executive functions, behavior problems, and self-restraint. In the third section, regression models predicting the three aspects of self-regulation from physiological, emotional, and attention regulatory functions are described. The final section presents structural models testing direct and mediated paths from regulatory functions across the first years to outcomes at 5 years.

Differences in Regulatory Functions Between Infants Born at High and Low Medical Risk

Neonatal period—physiological regulation. A multivariate analysis of variance (MANOVA) with biological risk (high, low) and infant gender as the between-subjects factors was computed for the neonatal measures: Sleep–wake cyclicity at 32 and 37 weeks GA and Vna at 32 and 37 weeks GA yielded a significant overall main effect for biological risk, Wilks's $F(4, 117) = 2.65$, $p < .01$, $\eta^2 = .13$. Univariate tests (Table 1) show that infants born at high risk had lower Vna at both times and showed a less organized sleep–wake cycle at 37 weeks GA.

A main effect for infant gender was also found, Wilks's $F(4, 117) = 2.21$, $p < .05$, $\eta^2 = .08$. Univariate tests indicated that boys showed poorer sleep–wake cyclicity at 37 weeks GA, $F(1, 115) = 4.126$, $p < .05$, $\eta^2 = .04$. No interaction effect was found. Sleep–wake cyclicity and cardiac vagal tone were individually stable, sleep–wake cyclicity, $r = .48$, $p < .01$, and vagal tone, $r = .51$, $p < .01$, and were each averaged into a single composite. Sleep–wake cyclicity at 37 weeks GA, but not at 32 weeks GA, was related to lower negative emotionality, indexed by the proportion of cry states during the observation, $r = -.23$, $p < .01$.

First year—emotion regulation. A MANOVA with biological risk and infant gender as the between-subjects factors computed for emotion regulation across the first year yielded a main effect for biological risk, Wilks's $F(3, 118) = 4.68$, $p < .01$, $\eta^2 = .11$. High-risk infants showed lower emotion regulatory capacities at each age; they used less regulatory behaviors during the BRP and arm-restraint episodes and had lower capacities for coping with maternal separation at 12 months (Table 1). Infants born at high risk showed higher negative emotionality at 3 months (low risk: $M = .15$, $SD = .14$; high risk: $M = .22$, $SD = .11$), 6 months (low risk: $M = .17$, $SD = .15$; high risk: $M = .24$, $SD = .19$), and 12 months (low risk: $M = .14$, $SD = .14$; high risk: $M = .21$, $SD = .15$), Wilks' $F(3, 118) = 4.89$, $p < .01$, $\eta^2 = .12$. Regulatory behaviors were related to lower levels of negative emotionality across infancy; 3 months, $r = -.48$; $p < .01$, 6 months, $r = -.41$, $p < .01$; and 12 months, $r = -.39$, $p < .01$. Emotion regulation indices were interrelated: between 3 and 6 months, $r = .46$, $p < .01$; between 3 and 12 months, $r = .38$, $p < .01$; and between 6 and 12 months, $r = .37$, $p < .01$, and the three measures were averaged into an Emotion Regulation composite.

Second year—attention regulation. A MANOVA with biological risk and gender as between-subjects factors of the three measures of attention—focused attention at 12 and 24 months and delayed response at 24 months—showed an overall main effect for biological risk, Wilks's $F(3, 118) = 2.83$, $p < .05$, $\eta^2 = .08$ (Table 1). High-risk infants showed less focused attention at 12 months and lower delayed response. Measures of attention regulation were interrelated: focused attention at 12 and 24 months, $r = .36$, $p < .01$; focused attention and delayed response at 24 months, $r = .50$, $p < .01$; and focused attention at 12 months and delayed response, $r = .31$, $p < .01$. Their standardized scores were averaged into an Attention Regulation composite. Differences between the high- and low-risk groups were observed on the Bayley (1993) MDI at 6 months, $F(1, 124) = 3.79$, $p < .05$, $\eta^2 = .03$, but not at 12 and 24 months.

Five years—self-regulation. At 5 years differences between children born at high and low risk were found in executive functions, suggesting poorer inhibition, planning, and multimodal coordination among children born at higher medical risk, Wilks's $F(4, 117) = 2.56$, $p < .01$, $\eta^2 = .08$ (Table 1). High-risk children scored lower on the Tower and Visual Attention subscales. No differences between

Table 1

Differences in Study Variables Between Infants Born at High and Low Medical Risk

	High risk			Low risk				
Regulatory functions	*M*	*SD*	Range	*M*	*SD*	Range	Univariate *F*	η^2
Neonatal period: Physiological regulation								
Sleep–wake cyclicity[a]—32 weeks GA	7.14	6.76	0.00–22.31	12.55	10.23	0.00–34.56	*ns*	
Vagal tone (Vna)—32 weeks GA	0.92	0.76	−1.69–3.55	1.43	1.02	−0.10–4.98	5.11*	.05
Sleep–wake cyclicity[a]—37 weeks GA	9.87	7.23	0.00–32.79	14.84	9.04	0.00–58.09	5.18*	.05
Vagal tone (Vna)—37 weeks GA	1.02	1.01	−.09–4.86	1.81	1.29	0.01–7.22	8.03**	.08
First year: Emotion regulation								
Emotion regulation (BRP): 3 months[b]	0.21	0.15	.09–.38	0.33	0.22	.10–.53	4.12*	.04
Emotion regulation (arm restraint): 6 months[b]	0.27	0.18	.08–.39	0.39	0.21	.17–.57	8.55**	.08
Emotion regulation (separation–reunion): 12 months[b]	0.09	0.05	.00–.22	0.16	0.10	.00–.43	3.98*	.04
Second year: Attention regulation								
Focused attention[c]—12 months	2.11	0.94	1.00–3.76	2.74	0.87	1.34–4.52	5.44*	.06
Focused attention[c]—24 months	2.97	1.12	1.33–4.25	3.24	1.22	1.25–4.67	*ns*	
Delayed response—24 months[d]	6.23	2.24	1–12	8.76	2.87	3–12	4.12*	.05
5 years: Self-regulation								
Executive function	91.11	14.29	56–121	99.02	12.19	62–128	5.41*	.06
Behavior problems (CBCL Total)	48.78	11.01	26–78	46.29	10.91	28–70	*ns*	
CBCL–Externalizing	45.72	9.05	26–77	43.11	10.53	26–76	*ns*	
CBCL–Internalizing	46.29	10.91	30–70	48.78	11.01	28–69	*ns*	
Self-restraint: Compliance[b]	0.64	0.34	.24–.91	0.72	0.37	.34–.88	*ns*	
Self-restraint: Resisting temptation[e]	40.75	37.30	5.00–180.00	44.92	32.87	7.00–180.00	*ns*	

Note. *df* range = (1, 115) to (1, 118).

GA = gestational age; BRP = Behavior Response Paradigm; CBCL = Child Behavior Checklist.

[a] Numbers represent amplitudes of the basic cycle on the power spectra (s^2/Hz) derived from 4 hr of observations.

[b] Numbers represent proportions of regulatory behaviors during the BRP, arm-restraint, separation–reunion, and temptation paradigms.

[c] Numbers are rated on a scale of 1–5.

[d] Numbers represent the number of successful trials (out of six) on the delayed response paradigm.

[e] Numbers represent latencies in seconds to the first touch in the temptation paradigm.

*$p < .05$. **$p < .01$.

groups were detected in behavior adaptation and self-restraint.

Correlations Between Physiological, Emotional, Attentional, and Self-Regulatory Capacities

Partial correlations between measures of regulation at the physiological, emotional, attentional, and self-regulatory levels, controlling for infant medical risk, appear in Table 2.

As seen, measures of regulation were interrelated. Correlations emerged between vagal tone and sleep–wake cyclicity. Vagal tone was related to emotion and attention regulation and to the three measures of self-regulation. Sleep–wake cyclicity correlated with emotion and attention regulation and executive functions. Emotion and attention regulation were interrelated and measures of emotion and attention regulation were related to the three measures of self-regulation at 5 years, which were also interrelated. However, the magnitudes of the correlations were mild to medium, indicating that most of the variance is independent and much change occurs over time.

Predicting Self-Regulatory Capacities at 5 Years

To examine the contributions of regulatory functions to self-regulation at 5 years, three hierarchical multiple regressions were computed, predicting executive functions, behavior problems, and self-restraint from measures across the first 2 years. In each model, medical risk indexed by the CRIB score was entered in the first step to partial out variance related to biological risk. In the next two steps, the neonatal measures were entered, vagal tone and sleep–wake cyclicity. The next step included emotion regulation across the 1st year, and the final step measures of attention regulation across the second year. Results appear in Table 3.

Table 2
Partial Correlations Among Study Variables Controlling for Infant Medical Risk

	1	2	3	4	5	6
Vagal tone (neonatal)						
Sleep–wake cyclicity (neonatal)	.21*	—				
Emotion regulation (first year)	.30**	.27**	—			
Attention regulation (second year)	.22*	.31**	.33*	—		
Executive functions (5 years)	.26**	.45**	.42**	.45**	—	
Behavior problems (5 years)	−.29**	−.10	−.22*	−.27**	−.29**	—
Self-restraint (5 years)	.18*	.06	.26**	.29**	.42**	−.23*

*$p < .05$. **$p < .01$.

Table 3
Predicting 5-Year Outcomes: Executive Functions, Behavior Adaptation, and Self-Restraint

	Executive functions			Behavior problems			Self-restraint		
Criterion predictors	Beta	R^2 change	*F* change	Beta	R^2 change	*F* change	Beta	R^2 change	*F* change
Medical risk (CRIB)	−.11	.02	2.38	.07	.02	2.56	−.10	.02	2.37
Vagal tone	.15*	.07	7.54**	−.18*	.04	4.12*	.19*	.04	4.22*
Sleep–wake cyclicity	.24*	.12	13.65**	−.09	.01	0.85	.05	.00	0.85
Emotion regulation (1st year)	.35*	.10	16.13**	−.19*	.03	3.99*	.21*	.04	4.52*
Attention regulation (2nd year)	.36**	.11	18.22**	−.25*	.04	4.86*	.30*	.04	5.97*
R^2 total	.42, $F(7, 110) = 11.97$, $p < .01$			.14, $F(7, 112) = 2.57$, $p < .05$			.14, $F(7, 113) = 2.39$, $p < .01$		

*$p < .05$. **$p < .01$.

As seen, all models were significant. Executive functions were uniquely predicted by physiological regulation—vagal tone and sleep–wake cyclicity—by emotion regulation and by attention regulation. Behavior problems and self-restraint were predicted by vagal tone, emotion regulation across the first year, and attention regulation across the second year.

Structural Modeling

Structural modeling was used to examine paths to self-regulatory capacities at 5 years from the three levels of regulation across early childhood. Modeling was conducted with Amos 4 (Arbuckle & Worthke, 1999), using the maximum likelihood estimation method. Five indices assessed the model fit; the chi-square statistic and the goodness-of-fit index (GFI) examine the general fit. The adjusted goodness-of-fit index (AGFI) considers model adaptiveness taking into account the degrees of freedom, and the normed fit index (NFI) provides an index for the relations between the proposed model and an independence model that assumes no associations between variables. The root mean square error of approximation (RMSEA) provides an index of model parsimony. A nonsignificant chi-square; a GFI, AGFI, and NFI of .90 or above; and RMSEA of .05 or below indicate a close fit to of the model to the data (Byrne, 2001).

Structural Model 1. Model 1 tested the hypothesis that links between the four levels of regulation—physiological, emotional, attentional, and self-regulation—are organized in a step-by-step hierarchical fashion. According to this model, direct paths between neonatal physiological substrates and the 5-year outcomes—for instance, between neonatal vagal tone and executive functions at 5 years—would not add to model parsimony. Links were charted between the latent factor of Vagal Tone (Vna at 32 and 37 weeks GA) and the latent factor of Sleep–Wake Cyclicity (cyclicity at 32 and 37 weeks GA) with the latent factor of Emotion Regulation in the 1st year (regulation at 3, 6, and 12 months). The two latent factors of Vagal Tone and Sleep–Wake Cyclicity were bidirectionally linked. The latent Emotion Regulation factor was then linked with the latent Attention Regulation factor (focused attention at 12 and 24 months and delayed response). Attention Regulation was then linked to the three outcomes at 5 years: the latent factor of Behavior Problems (externalizing and internalizing symptoms), the Executive Functions score of the NEPSY, and the latent factor of Self-Restraint (compliance and resisting temptation). Results showed that the model provided an acceptable, but not a good fit to the data; $\chi^2(98) = 144.62$, $p = .02$, NFI = .82, GFI = .87, AGFI = .82, RMSEA = .07, with the chi-square statistic being significant and the RMSEA index above .05 (Byrne, 2001).

Structural Model 2. In this model, all paths charted in Model 1 remained and three additional direct paths were charted, between Vagal Tone and Attention Regulation, between Vagal Tone and Behavior Adaptation, and between Sleep–Wake Cyclicity and Attention Regulation. These paths were added based on research showing direct links between neonatal vagal tone with cognition and attention and behavior problems in premature infants during the toddler and preschool years (Doussard-Roosevelt et al., 1997, 2001; Feldman & Eidelman, 2009), and between neonatal sleep–wake cyclicity and toddlers' attention (Feldman, Eidelman, et al., 2002; Feldman, Weller, et al., 2002). Same-level bidirectional links were added at 5 years to reflect the interrelatedness of these functions—a bidirectional link between Behavior Problems and Executive Functions and from Executive Function to Self-Restraint—in line with research suggesting that self-restraint develops on the basis of inhibitory abilities (Kochanska & Knaack, 2003). This model provided a good fit to the data, $\chi^2(92) = 78.11$, $p = .14$, GFI = .93, AGFI = .92, NFI = .91, RMSEA = .04. This model was a significant improvement over Model 1, $\Delta\chi^2(6) = 66.51$, $p < .01$, confirming the hypothesis that the progression from neonatal physiological regulation to 5-year outcome consists of both direct and mediated paths. Results of structural Model 2 are presented in Figure 1. Conducting the same structural

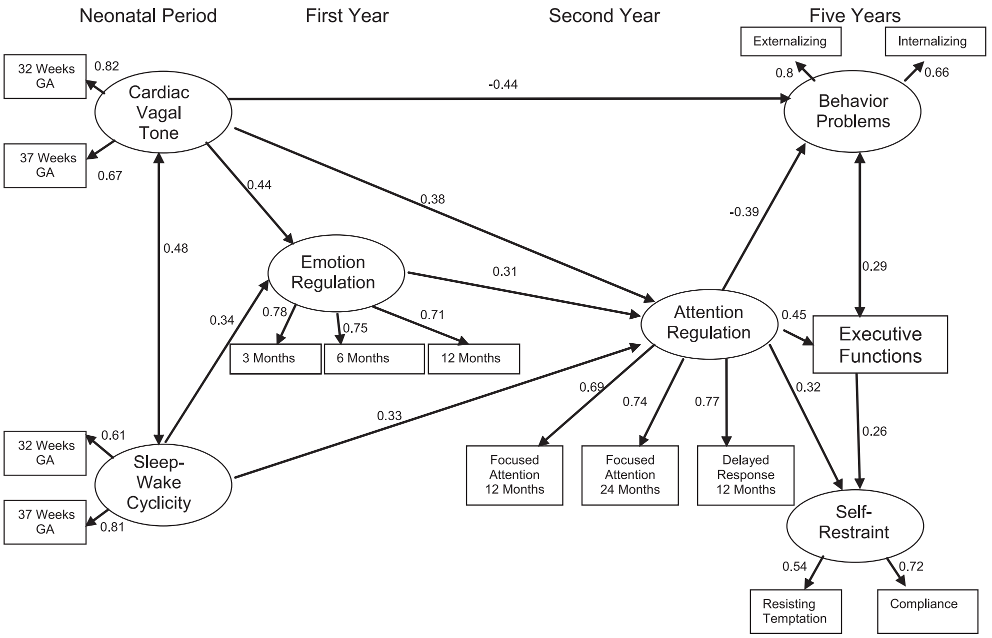

Figure 1. Model 2 standardized coefficients indicating paths from physiological regulation in the neonatal period to self-regulation at 5 years.

Note. Paths are charted between each level of regulation and the next: from the latent factors of cardiac vagal tone and sleep–wake cyclicity, each including measurement at 32 and 37 weeks GA, to the latent factor of emotion regulation, including measures at 3, 6, and 12 months. Links are then charted between the latent factor of emotion regulation to the latent factor of attention regulation, consisting of focused attention at 12 and 24 months and delayed response at 24 months. This latent factor is then linked with the three aspects of self-regulation at 5 years: the latent factor of behavior adaptation, including externalizing and internalizing symptoms; the executive function score; and the latent factor of self-restraint, including compliance and resisting temptation. Within-level bidirectional paths are charted between cardiac vagal tone and sleep–wake cyclicity and between behavior adaptation and executive function. Finally, direct links are charted from neonatal vagal tone to attention regulation and behavior adaptation and from sleep–wake cyclicitiy to attention regulation. Beta coefficients above .25 are significant at $p < .05$, $\chi^2(92) = 78.11$, $p = .14$, goodness-of-fit index = .93, adjusted goodness-of-fit index = .92, normed fit index = .91, root mean square error of approximation = .04.

model separately for the high- and low-risk groups showed similar results in the two models, although the small sample size in each group precludes definitive conclusions.

Discussion

Several global questions guided this study. The first question asks whether the term *regulation,* extensively used in psychological research, has a specific meaning or whether it is too broad a construct to be of any scientific use. The second question taps the issue of developmental continuity and the insights that can be gained from the study of regulatory functions to the debate on continuity in development. The third question considers whether the assessment of regulation across the first years is consistent with neurobiological models on brain maturation. The data provide some answers to these questions that, as typically is the case in the study of core concepts, need to be further researched and refined. Yet, several caveats should be noted in the interpretation of the findings in relation to these questions. First, the hierarchical-integrative model provides one theoretically plausible perspective for the interpretation of the data, and alternative models should be considered as well. Second, the present study focused on regulatory capacities without considering the critical impact of the parent–child relationship on the emergence of regulatory skills. Finally, the period between 2 and 5 years is an important time point for the maturation of self-regulation (Kopp, 1982), and an additional observational point around the child's third birthday would have provided important information.

A remarkable coherence was found for the measures of regulation across the first 5 years. Associations emerged between measures of regulation at the same time point, for instance, sleep–wake cyclicity and vagal tone at term age or the three aspects of regulation at 5 years; between the same factor measured at different time points, such as focused attention at 12 and 24 months; between indices of the same level measured at different times, such as emotion regulation at 3, 6, and 12 months; and between the four levels of regulation, physiological, emotional, attentional, and self-regulation. Such across-the-board coherence may suggest that the construct of *regulation* is continuous across time, measures, and levels of observations and, thus, has a heuristic value as a core concept in the study of early development. This coherence may also suggest that measures that assess microlevel changes in physiology and behavior capture a basic feature of the infant's orientation to the environment, and their stability reflects the child's habitual mode of handling information, meeting challenges, or maintaining homeostasis. Notwithstanding this coherence, correlations were typically low to medium in magnitude. This suggests that much of the variance is nonshared and points to the malleability of the trajectories of regulatory functions during the plastic period of early development. It is possible that the lack of associations between physiological and behavioral measures observed in previous research (e.g., Weinberg & Tronick, 1996) may be related to the relatively low magnitude of correlations among levels of regulation.

In addition to coherence, all variables tested in this study address two central aspects in the construct of *regulation*: They tap the balance between mechanisms of excitation and inhibition and they index the ongoing interplay between environmental challenges and internal organization. As such, these variables chart a developmental progression in the infant–environment exchange. The neonatal measures addressed the infant's handling of changes inherent in the internal or external milieu, such as light–dark cycle or the sympathetic—-parasympathetic interplay. The regulatory goal at this level is for the body to adapt to cyclic changes between polarized states, whether occurring in seconds, hours, or seasons. The emotion regulation factors assessed the infant's response to disruptions in homeostasis, and the regulatory goal was to maintain a steady state or return to a baseline state in such moments. The attention regulation measures required that the infant not only maintain a steady state but be able to learn, keep focus, retain a goal in memory, and contain the frustrations inherent in trial-and-error and skill acquisition. The regulatory goal, therefore, is mastery of the environment, not a mere withholding of state in response to its challenges. These three levels of regulation cumulatively predicted self-regulation in the preschool years, which carry the goals of consolidating the sense of self and utilizing higher order skills, such as planning, inhibition, and the hierarchical order of input, for the acquisition of meaningful knowledge. As seen, regulatory functions were consistently related to lower negative emotionality: Sleep–wake cyclicity was related to less cry states, emotion regulatory tactics correlated with less negative emotions, and focused attention was related to lower negative affect. Thus, a bidirectional influence may exist between the development of regulatory functions and the capacity to manage negative affect beginning at birth, which leads, in turn, to the emergence of more mature regulatory skills across early development. These findings underscore both the negative impact of inborn dispositions for negative emotionality on the formation of regulatory structures as well as the risk imposed by environments marked by high levels of stress and negative affect to the consolidation of the child's physiological, emotional, attentional, and self-regulatory skills.

Differences between infants born at high and low medical risk changed across development. Whereas high-risk infants performed less optimally on the neonatal and 1st-year measures, they showed comparable focused attention at 2 years, and behavior adaptation and self-restraint at 5 years to the low-risk group. Similarly, although differences in general cognitive skills emerged at 6 months, they attenuated by 12 and 24 months. These findings point to the plasticity of development, even in cases of high medical risk. With time, the effects of contextual conditions on regulatory functions may increase and the balance between biological givens and environmental provisions may shift toward the environmental end. Still, the links between neonatal regulation and 5-year outcome for the entire sample may suggest that it is those high-risk infants with more intact physiology that eventually reach more optimal growth. According to Rutter (2006), the study of resilience—defined as positive outcome despite initial adversity—must test specific mechanisms that could have led to the unexpected outcome. Future research is thus needed to tease apart global medical risk into specific physiological processes and examine their interactions with ongoing parent–infant co-regulatory experiences as they shape the trajectories of regulatory functions.

The longitudinal assessment of specific developmental abilities, such as regulatory skills, may contribute to the debate on developmental continuities, among the central controversies in developmental thought. Although some authors question whether continuity or change is the typical course of early development, most agree that some form of continuity does exist, particularly in high-risk conditions (Emde, 1994; Rutter, Kim-Cohen, & Maughan, 2006). The two structural models tested here may represent two mechanisms of continuity. The first mechanism describes gradual, step-by-step continuity where each level of development directly contributes to the next, assimilates into it, and shapes, in turn, the next level. This developmental continuity model is consistent with the dynamic system's view on the development of perception, action, emotion, and communication systems (Fogel, 1993; Lewis, 2005; Thelen & Smith, 1994) and underlies, to some extent, the Piagetian model of development. As seen, this approach was somewhat consistent with the data, and the first model received moderate support. Still, it appears that early-maturing brain-stem-mediated mechanisms contribute to regulatory outcomes not only by initiating the step-by-step continuity but also through a direct impact on higher cortical functions, as suggested by Luria (1973). Cardiac vagal tone contributed directly to the attentional and self-regulation levels, and sleep–wake cyclicity contributed to attention regulation, above and beyond the mediated paths. Theoretically, the model combining direct and mediated paths suggests that although development is generally gradual and functioning at one point is constrained by the system's state at a previous point, it is also highly dependent on initial conditions. Such initial conditions shape outcomes not only by providing the starting point for gradual growth but also through direct impact on each level of functioning across the developmental span (Feldman & Eidelman, 2009). As such, individual variations in fundamental physiological support systems at critical time points may shape later development through both repeated iterations and direct impact. Because the development of regulatory functions integrates internal and external inputs into an organized ability, assessing the trajectories of regulatory skills may be especially useful to the debate on developmental continuity.

Finally, the findings are consistent with the hierarchical-integrative model on brain maturation (MacLean, 1990; Tucker et al., 2000). The level-by-level correlations between brain stem, limbic, and cortical regulatory mechanisms across the first 5 years of life is consistent with the evolutionary perspective adapted by these models and the theoretical comparability of ontogenesis and phylogenesis. The findings that both direct and mediated paths were charted from the physiological, emotional, and attentional levels to aspects of self-regulation are in line with current models on the neurobiological basis of the self (Damasio, 2003; Edelman, 1989, 2004; Llineas, 2001). These models suggest that self and consciousness are supported by multiple first- and higher order systems across the neuroaxis, in particular systems that register second-by-second changes in the internal milieu and keep, through synchronous integration, a continuous mapping of the self as an emergent structure. The contribution of cardiac vagal tone across the period corresponding to the third trimester of pregnancy to the development of regulatory functions at all levels supports Porges (2003) polyvagal theory and marks the vagal system as an important foundation for the child's later capacity to manage stress, orient, focus attention, and flexibly adapt to the environment. It thus appears that a developmental perspective on regulatory functions matches the bottom-up perspective on brain functioning that is proposed to underlie the execution of complex emotion regulatory and neurocognitive tasks (Damasio, 1994).

Limitations of the study are important to consider in the interpretation of the findings. An additional assessment at around 3 years, during the emergence of the sense of self (Kopp, 1982), would have contributed to the understanding of the trajectories of regulatory processes. In addition, the study measured premature infants, and although all infants were neurologically intact and premature infants typically follow the same developmental course as full-term infants, replication in full-term samples is required. Further, although it is proposed that each level is integrated into the next level and supports its functioning, physiological and emotional regulatory processes were not measured beyond infancy, and their assessment at each time point would have contributed to a fuller model. In addition, indices of the parent–child coregulation were not included, yet such information is much needed in order to provide a more comprehensive view on the development of regulatory functions. Finally, from a theoretical standpoint, one can argue whether the term *development*, defined as the change in a specific function over time (Werner, 1964), applies to the multifaceted, multilevel construct of regulation, and the approach taken here, which underscores the coherence of regulation across time and levels, is open for debate.

Future research should further specify the construct of *regulation* and its implications by assessing multiple brain-stem-mediated systems at the neonatal period, related to hunger, pain, and time-keeping mechanisms, and chart their impact across childhood, incorporate second-by-second assessments of parent-child coregulatory experiences into models on the development of regulation, and evaluate the contribution of early regulatory abilities in the physiological, emotional, attentional, neuro-cognitive, social, and moral domains to the individual's well-being, adaptation, intimate relationships, and the capacity to self-regulate across the life span.

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