IV. REACTIVITY AND SLEEP IN INFANTS: A LONGITUDINAL OBJECTIVE ASSESSMENT

Gali S. De Marcas, Nirit Soffer-Dudek, Shaul Dollberg, Yair Bar-Haim, and Avi Sadeh

ABSTRACT Sleep patterns and temperament in the first year of life are closely related. However, research utilizing objective, rather than subjective measurements of sleep and temperament is scarce and results are inconsistent. In addition, a relative lack of longitudinal data prevents inference of causality between the two constructs. In this study, infant sleep was objectively assessed among 95 infants at 3, 6, and 12 months-of-age with an actigraph in the home setting. Reactivity to sound, light, and touch, a specific aspect of temperament, was behaviorally assessed at 3 and 6 months, both during sleep (at home) and during waking (at the laboratory). Expected maturational trends were recorded in sleep, with a temporal increase in sleep efficiency and percent of motionless sleep. Quadratic (i.e., inverse U shape) relations were found, especially among girls, when predicting change in sleep by reactivity thresholds, suggesting that both hyposensitive and hypersensitive infants are at risk for poor sleep quality. These are the first research findings suggesting that low reactivity in infancy might be associated with compromised sleep quality. The observed nonlinear effects may account for null or inconsistent results in previous studies that explored only linear associations between temperament and sleep. Future studies should address both extremes of the temperament continuum when exploring relations with sleep patterns.

Sleep and temperament in infancy are closely linked and both have important developmental implications (Ednick et al., 2009). Within the systems perspective, both sleep and temperament are among the child's intrinsic characteristics that exert influence on and are affected by the *child context* (see El-Sheikh & Sadeh, Figure 1, Chapter I, in this volume).

Early sleep problems are related to psychopathology and behavioral difficulties later in development (see Ednick et al., 2009; Gregory & Sadeh,

---

Corresponding author: Avi Sadeh, School of Psychological Sciences, Tel Aviv University, Tel Aviv 69978, Israel, email: sadeh@post.tau.ac.il
This research was supported by the Israel Foundation Trustees.

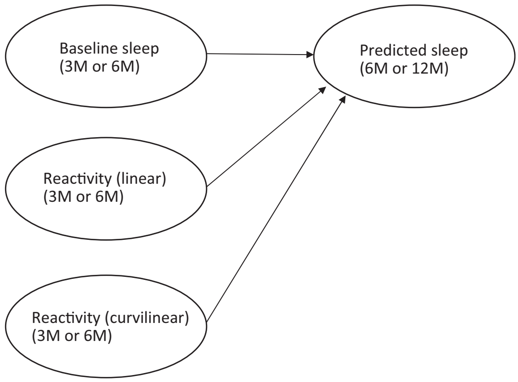

FIGURE 1.—The models tested. Three prospective models were tested: from age 3 months to 6 months, from age 3 months to 12 months, and from age 6 months to 12 months.

2012, for reviews). Sleep disorders in young children are persistent; for instance, 41% of children who had sleep difficulties at 8 months-of-age still had them at age 3 years (Zuckerman, Stevenson, & Bailey, 1987). Early screening of sleep-related issues may be useful for prevention of cognitive and behavioral deficits (Ednick et al., 2009). In addition, sleep problems may cause fatigue in the parents and disrupt family functioning (Sadeh, Mindell, & Owens, 2011; see Tikotzky et al., Chapter VII, in this volume).

Temperament is another key construct in early child development. Difficult temperament has been described as a characteristic of infants who tend to be very emotional, irritable, and fussy, and cry a lot and is found in about 10% of the infants (Thomas & Chess, 1977). Infants with difficult temperaments have been reported to receive less optimal caregiving, rendering them at risk for behavioral problems and other adverse developmental outcomes (Allen & Prior, 1995; Gjone & Stevenson, 1997; Thomas, Chess, & Korn, 1982). In addition, temperament has been linked to various psychopathologies such as Attention Deficit Hyperactivity Disorder (Martel & Nigg, 2006), affective disorders (Mezulis, Hyde, & Abramson, 2006), anxiety symptoms (Kagan, Snidman, Zentner, & Peterson, 1999), and attachment issues (Zeanah & Fox, 2004).

The construct of temperament includes a number of different infant characteristics including activity level, approach-withdrawal tendencies, mood, adaptability, and sensory thresholds. In the present study, we focus on a key component of temperament—reactivity to external stimulation, reflecting infants' sensory threshold or the stimulus intensity level needed to evoke a discernible response (Chess & Thomas, 1996). It has been argued that the concept of temperament is largely based on two processes: reactivity to sensory stimuli and the ability to regulate such reactivity (Rothbart &

Derryberry, 1981). Reactivity to sensory stimuli includes motor, affective, and physiological reactions. Infants differ in their response thresholds (Korner, 1973), and these thresholds have been related to cognitive ability (Derryberry & Rothbart, 1997) and to psychopathology and personality (Kagan & Snidman, 1991; Kagan et al., 1999) later in childhood. Thus, reactivity thresholds have been considered a predisposition for personality development during childhood (Fox & Calkins, 1993).

Temperament is related to infant sleep patterns and sleep quality (Ednick et al., 2009). Several studies have shown that infants and toddlers with reported sleep problems were more likely to be classified as more difficult in temperament than other children (Atkinson, Vetere, & Grayson, 1995; Jimmerson, 1991; Kelmanson, 2004; Shaefer, 1990; Weissbluth, 1981). With a few exceptions, most findings in this field rely on subjective parental reports for both sleep and temperament. However, the validity of parental reports on infant sleep has been criticized on various grounds related to parents' potential reporting biases and their limited knowledge and awareness (Sadeh, 1994, 1996; Scher, Epstein, Sadeh, Tirosh, & Lavie, 1992; see also Sadeh, Chapter III, in this volume). Similarly, parental reports of infant temperament have been criticized because of their subjective nature and vulnerability to perceptual and reporting biases (Keener, Zeanah, & Anders, 1988).

In a review of 10 studies on sleep and temperament in the first year of life (Ednick et al., 2009), sleep was objectively assessed in only one-half of the studies, and temperament was assessed with subjective self-reports in all 10 studies. Inconsistent results emerge from studies that used objective sleep assessments along with subjective temperament assessments. For example, a longitudinal study with objective sleep assessment and subjective reports of infant temperament showed that increased sleep in the first year of life was related to an "easy" temperament (Spruyt et al., 2008). In contrast, Scher, Tirosh, and Lavie (1998) concluded that their results do not support a link between sleep regulation and quality and temperament in infancy.

Studies on infant temperament and sleep using objective measures are scarce, and their results are inconsistent. One longitudinal study objectively measured sleep and temperament and used a parent-reported temperament questionnaire (Halpern, Anders, Garcia Coll, & Hua, 1994). Sleep patterns at 3 weeks-of-age and at 3 months-of-age were related to behavioral temperament assessments at 3 months-of-age; for example, more time awake during the night at 3 weeks-of-age was related to both higher observed irritability scores and higher observed inhibition scores at 3 months-of-age. In this study, maternal reports of temperament were mostly unrelated to sleep indices (Halpern et al., 1994).

As indicated above, the focus of our study was on reactivity or sensory threshold; a key component of temperament. Carey (1974) suggested that the relation between temperament and sleep might stem from an underlying physiological reactivity factor. Such a factor could cause both difficult temperament and poor sleep. That is, a lower sensory threshold could lead to difficulties in regulating stimulation during wakefulness (difficult temperament) and also difficulties in disengaging from external and internal stimulation needed for initiating and maintaining sleep (Carey, 1974). Sadeh et al. (1994) suggested two additional explanations for the link between temperament and sleep in young children. First, sleep fragmentation might impair emotional and cognitive regulation, causing hypervigilance, distractibility, and other characteristics of difficult temperament. Second, parental styles in domains such as limit setting might act as an external factor bringing about both sleep problems and behaviors characteristic of difficult temperament. In this study, we focused on Carey's physiological threshold explanation, that is, we explored the possibility that sensory reactivity predicts subsequent changes in sleep quality. We measured both sensory reactivity and sleep using objective assessment methods. Sleep was assessed at 3, 6, and 12 months of age and sensory reactivity was tested at 3 and 6 months of age. These ages were chosen as good representative points of the process of sleep consolidation and reactivity changes (e.g., Coll, Halpern, & Vohr, 1992; Henderson, France, Owens, & Blampied, 2010).

To our knowledge, sensory reactivity during sleep and its relations to regular sleep quality has not been assessed in infants. Most studies assessing reactivity during sleep focused on an auditory arousal threshold (e.g., Busby, Mercier, & Pivik, 1994; Franco et al., 1998). Furthermore, differences between boys and girls at this age in temperament (Mezulis et al., 2006), response threshold (Klein, 1982), and sleep (Adams, Jones, Esmail, & Mitchell, 2004; Scher & Cohen, 2005), and in patterns of relations among activity, arousal, and sleep (Fisher & Rinehart, 1990) suggest that that gender may play a significant role that should be explored.

The literature on temperament emphasizes the role of both overregulation and underregulation in temperament (Derryberry & Rothbart, 1997). Derryberry and Rothbart suggest that both a lack of inhibition (impulsivity) and overinhibition (fearfulness) may lead to social and emotional difficulties. In other words, both extremes of the temperament continuum may lead to adjustment problems. The same principle may apply to links between sensory reactivity and sleep. We did not find earlier research on sleeping patterns in hyposensitive or overly inhibited children. However, Minard and colleagues found a quadratic association between cyclicity of sleep at 6 months and infant mental performance scores at 12 months (Minard, Freudigman, & Thoman, 1999). In addition, Boismier, Chappell, and Meier (1974) noted a quadratic relation between waking activity level and REM sleep in neonates. This literature underscores the need to explore nonlinear links between sleep and temperament.

Aims and Hypotheses

The purpose of the current study was to conduct a thorough examination of the links between sleep and sensory reactivity. Our specific aims were: (a) to examine to links of sleep and sensory reactivity longitudinally during the first year; (b) to use objective measures of both sleep and sensory reactivity; (c) to assess sensory reactivity during sleep as well as during wakefulness; (d) to explore the role of gender in moderating the links between sleep and sensory reactivity; and (e) to examine these links using both linear and nonlinear methods. Our main hypotheses were: (a) very high, and perhaps very low, sensory reactivity would predict lower sleep quality; (b) both reactivity during wakefulness and during sleep would be linked to sleep quality; and (c) gender would play a role in moderating these links.

Our main hypotheses were: (a) high, and possibly very low, sensory reactivity would predict lower sleep quality; (b) sensory reactivity during sleep as well as during wakefulness would be linked to sleep quality; and (c) gender would play a role in moderating the links between sleep and sensory reactivity.

METHOD

Participants

Participants were 95 full-term infants (43 female). Mean gestational age was 39.55 weeks ($SD = 1.26$), all had a second Apgar score of 9 or 10, and mean birth weight was 3.21 kg ($SD = 0.46$). None of the infants had chronic or acute medical problems. Table 1 describes sample characteristics. The socioeconomic characteristics (education level of parents, number of children in the family, and number of rooms in the house) suggest that the sample was mostly representative of middle and upper-middle socioeconomic status.

Ten participants did not have laboratory temperament scores at age 3 months, and 13 did not have those scores at age 6 months. One participant did not have a home temperament score at age 3 months, and two participants did not have that score at age 6 months. Five, two, and ten participants did not have sleep scores at age 3, 6, and 12 months, respectively. Missing data resulted from technical failures or inability of infants (or parents) to complete the procedures within the predetermined infant's age window. We did not impute missing data, all available data were used for each analysis.

Procedures

The study was approved by the university Ethics Committee and by the hospital Helsinki Committee. Participants were recruited at a hospital maternity ward. Informed consent was obtained from mothers following

TABLE 1

SAMPLE CHARACTERISTICS

Variable	Mean ± *SD*	Range
Gestational age (weeks)	39.66 ± 1.30	37–42
Birth weight (kg)	3.22 ± .46	2.11–4.35
Head circumference (cm)	34.53 ± 2.49	31–53
Mother's age (years)	32.50 ± 4.35	24–42
Father's age (years)	34.89 ± 5.59	23–61
Mother's education (years)	16.17 ± 2.40	12–25
Father's education (years)	15.71 ± 2.56	11–30
Number of children in family	1.94 ± .92	1–4
Number of rooms in the house	3.64 ± .90	2–7

description of the study and its aims. Infants were assessed three times: at ages 3 months (Wave 1; W1), 6 months (Wave 2; W2), and 12 months (Wave 3; W3). W1 and W2 assessments were conducted both at participants' homes and at a laboratory, and W3 assessments were conducted at participants' homes. Sleep was measured at home in all the assessment waves, whereas sensory reactivity was measured at W1 and W2, both at the laboratory (waking reactivity) and at home (sleep reactivity). For each assessment wave, parents were instructed to attach the actigraph to their child's left ankle for at least four nights and to keep a sleep diary. On the fifth night of each assessment wave, a home visit was conducted in which the actigraph was collected. At W1 and W2, reactivity during sleep was assessed.

Measures

Sleep Assessments

Activity monitoring with complementing daily sleep diaries were used to assess sleep–wake patterns. Sleep data were collected for four consecutive nights using actigraphs (AMA-32, Ambulatory Monitoring Inc., Ardsley, NY). Actigraphy has been established as a reliable and valid method for naturalistic study of sleep in infants, children, and adults (Sadeh, 1994; Sadeh, Acebo, Seifer, Aytur, & Carskadon, 1995; Sadeh, Hauri, Kripke, & Lavie, 1995). At age 3 months (W1), the actigraph was attached for 24 hours, but sleep parameters were calculated only for nights between 8 p.m. and 8 a.m. These boundaries, which are somewhat arbitrary, were based on reviewing the data from this study's sample as well as earlier samples. These boundaries to the definition of nocturnal sleep have been established in previous research to create standards that can be compared across studies (Sadeh, 2004). At 6 and 12 months (W2, W3), the actigraph was attached at night only. Our past experience has led us to realize that having infants at this age continuously wear actigraphs, during a time when infants start crawling and become more aware of their body, leads to many failures in compliance. Furthermore, daytime naps are often occurring in unpredictable places and in circumstances that lead to actigraphy artifacts (e.g., baby sleeping in a moving vehicle or stroller or in his parent's arms, creating externally induced movement artifacts). Therefore we decided to focus on the main nocturnal sleep period that has been the focus of previous research as well. Sleep variables were based on actigraphic data using a validated algorithm (Sadeh, Lavie, Scher, Tirosh, & Epstein, 1991). The following parameters were used for this study: (a) sleep efficiency, defined as time spent asleep out of the total sleep period; and (b) motionless sleep—percent of quiet sleep time with no activity. These measures were chosen as they represent measures of sleep quality that are comparable from 3 to 12 months of age. We did not include measures of sleep duration as they were not linked to temperament in any of past studies on the links between reactivity and sleep. Sleep diaries were used to identify and remove artifacts and to verify schedules before sleep–walk algorithms were applied to the actigraphy data (Acebo et al., 2005; Acebo et al., 1999).

Sensory Reactivity Assessments

Sensory reactivity levels were assessed during sleep and wakefulness. Assessment of sleep reactivity took place at the infant's home during a night visit. Once infants were in their first quiet sleep episode after nocturnal sleep onset they were stimulated with tactile, auditory, and light stimuli. Tactile stimulation consisted of 10 hairbrush strokes on the infant's temple, each lasting 1 second. Sound stimuli consisted of human voices recorded at a playground. The sounds were delivered through speakers placed one meter away from the infant's ears. Sound was presented at three intensities (70, 80, and 90 dB hearing level). Rise time of the stimulus was about 2 seconds. Sound intensity was monitored using a digital sound meter (RadioShack, Model: 33-2055). Light stimuli were presented with three intensities: 10-15 Lux, 340-345 Lux, 595-600 Lux. Light was produced by a halogen lamp (Zf-L300/500p, 230v-50Hz, Max500w, IP54) connected to a dimmer and a white plastic lampshade. The lamp was placed one meter away from the infant's head. Light intensity was monitored using Digital Lux Tester (YF-1065, Test Lab). Light presentations lasted 10 seconds each. At 3- and 6-months of age, 15 and 18 infants, respectively, woke up at some point during the test.

Infant's reactions to all stimuli were coded for an additional 10 seconds. A 10-second interval elapsed before presenting the next stimulus. The test was stopped if the infant awoke. Sequences of stimuli (tactile, sound, and light) were counterbalanced. Infants were examined during quiet sleep (no eye or body movement for 5 minutes before the start of the procedure). Trained observers (blind to all other parameters of the study) recorded infant's responses (e.g., eye opening, startle, crying, arm and leg movements, sucking, head movement, change in body position). Inter-rater reliability, based on parallel live scoring by two observers, was acceptable (kappa = .80, $p < .001$). The number of discrete responses (e.g., cry, movement, eye opening) created a reactivity score for each stimulus type (tactile, sound, light). Based on the methods described by Kisilevsky and Muir (1984), the scoring was based on frequency of responses and each response received a score of 1 and then responses were summed across situations. The reactivity scores were averaged to create an overall reactivity score during sleep (REACT-SLP).

Reactivity during the waking state was assessed in the laboratory. Testing was conducted in a room (3.5 m × 4 m). The infant was initially placed unstrapped in an infant car safety seat. As described above, tactile, auditory, and light stimuli were presented and the infant's reactivity was recorded with one difference: presentation of light was initiated with a low amount of light (5 Lux) rather than in darkness to avoid frightening the infants. These reactivity scores were averaged to create an overall reactivity score during wakefulness (REACT-WK). Inter-rater reliability for the awake condition was acceptable (kappa = .82, $p < .001$). Additional subtypes of waking responses that included coding gross *motor* movements such as arm waving, kicking, and back arching were also scored (REACT-MTR).

If an infant cried for more than 10 seconds, a researcher would attempt to soothe him or her gradually, using the following sequence: (1) presenting the infant with a toy for 10 seconds; (2) talking to the infant for 10 seconds; and (3) caressing the infant for 10 seconds. Once the infant was soothed testing proceeded as planned. If the infant persisted in crying, the testing was stopped and parents were invited into the room to sooth their child. At 3 months of age, three infants needed soothing to resume the test and nine could not be soothed back to testing. At 6 months of age, one infant required soothing to continue and 13 needed to stop the testing.

Plan of Analysis

Univariate analyses for sleep parameters and reactivity were conducted. We also screened reactivity and sleep variables for univariate outliers. Individual scores higher than $Z = 3.29$ (corresponding to a probability of 99.9%), separate from the rest of the distribution, were considered extreme outliers that might cause distortion in regression analyses (Tabachnick & Fidell, 2007). There were a total of six extreme scores. These were distributed among periods and measures with no more than one score per measure, per period needing correction. As suggested by Tabachnick and Fidell (2007), the Winsorising procedure was used and these raw scores were changed to equal one unit above the next highest score within that distribution.

To predict changes in sleep by sensory reactivity scores, we conducted regressions of data collected from age 3 months to 6 months, 3 months to

12 months, and 6 months to 12 months. As mentioned earlier, we opted to analyze data for boy and girl infants separately, to identify associations between reactivity and sleep that might vary by gender. Thus, all predictors were centered separately for boys and for girls. Each regression equation predicted a sleep outcome (sleep efficiency or motionless sleep), with the following predictors: baseline (earlier time point) sleep (sleep efficiency or motionless sleep), a reactivity variable (REACT-SLP, REACT-WK, or REACT-MTR), and the squared score of the respective reactivity variable (to investigate nonlinear effects). Controlling for baseline sleep scores in the regression analyses means that what is predicted is the *change* over time in sleep patterns. The Apgar score and gestational age did not contribute to the explained variance and were removed from the primary analyses. Figure 1 illustrates the model tested. The term baseline in this model (and in Figure 1) relates to the earlier time point (e.g., 3-month measures serve as baseline for 6-month measures).

RESULTS

Sleep Univariate Analyses

Figure 2 depicts means and standard errors of sleep efficiency (2a) and motionless sleep (2b) for boys and girls at all three assessment waves. Stability correlations for sleep efficiency were $r = .10$, *ns*; $r = .25$, $p = .02$; and $r = -.01$, *ns* for W1-W2, W2-W3, and W1-W3, respectively. Stability correlations for motionless sleep were $r = .40$, $p < .001$; $r = .38$, $p < .001$; and $r = .23$, $p = .04$ for W1-W2, W2-W3, and W1-W3, respectively. Repeated measures ANOVAs, controlling for between-subjects gender differences, revealed that there were significant developmental changes in both sleep efficiency and motionless sleep across the three measurement waves. For sleep efficiency, the repeated measures effect of time was statistically significant ($F_{[2,156]} = 178.55$, $p < .001$, *partial* $\eta^2 = .70$), and tests of within-subject contrasts revealed that sleep efficiency at W2 was higher than at W1 ($F_{[1,78]} = 169.95$, $p < .001$, *partial* $\eta^2 = .69$), and that at W3 was higher than at W2 ($F_{[1,78]} = 11.48$, $p = .001$, *partial* $\eta^2 = .13$). The effect of gender was also statistically significant ($F_{[1,78]} = 5.52$, $p = .02$, *partial* $\eta^2 = .07$) with girls exhibiting higher sleep efficiency than boys. The two-way interaction between gender and time was not significant.

For motionless sleep, the repeated measures effect of time was also statistically significant ($F_{[2,156]} = 22.16$, $p < .001$, *partial* $\eta^2 = .22$), and tests of within-subject contrasts revealed that at W2 motionless sleep was higher than at W1 ($F_{[1,78]} = 45.85$, $p < .001$, *partial* $\eta^2 = .37$), but at W3 it was lower than at W2 ($F_{[1,78]} = 11.49$, $p = .001$, *partial* $\eta^2 = .13$). Gender and the two-way

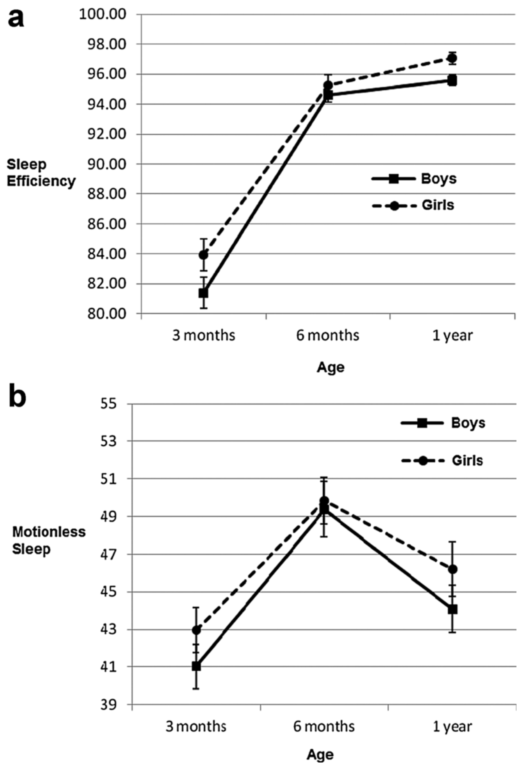

FIGURE 2.—Means and standard errors of sleep efficiency (a) and motionless sleep (b) for boys and girls at 3 months, 6 months, and 1 year.

interaction between gender and time did not exhibit statistically significant effects.

Reactivity Univariate Analyses

Figure 3 depicts means and standard errors of REACT-WK (3a), REACT-MTR (3b), and REACT-SLP (3c) for boys and girls at W2 and W3. Stability (from T2 to T3) for reactivity during sleep (REACT-SLP) was $r = .21$, $p = .04$. Reactivity during waking (REACT-WK, REACT-MTR) was unstable. Specifically, stability (from W2 to W3) for REACT-WK was $r = .18$, *ns*, and for REACT-MTR was $r = .20$, *ns*. Repeated measures ANOVAs, controlling for gender as before, revealed that there were no significant developmental changes in REACT-WK ($F_{[1,71]} = 1.84$, *ns, partial* $\eta^2 = .03$) or in REACT-SLP ($F_{[1,90]} = .44$, *ns, partial* $\eta^2 = .01$). For REACT-MTR, the repeated measures effect of time was statistically significant ($F_{[1,71]} = 12.16$, $p = .001$, *partial*

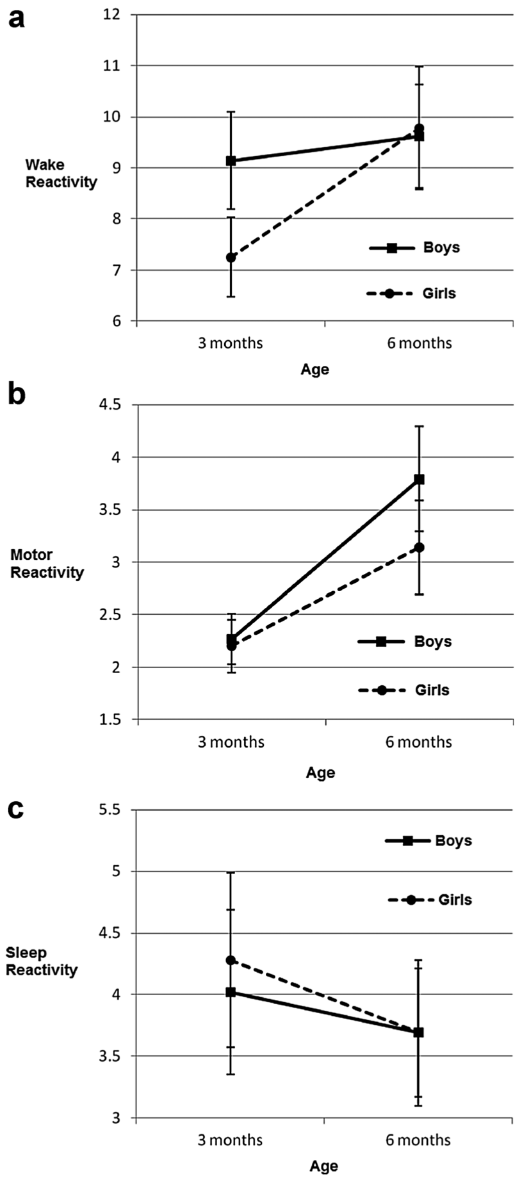

FIGURE 3.—Means and standard errors of REACT-WK (a), REACT-MTR (b), and REACT-SLP (c) for boys and girls at 3 and 6 months. REACT-WK = Total reactivity score during wakefulness; REACT-MTR = Motor reactivity score; REACT-SLP = Total reactivity score during sleep.

$\eta^2 = .15$), showing a higher score at W3 than at W2. In all three ANOVAs (REACT-WK, REACT-MTR, and REACT-SLP), gender and the two-way interaction between gender and time did not exhibit statistically significant effects.

Sleep and Reactivity Multivariate Analyses

Next, we explored relations between sensory reactivity and sleep. Using the entire sample, we calculated Pearson product-moment correlations between the three reactivity variables at ages 3 and 6 months, and the two sleep variables at ages 3, 6, and 12 months. Only four of the 36 correlations were statistically significant: W1 motionless sleep was associated with lower W2 REACT-WK ($r = -.27$, $p = .02$), and W2 REACT-MTR ($r = -.25$, $p = .03$), suggesting that poorer sleep at 3 months was related to higher reactivity at 6 months. Additionally, W1 REACT-MTR was associated with higher W3 motionless sleep ($r = .25$, $p = .03$), and W2 REACT-MTR was associated with higher W3 sleep efficiency ($r = .26$, $p = .03$), suggesting that higher reactivity at 3 and 6 months was related to better sleep at 12 months. These scarce and conflicting results strengthened our decision to separate the data by gender and to explore nonlinear (as opposed to linear) relations.

Next, we computed regression equations, separately for girls and boys. Each regression equation included baseline sleep, reactivity, and squared reactivity.

Prediction of Sleep as It Develops From 3 to 6 Months-of-Age

In girls, REACT-SLP and REACT-MTR had significant effects on sleep. Specifically, when predicting motionless sleep by REACT-SLP ($R^2 = .25$, $F_{[3,35]} = 3.90$, $p = .02$, $n = 39$), significant effects were found for REACT-SLP ($\beta = .52$, $p = .02$) and REACT-SLP squared ($\beta = -.59$, $p = .01$). In this model, the main effect of sensory reactivity on motionless sleep was positive and the squared score was negative. This suggests a predominantly positive, concave downward curve (Aiken & West, 1991), and low reactivity scores predict less improvement in sleep, although high reactivity scores did not differ from mid-range reactivity scores. This model is illustrated in Figure 4a. When predicting motionless sleep by REACT-MTR ($R^2 = .32$, $F_{[3,33]} = 5.25$, $p = .004$, $n = 37$), significant effects were baseline sleep ($\beta = .31$, $p = .04$) and REACT-MTR squared ($\beta = -.39$, $p = .03$). In this model, the main effect of reactivity on motionless sleep was nonsignificant, but the squared score was negative and significant. This suggests an inverted U-shaped function (Aiken & West, 1991) describes the relationship between sensory reactivity and sleep. That is, both low scores and high scores in sensory reactivity predict less improvement in sleep with age. This model is illustrated in Figure 4b. REACT-WK did not

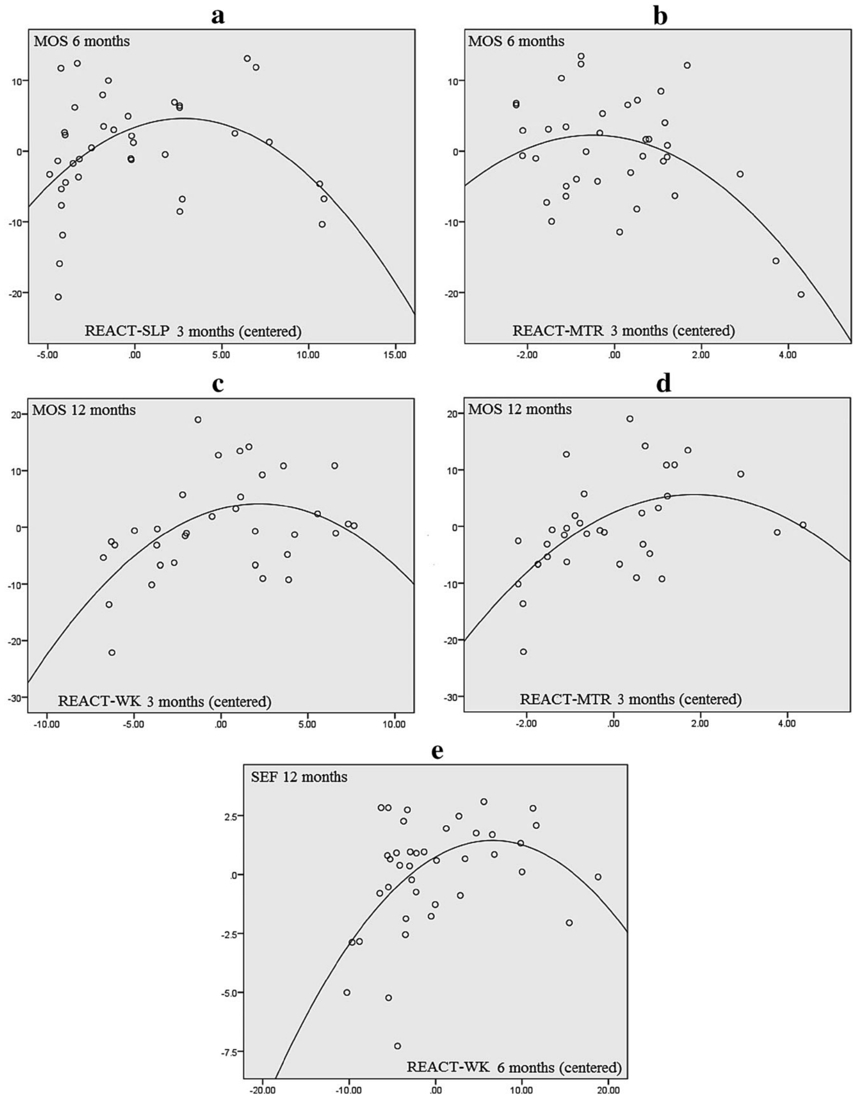

FIGURE 4.—Illustrations depicting statistically significant curvilinear effects, controlling for baseline sleep. (a–d): Effects found in girls, and (e) represents an effect found in boys. MOT = Motionless Sleep; SEF = Sleep Efficiency; REACT-SLP = Total reactivity score during sleep; REACT-WK = Total reactivity score during wakefulness; REACT-MTR = Motor reactivity score.

evince statistically significant effects on sleep. In boys aged 3–6 months, there were no statistically significant effects of sensory reactivity on sleep.

Prediction of Sleep as It Develops From 3 to 12 Months-of-Age

In girls, REACT-MTR and REACT-WK predicted sleep. Specifically, when predicting motionless sleep by REACT-WK (R^2 =.32, $F_{[3,30]} = 4.61$, $p = .01$, $n = 34$), statistically significant effects were those of REACT-WK ($\beta = .47$, $p = .01$) and REACT-WK squared ($\beta = -.39$, $p = .02$), suggesting a predominantly positive, concave downward curve, as explained above. This model is illustrated in Figure 4c. When predicting motionless sleep by REACT-MTR ($R^2 = .36$, $F_{[3,30]} = 5.54$, $p = .004$, $n = 34$), statistically significant effects were baseline motionless sleep ($\beta = .32$, $p = .04$), REACT-MTR ($\beta = .66$, $p = .001$) and REACT-MTR squared ($\beta = -.44$, $p = .02$), again suggesting a predominantly positive, concave downward curve. This model is illustrated in Figure 4d. REACT-SLP did not evince effects on sleep in girls. In boys, there were no statistically significant effects of sensory reactivity on sleep.

Prediction of Sleep as It Develops From 6 to 12 Months-of-Age

In girls, there were no statistically significant effects of reactivity on sleep. In boys, REACT-WK at 6 months predicted sleep efficiency at 12 months (R^2 =.26, $F_{[3,36]} = 4.24$, $p = .01$). Specifically, REACT-WK ($\beta = .66$, $p = .002$) and REACT-WK squared ($\beta = -.51$, $p = .01$), predicted 12-month sleep efficiency, again suggesting a predominantly positive, concave downward curve. This model is illustrated in Figure 4e. Models of REACT-SLP and REACT-MTR in infants from 6 to 12 months did not reach statistical significance.

Notably, in most of the regression equations, for all ages, baseline sleep was not statistically significant. The only exceptions to this were when predicting motionless sleep in boys from 3 to 6 months (e.g., $\beta = .45$, $p = .004$ when REACT-WK was in the model), and from 6 to 12 months (e.g., $\beta = .52$, $p = .001$ when REACT-WK was in the model), and in girls from 3 to 12 months as described above.

DISCUSSION

This is the first study to longitudinally assess sleep and sensory reactivity in infants during the first year of life using objective sleep and reactivity measures examined both at the lab during waking and at home during sleep. We will first address developmental findings and subsequently discuss relations found between reactivity and sleep.

The results reflect the expected maturational trends in sleep–wake patterns during the first year of life with sleep becoming more consolidated as manifested by the significant increase in both sleep efficiency and the percentage of motionless sleep (Burnham, Goodlin-Jones, Gaylor, & Anders, 2002; Tikotzky & Sadeh, 2009). Although sleep efficiency manifested a linear improvement, motionless sleep exhibited a decline in W3. This suggested that in our sample, motionless sleep peaked at 6 months, which differs from a previous report in which motionless sleep exhibited a linear increase during early development (Burnham et al., 2002). Motionless sleep showed more overall stability than sleep efficiency. Although motionless sleep has been used less extensively in the literature, it has been shown to be highly related to maturation in newborns (i.e., significantly correlated with gestational age and other anthropometric measures) (Gertner et al., 2002; Sadeh, Dark, & Vohr, 1996), but relatively stable and unaffected by behavioral sleep problems (Sadeh, 1994). Considering our findings, we suggest that perhaps motionless sleep represents a useful indicator of sleep that is linked to underlying physiological features related to sensory reactivity in the first year of life. Indeed, motionless sleep was also better predicted by reactivity, compared to sleep efficiency.

As for reactivity variables, stability reached statistical significance only for reactivity during sleep (REACT-SLP). A developmental change was shown only in REACT-MTR. Possibly, gross motor movements significantly increase in infants from 3 to 6 months, due to maturational processes in motor control (Thelen, 1995).

Curvilinear relations emerged between reactivity and sleep suggesting that both hypersensitive and hyposensitive infants are at risk for poorer sleep, compared to infants with sensory reactivity in the average range. The link between hypersensitivity and poor sleep has been demonstrated before using subjective reports of temperament (Carey, 1974; Sadeh et al., 1994). However, the link between low reactivity and poor sleep has rarely been addressed in the literature. In our study, this result was replicated across several measures and assessment waves, especially in girls.

A relevant issue to the current findings is the effect of swaddling on infant sleep and crying (Franco et al., 2005; Richardson, Walker, & Horne, 2010). Studies have demonstrated that swaddling improves infant sleep by reducing spontaneous arousals. The underlying mechanisms explaining the effects of swaddling on sleep are not clear, but one possibility is that swaddling provides more consistent sensory stimulation to infants who are low in sensory reactivity and need a sense of being held. The example of swaddling is only relevant to touch stimulation and limiting movements (with all their related sensations), but it may demonstrate a broader principle of a need for constant stimulation for creating a sense of security.

Another possible explanation is that infants with low reactivity to external stimuli are less attuned to their surroundings. These children may have a dysregulated sleep schedule and difficulty in consolidating sleep at night according to environmental cues. Indeed, infants who were more withdrawn in play interactions with their mothers (i.e., less reactive to stimuli presented by mothers) were more likely to be characterized by the mothers as generally unpredictable (Dollberg, Feldman, Keren, & Guedeney, 2006). Additionally, high thresholds (low reactivity) have been related to adjustment problems and anxiousness in children (Klein, 1982). Possibly, low reactivity points to low sensitivity to one's surroundings, which may bring about problems in adjustment in sleeping and in waking. Whatever the specific underlying mechanism, our findings suggest that low reactivity in infancy is related to poor sleep, and thus should be explored in future studies, along with high reactivity, as possible negative developmental indicators.

Our findings extend previous literature, largely based on parental reports, that showed a linear relation between sensory reactivity and sleep (e.g., Carey, 1974; Ednick et al., 2009; Kelmanson, 2004) with few exceptions (e.g., Halpern et al., 1994). The present findings are compatible with a view of temperament as a dimension in which both extremes might interfere with healthy adjustment (Derryberry & Rothbart, 1997). The curvilinear relation was not reported in previous studies, and might explain the null results obtained with objective sleep measures in previous research examining only linear relations (e.g., Scher, Tirosh, & Lavie, 1998). Our findings only partially support Carey's (1974) hypothesis. Although high reactivity was indeed associated with poor sleep, so was low reactivity. Thus, Carey's theory of the role of low sensory threshold (high reactivity) does not fully explain our findings.

Notably, although some of the curvilinear effects found in this study were symmetrical, some exhibited a predominantly positive, concave downward curve (Aiken & West, 1991), suggesting that hyposensitivity was *a better predictor* of poor sleep than hypersensitivity. This conclusion is contrary to our hypotheses and to the linear associations found in previous literature. In addition, the observed lack of consistent linear correlations among our study measures is incompatible with previous findings of studies that used subjective measures for sleep and general temperament. These results might stem partly from our focus on sensory reactivity, a specific aspect of temperament. However, studies utilizing subjective measures for reactivity or sensory thresholds have also shown linear relations with sleep in the past (e.g., Carey, 1974). Possibly, subjective parental reports in previous studies may have inflated relations focusing on the "hypersensitive" side of the parabola, since difficult temperament (e.g., hyper-responsiveness) is more easily detected by parents than reduced or nonresponsiveness (e.g., hypo-responsiveness). The present findings are important, because even if parents are unaware of their child's disturbed sleep, it still has negative consequences (e.g., Scher, Zukerman, & Epstein, 2005).

Our findings also show differences between boys and girls in the relations between sensory reactivity and sleep. Specifically, most effects emerged for girls, a result that is compatible with previous findings in a different age group showing that even if group means are similar, the pattern of associations of arousal and sleep differ between boys and girls (Fisher & Rinehart, 1990). Specifically, Fisher and Rinehart showed that baseline sensory activity levels were related to sleep only in girls. These findings may indicate differential susceptibility (Belsky & Pluess, 2009) for poor sleep quality between boys and girls. Gender differences in sleep have been well-documented, particularly following puberty onset (Manber & Armitage, 1999; Mong et al., 2011). In comparison to men, women are more likely to have poorer sleep quality and present more complaints of insomnia. Furthermore, it has been documented that in young children, sleep is more adversely affected by atopic dermatitis in girls (Chernyshov, 2012), suggesting that perhaps girls' sleep is more vulnerable to skin related sensations. It is possible that our findings reflect early signs of this differential susceptibility.

It is also important to mention that motionless sleep was predicted only in girls and sleep efficiency was predicted only in boys. In addition, reactivity measured at 3 months-of-age predicted sleep only in girls and reactivity at 6 months-of-age predicted sleep only in boys. Again, these results highlight differences between the sexes even at young ages and underscore the importance of using multiple measures and assessment waves.

Limitations

Despite a good initial sample size, missing data and the analyses conducted separately by gender reduced the sample size. Thus, the statistical power of the study may have been compromised, and thus generalization may be somewhat tempered. Second, our sample consisted mainly of educated upper-middle class families, which again limits generalization. Finally, our sleep assessment was based on nocturnal sleep only, which excludes understanding of the role of daytime sleep in this context.

Future Directions

Future research on sleep and sensory reactivity in infancy should explore both extremes of the reactivity continuum using both objective and subjective measures of these domains. The gender-related differential susceptibility found in our research should be further explored to see if indeed sleep is more likely to be affected by sensory stimulation in girls in comparison to boys. Additional attention should be given to the possibility that sensory reactivity may play a role in the evolution of sleep problems in infants and children.

CONCLUSION

Notwithstanding the study limitations, this study has important strengths including: (a) the use of objective assessments for both sensory reactivity and sleep, thus reducing potential bias caused by parental reports; (b) the longitudinal design, enabling baseline sensory reactivity to predict change in sleep over time; and (c) the assessment of both sleep and wake reactivity. This is the first study, to the best of our knowledge, to assess and to reveal quadratic associations between sensory reactivity and sleep during the first year of life. This may explain null or inconsistent results obtained in some previous studies that explored only linear associations.

ACKNOWLEDGMENTS

We would like to thank all the families who participated and the students who served as research assistants. Special thanks to Ornit Arbel who coordinated study logistics.

REFERENCES

Acebo, C., Sadeh, A., Seifer, R., Tzischinsky, O., Hafer, A., & Carskadon, M. A. (2005). Sleep/wake patterns derived from activity monitoring and maternal report for healthy 1- to 5-year-old children. *Sleep*, **28**, 1568–1577.

Acebo, C., Sadeh, A., Seifer, R., Tzischinsky, O., Wolfson, A. R., Hafer, A., et al. (1999). Estimating sleep patterns with activity monitoring in children and adolescents: How many nights are necessary for reliable measures? *Sleep*, **22**, 95–103.

Adams, S. M., Jones, D. R., Esmail, A., & Mitchell, E. A. (2004). What affects the age of first sleeping through the night? *Journal of Paediatrics and Child Health*, **40**, 96–101. doi: 10.1111/j.1440-1754.2004.00317.x

Aiken, L. S., & West, S. G. (1991). *Multiple regression: Testing and interpreting interactions.* Newbury Park, CA: SAGE.

Allen, K., & Prior, M. (1995). Assessment of the validity of easy and difficult temperament through observed mother-child behaviours. *International Journal of Behavioral Development*, **18**, 609–630.

Atkinson, E., Vetere, A., & Grayson, K. (1995). Sleep disruption in young children: The influence of temperament on the sleep patterns of pre-school children. *Child: Care, Health and Development*, **21**, 233–246.

Belsky, J., & Pluess, M. (2009). Beyond diathesis stress: Differential susceptibility to environmental influences. *Psychological Bulletin*, **135**(6), 885–908. doi: 10.1037/a0017376

Boismier, J. D., Chappell, P. F., & Meier, G. W. (1974). Wakefulness and REM sleep in human neonates. *Developmental Psychobiology*, **7**, 304. doi: 10.1002/dev.420070406

Burnham, M. M., Goodlin-Jones, B. L., Gaylor, E. E., & Anders, T. F. (2002). Nighttime sleep–wake patterns and self-soothing from birth to one year of age: A longitudinal intervention study. *Journal of Child Psychology and Psychiatry*, **43**, 713–725.

Busby, K. A., Mercier, L., & Pivik, R. T. (1994). Ontogenetic variations in auditory arousal threshold during sleep. *Psychophysiology*, **31**, 182–188.

Carey, W. B. (1974). Night waking and temperament in infancy. *The Journal of Pediatrics*, **84**, 756–758.

Chernyshov, P. V. (2012). Gender differences in health-related and family quality of life in young children with atopic dermatitis. *International Journal of Dermatology*, **51**(3), 290–294. doi: 10.1111/j.1365-4632.2011.04997.x

Chess, S., & Thomas, A. (1996). *Temperament: Theory and practice*. New York, NY: Bruner-Mazel.

Derryberry, D., & Rothbart, M. K. (1997). Reactive and effortful processes in the organization of temperament. *Development and Psychopathology*, **9**, 633–652.

Dollberg, D., Feldman, R., Keren, M., & Guedeney, A. (2006). Sustained withdrawal behavior in clinic-referred and nonreferred infants. *Infant Mental Health Journal*, **27**, 292–309. doi: 10.1002/Imhj.20093

Ednick, M., Cohen, A. P., McPhail, G. L., Beebe, D., Simakajornboon, N., & Amin, R. S. (2009). A review of the effects of sleep during the first year of life on cognitive, psychomotor, and temperament development. *Sleep*, **32**, 1449–1458.

Fisher, B. E., & Rinehart, S. (1990). Stress, arousal, psychopathology and temperament: A multidimensional approach to sleep disturbance in children. *Personality and Individual Differences*, **11**, 431–438.

Fox, N. A., & Calkins, S. D. (1993). Multiple-measure approaches to the study of infant emotion. In M. Lewis & J. M. Haviland (Eds.), *Handbook of emotions* (pp. 167–184). New York, NY: Guilford Press.

Franco, P., Pardou, A., Hassid, S., Lurquin, P., Groswasser, J., & Kahn, A. (1998). Auditory arousal thresholds are higher when infants sleep in the prone position. *Journal of Pediatrics*, **132**, 240–243. doi: 10.1016/S0022-3476(98)70438-X

Franco, P., Seret, N., Van Hees, J.N., Scaillet, S., Groswasser, J., & Kahn, A. (2005). Influence of swaddling on sleep and arousal characteristics of healthy infants. *Pediatrics*, **115**, 1307–1311. doi: 10.1542/peds.2004-1460

Garcia Coll, C. T., Halpern, L. F., & Vohr, B. R. (1992). Stability and correlates of change of early temperament in preterm and full-term infants. *Infant Behavior and Development*, **15**, 137–153.

Gertner, S., Greenbaum, C. W., Sadeh, A., Dolfin, Z., Sirota, L., & Ben-Nun, Y. (2002). Sleep–wake patterns in preterm infants and 6 month's home environment: Implications for early cognitive development. *Early Human Development*, **68**, 93–102. doi: 10.1016/S0378-3782(02)00018-X

Gjone, H., & Stevenson, J. (1997). A longitudinal twin study of temperament and behavior problems: Common genetic or environmental influences? *Journal of the American Academy of Child & Adolescent Psychiatry*, **36**, 1448–1456. doi: 10.1097/00004583-199710000-00028

Gregory, A. M., & Sadeh, A. (2012). Sleep, emotional and behavioral difficulties in children and adolescents. *Sleep Med Rev*, **16**, 129–136. doi: 10.1016/j.smrv.2011.03.007

Halpern, L. F., Anders, T. F., Garcia Coll, C., & Hua, J. (1994). Infant temperament: Is there a relation to sleep–wake states and maternal nighttime behavior? *Infant Behavior and Development*, **17**, 255–263. doi: 10.1016/0163-6383(94)90004-3

Henderson, J. M., France, K.G., Owens, J. L., & Blampied, N. M. (2010). Sleeping through the night: The consolidation of self-regulated sleep across the first year of life. *Pediatrics*, **126**, e1081–1087. doi: 10.1542/peds.2010-0976

Jimmerson, K. R. (1991). Maternal, environmental, and temperamental characteristics of toddlers with and toddlers without sleep problems. *Journal of Pediatric Health Care*, **5**, 71–77.

Kagan, J., & Snidman, N. (1991). Infant predictors of inhibited and uninhibited profiles. *Psychological Science*, **2**, 40–44. doi: 10.1111/j.1467-9280.1991.tb00094.x

Kagan, J., Snidman, N., Zentner, M., & Peterson, E. (1999). Infant temperament and anxious symptoms in school age children. *Development and Psychopathology*, **11**, 209–224. doi: 10.1017/S0954579499002023

Keener, M. A., Zeanah, C. H., & Anders, T. F. (1988). Infant Temperament, sleep organization, and nighttime parental interventions. *Pediatrics*, **81**, 762.

Kelmanson, I. A. (2004). Temperament and sleep characteristics in two-month-old infants. *Sleep and Hypnosis*, **6**, 78–784. doi: 10.1017/S0022112004000515

Kisilevsky, B. S., & Muir, D. W. (1984). Neonatal habituation and dishabituation to tactile stimulation during sleep. *Developmental Psychology*, **20**(3), 367–373.

Klein, H. A. (1982). The relationship between children's temperament and adjustment to kindergarten and Head Start settings. *Journal of Psychology: Interdisciplinary and Applied*, **112**, 259–268.

Korner, A. (1973). Individual differences at birth: Implications for early experience and later development. In J. C. Westman (Ed.), *Individual differences in children.* New York, NY: Wiley.

Manber, R., & Armitage, R. (1999). Sex, steroids, and sleep: A review. *Sleep*, **22**(5), 540–555.

Martel, M. M., & Nigg, J. T. (2006). Child ADHD and personality/temperament traits of reactive and effortful control, resiliency, and emotionality. *Journal of Child Psychology and Psychiatry*, **47**, 1175–1183. doi: 10.1111/j.1469-7610.2006.01629.x

Mezulis, A. H., Hyde, J. S., & Abramson, L. Y. (2006). The developmental origins of cognitive vulnerability to depression: Temperament, parenting, and negative life events in childhood as contributors to negative cognitive style. *Developmental Psychology*, **42**, 1012–1025. doi: 10.1037/0012-1649.42.6.1012

Minard, K. L., Freudigman, K., & Thoman, E. B. (1999). Sleep rhythmicity in infants: Index of stress or maturation. *Behavioural Processes*, **47**, 189–203. doi: 10.1016/S0376-6357(99)00065-0

Mong, J. A., Baker, F. C., Mahoney, M. M., Paul, K. N., Schwartz, M. D., Semba, K., et al. (2011). Sleep, rhythms, and the endocrine brain: Influence of sex and gonadal hormones. *The Journal of Neuroscience*, **31**(45), 16107–16116. doi: 10.1523/jneurosci.4175-11.2011

Richardson, H. L., Walker, A. M., & Horne, R. S. C. (2010). Influence of swaddling experience on spontaneous arousal patterns and autonomic control in sleeping infants. *The Journal of Pediatrics*, **157**, 85–91. doi: 10.1016/j.jpeds.2010.01.005

Rothbart, M. K., & Derryberry, D. (1981). Development of individual differences in temperament. In M. E. Lamb & A. L. Brown (Eds.), *Advances in developmental psychology* (Vol. 1, pp. 37–86). Hillsdale, NJ: Lawrence Erlbaum.

Sadeh, A. (1994). Assessment of intervention for infant night waking: Parental reports and activity-based home monitoring. *Journal of Consulting and Clinical Psychology*, **62**, 63–68.

Sadeh, A. (1996). Evaluating night wakings in sleep-disturbed infants: A methodological study of parental reports and actigraphy. *Sleep*, **19**, 757–762.

Sadeh, A. (2004). A brief screening questionnaire for infant sleep problems: Validation and findings for an Internet sample. *Pediatrics*, **113**(6), E570–E577.

Sadeh, A., Acebo, C., Seifer, R., Aytur, S., & Carskadon, M. A. (1995). Activity-based assessment of sleep–wake patterns during the 1st year of life. *Infant Behavior & Development*, **18**, 329–337.

Sadeh, A., Dark, I., & Vohr, B. R. (1996). Newborns' sleep–wake patterns: The role of maternal, delivery and infant factors. *Early Human Development*, **44**, 113–126. doi: 10.1016/j.jpeds.2010.01.005

Sadeh, A., Hauri, P. J., Kripke, D. F., & Lavie, P. (1995). The role of actigraphy in the evaluation of sleep disorders. *Sleep*, **18**, 288–302.

Sadeh, A., Lavie, P., & Scher, A. (1994). Sleep and temperament: Maternal perceptions of temperament of sleep-disturbed toddlers. *Early Education and Development*, **5**, 311–322. doi: 10.1207/s15566935eed0504_6

Sadeh, A., Lavie, P., Scher, A., Tirosh, E., & Epstein, R. (1991). Actigraphic home-monitoring sleep-disturbed and control infants and young children: A new method for pediatric assessment of sleep–wake patterns. *Pediatrics*, **87**, 494–499.

Sadeh, A., Mindell, J. A., & Owens, J. (2011). Why care about sleep of infants and their parents? *Sleep Medicine Reviews*, **15**, 335–337. doi: 10.1016/j.smrv.2011.03.001

Scher, A., & Cohen, D. (2005). Locomotion and nightwaking. *Child: Care, Health and Development*, **31**, 685–691. doi: 10.1111/j.1365-2214.2005.00557.x

Scher, A., Epstein, R., Sadeh, A., Tirosh, E., & Lavie, P. (1992). Toddlers' sleep and temperament: Reporting bias or a valid link? A research note. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, **33**, 1249–1254.

Scher, A., Tirosh, E., & Lavie, P. (1998). The relationship between sleep and temperament revisited: Evidence for 12-month-olds: A research note. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, **39**, 785–788.

Scher, A., Zukerman, S., & Epstein, R. (2005). Persistent night waking and settling difficulties across the first year: Early precursors of later behavioural problems? *Journal of Reproductive and Infant Psychology*, **23**, 77–88. doi: 10.1080/02646830512331330929

Shaefer, C. E. (1990). Night waking and temperament in early childhood. *Psychological Reports*, **67**, 192–194.

Spruyt, K., Aitken, R. J., So, K., Charlton, M., Adamson, T. M., & Horne, R. S. C. (2008). Relationship between sleep/wake patterns, temperament and overall development in term infants over the first year of life. *Early Human Development*, **84**, 289–296. doi: 10.1016/j.earlhumdev.2007.07.002

Tabachnick, B. G., & Fidell, L. S. (2007). *Using multivariate statistics* (5 ed.). Boston: Allyn and Bacon.

Thelen, E. (1995). Motor development: A new synthesis. *American Psychologist*, **50**, 79–95.

Thomas, A., & Chess, S. (1977). *Temperament and development*. New York, NY: Brunner/Mazel.

Thomas, A., Chess, S., & Korn, S. J. (1982). The reality of difficult temperament. *Merrill–Palmer Quarterly: Journal of Developmental Psychology*, **28**, 1–20.

Tikotzky, L., & Sadeh, A. (2009). Maternal sleep-related cognitions and infant sleep: A longitudinal study from pregnancy through the first year. *Child Development*, **80**, 860–874. doi: 10.1111/j.1467-8624.2009.01302.x

Weissbluth, M. (1981). Sleep duration and infant temperament. *The Journal of Pediatrics*, **99**, 817–819.

Zeanah, C. H., & Fox, N. A. (2004). Temperament and attachment disorders. *Journal of Clinical Child and Adolescent Psychology*, **33**, 32–41. doi: 10.1207/S15374424jccp3301_4

Zuckerman, B., Stevenson, J., & Bailey, V. (1987). Sleep problems in early childhood—Continuities, predictive factors, and behavioral correlates. *Pediatrics*, **80**, 664–671.