REM SLEEP, EARLY EXPERIENCE, AND THE DEVELOPMENT OF REPRODUCTIVE STRATEGIES

Patrick McNamara, Jayme Dowdall
Boston University School of Medicine and VA New England Healthcare System

and

Sanford Auerbach, M.D.
Sleep Disorders Center, Boston Medical Center

We hypothesize that rapid eye movement or REM sleep evolved, in part, to mediate sexual/reproductive behaviors and strategies. Because development of sexual and mating strategies depends crucially on early attachment experiences, we further hypothesize that REM functions to mediate attachment processes early in life. Evidence for these hypotheses comes from (1) the correlation of REM variables with both attachment and sexual/reproductive variables; (2) attachment-related and sex-related hormonal release during REM; (3) selective activation during REM of brain sites implicated in attachment and sexual processes; (4) effects of maternal deprivation on REM; (5) effects of REM deprivation on sexual behaviors; and (6) the REM-associated sexual excitation. To explain *why* we find associations among REM sleep, attachment, and adult reproductive strategies, we rely on recent extensions of parent-offspring conflict theory. Using data from recent findings on genomic imprinting, Haig (2000) and others suggest that paternally expressed genes are selected to promote growth of the developing fetus/child at the expense of the mother, while maternally expressed genes counter these effects. Because developmental REM facilitates attachment-related outcomes in the child, developmental REM may be regulated by paternally expressed genes. In that case, REM

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Address all correspondence to Patrick McNamara, Department of Neurology (127), Boston University School of Medicine and VA New England Healthcare System, 150 South Huntington Avenue, Boston, MA 02130. E-mail: mcnamar@bu.edu

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may have evolved to support the "aims" of paternal genes at the expense of maternal genes.

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Despite decades of investigation, the function or functions of REM are still not known. The question of the function of REM may be important for a theory of the evolution of human behavior as it is now understood that REM constitutes a major, well-defined physiologic process that is part of normal brain functioning (Carskadon and Dement 2000; Dement 1978; Hartmann 1973; Hobson et al. 1998a: McCarley 1989; Siegel 1993). In this paper we utilize middle-level evolutionary models such as developmental psychobiology, attachment theory, life-history theory, and parent-offspring conflict theory (Trivers 1974) to evaluate the role REM might play in mediating unconscious development, fixation, and implementation of reproductive strategies. Because developmental and attachment theories suggest that adult reproductive strategies may depend in part on early attachment experiences, we also ask whether REM might support psychobiological *attachment processes* in the child as well. We found strong evidence that it does, which we review below. In the first part of this paper we briefly summarize relevant evolutionary models that link developmental attachment processes to later reproductive success. In the second and third parts we summarize evidence for a role for REM in attachment and sexual behaviors. In the final part we attempt to address the evolutionary question of *why* the neurobiology of REM sleep should be related to attachment and reproductive strategies.

RELEVANT EVOLUTIONARY THEORY

Life History Theory

According to life history theory (Clutton-Brock 1991; Stearns 1992), life-cycle traits such as gestation length, size and number of offspring, age at first reproduction, lactation/weaning period, ongoing reproductive strategy, and length of life are all influenced by local ecologic context and contribute to reproductive fitness. Individuals develop mechanisms or bio-behavioral strategies that help them solve problems of infant survival, childhood growth, adult development, and reproduction across the lifespan. Perceptual-emotional information about current environmental conditions (e.g., local mortality rates) is used to make (unconscious) decisions about optimal allocation of limited resources. Trade-offs have to be made

between time/energy devoted to "somatic effort" (investing in growth and development of the body) versus "reproductive effort" (funneling effort toward producing and raising offspring). Similarly the developing organism needs to "decide" whether to invest in reproduction sooner (an early maturity) as opposed to some later, more propitious time. Reproductive effort has two further components: mating effort (locating, courting, and retaining a suitable mate) and parenting effort (gestating, giving birth, and engaging in postnatal care). In short, life history theory deals with how individuals optimally allocate somatic versus reproductive effort now versus in the future, given an assessment of current life circumstances. We focus our discussion of REM on its possible contributions to development of behavioral strategies to support reproductive effort (parent-offspring relations and mating strategies).

Attachment Theory and Ecologically Contingent Behavioral Strategies

Several investigators (e.g., Belsky et al.1991; Chisholm 1999; Simpson 2000) have suggested that for the neonate and the juvenile, evaluation of local ecologic conditions reduces to their experience of their caregivers. The neonate does not make conscious decisions, and thus its decision-making processes must occur "unconsciously" or automatically. If the neonate/child can form a secure emotional attachment to the mother the child will "conclude" that the local environment will support a long-term reproductive strategy of delayed maturity and high investment in a few, "high-quality" offspring. If, on the other hand, the child meets a cold, rejecting mother or faces threats of abandonment, then a strategy of rapid maturation and early reproduction with greater numbers of offspring will most likely obtain. Thus, development of adult reproductive strategies depends crucially on the juvenile's early experience of attachment.

Belsky and Colleagues' Model

Belsky, Steinberg, and Draper (1991) developed one of the first models of childhood attachment patterns as they relate to later reproductive behaviors. Belsky and colleagues suggest that early environmental factors in the family of origin (e.g., the amount of stress, spousal harmony, and financial resources) affect early childrearing experiences (the level of sensitive and responsive care-giving). These child-rearing experiences then affect psychological and behavioral development of the child (e.g., patterns of attachment, the nature of internal working models of self and of others), which influences both somatic development (how quickly sexual maturation is reached) and development of reproductive effort.

Behavioral and reproductive strategies are conceived as ensembles of cognitive, brain, physiologic, and social processes and behaviors that im-

plement a series of adaptive behaviors that increase reproductive fitness. Two developmental trajectories are conceived, eventuating in two reproductive strategies in adulthood. One strategy involves a short-term opportunistic orientation toward mating and parenting in which sexual intercourse with multiple partners occurs earlier and romantic relationships are short-term and unstable. This orientation is geared toward increasing the *quantity* of offspring as early as possible. The second strategy involves a long-term investing orientation in which sexual intercourse occurs later in life with fewer partners, pair bonds are long-term and more stable, and personal investment is greater. This orientation is associated with delayed maturity and with maximizing the *quality* of offspring.

Chisholm's Model

Building on the work by Belsky and colleagues (1991) and Stearns (1992), Chisholm (1993, 1996, 1999) notes that local mortality rates may act as a proximal environmental cue that directs people toward different developmental/reproductive strategies. Where mortality rates are high the optimal reproductive strategy should be to "start early" and maximize current fertility rates. Where local mortality rates are low the best strategy involves deferred long-term reproduction in which fewer offspring are given better and more long-term care. In environments with abundant resources a delayed maturation/high investment reproductive strategy should increase the total number of descendants over multiple generations by minimizing the variance of surviving offspring between generations. Parental indifference or insensitivity may be used by children as cues or indicators of local high mortality rates, leading them to develop, for example, "avoidant attachment" styles better suited to facilitating fitness in harsh environments. In addition, parents' inability and/or unwillingness to invest in offspring would be used as indicators of harshness of the local environment. Chisholm reconceptualizes the three classic attachment patterns (secure, ambivalent, and avoidant) in terms of parent-offspring conflict and how the behavioral pattern might maximize the child's later reproductive interests. Secure attachment is seen as the result of having parents who are both willing and able to invest in the child. Avoidant attachment is an adaptation to parents' unwillingness to invest regardless of ability, and ambivalent attachment is an adaptation to parents' inability to invest (most likely because of limited resources) regardless of willingness. Using Chisholm's logic we might advance a final attachment outcome correlated with parents who are both unwilling and unable to invest adequately in their offspring. For children in this particularly harsh situation, what behavioral strategy would be most adaptive? Perhaps this social environment might result in so-called disorganized at-

tachment patterns wherein the child's attachment and later reproductive behaviors are unpredictable and disorganized.

Evidence for Developmental Models

These models concerning the development of reproductive strategies out of early attachment experiences are supported by several lines of data (see also Simpson 2000). It is known, for example, that early indicators of familial stress are associated with poor parenting styles and subsequent behavioral problems in the children (Bronfenbrenner and Crouter 1982; Burgess and Draper 1989; Emery 1988; McLoyd 1990). For girls, father absence and early familial conflict predict earlier menarche even when body weight is controlled for (Surbey 1990; Graber et al. 1995; Smith et al. 1985; Steinberg 1988). Nonhuman primates who undergo early maternal deprivation do not behave normally sexually as adults (Hrdy 1999; Kraemer 1992). Similarly, Bischof (1997) has shown that early experience in Avian species in the forms of song exposure/learning, filial imprinting, and sexual imprinting determine later reproductive behaviors and mating strategies. Sexual imprinting, in particular, is a process whereby adult mate preferences are affected by learning at a very young age, usually using a parent as the model.

A Special Role for REM

Interestingly, there appears to be a special relationship between early sexual imprinting mechanisms and paradoxical/active sleep (REM is sometimes called paradoxical sleep or "PS" in nonhuman species). The total amount of time spent in PS sleep as well as the number of PS episodes increase significantly following an imprinting session in the laboratory. Solodkin et al. (1985) demonstrated that the effect was selective for PS sleep as no changes occur in slow wave sleep after an imprinting session. There is also evidence to suggest that blocking REM early in life yields sexual dysfunction later in life in mammalian species. Mirmiran et al. (1983), for example, found that masculine sexual responses (mounts and ejaculations) were significantly impaired in rats that had been treated early in life (when neonates) with REM suppressant agents (e.g., clomipramine). Early REM deprivation may also be associated with profound anatomic and metabolic lesions later in life. Mirmiran and colleagues found significant reductions in cerebral cortex and medulla oblongata volumes in rats that had been treated as neonates with REM suppressant agents. These data are consistent with the large literature on effects of attachment-related early psychosocial stress on later adult functioning and health, including adult cortisol levels, adult stature, and sleep quality (see Maunder and Hunter 2001 for a review).

In a series of well-controlled studies, Vogel and Hagler (1996) demonstrate that administration of REM suppressant and antidepressant drugs (clorimipramine, zimeldine, or desipramine) to neonatal rats produced abnormalities at maturity including depressive symptoms and sexual dysfunction. Although these three drugs affect different neurotransmitter systems, all cause REM sleep deprivation (RSD). This suggests that RSD is the causative factor in the adult depressive syndrome and sexual dysfunction. To test that idea Vogel and Hagler administered iprindole to neonates. Iprindole is an antidepressant drug that does not produce RSD. When the iprindole-treated rats matured they evidenced no sexual dysfunction or depressive symptoms. These data, taken together with the other studies reviewed above, strongly suggest that *(a)* early experience can significantly influence adult sexual functioning and *(b)* impairment in neonatal or juvenile active sleep (but not slow wave sleep) can significantly influence later adult sexual functioning.

Summary

In summary, evolutionary theory now has relatively explicit models of the ways in which early social experiences, as embedded in attachment patterns, influence later reproductive behaviors. Our reading of the Belsky et al. (1991) and Chisholm (1993) models of developmental attachment processes suggests the following predictions that may be relevant to the problem of REM:

1. There must be a physiological process in infancy that accomplishes unconscious appraisals of local ecologic conditions.
2. This appraisal mechanism must be linked with a biasing mechanism (presumably a neuroendocrine regulatory system) that adjusts behavioral strategies dependent upon outcomes of the appraisal process.
3. This physiological process (appraisal/adjustment) must be operative and abundant early in life.
4. Its values must vary with maternal behaviors given the role of attachment processes in the Belsky/Chisholm models. Finally,
5. The process must persist into adulthood and influence sexual behaviors.

In the second part of this paper we present evidence for involvement of REM in all five of these predictions. We show that REM selectively activates the amygdala—the appraisal organ of the brain/mind (1). It exerts a chronic regulatory influence on several neuroendocrine circuits that regulate growth, attachment, and reproductive behaviors (2). It is operative and abundant in early life (3). Its values vary systematically with maternal sta-

tus, whereas non-REM (NREM) sleep values do not (4). For example, REM but not NREM values increase when co-sleeping with the mother and when nursing. Conversely, REM but not NREM values decrease under conditions of maternal separation. Finally, REM persists into adulthood and is associated with hormonal and behavioral sexual activation (5).

The remainder of this paper is organized as follows: We first review the evidence for a selective REM contribution to attachment in the infant and then we review the evidence for a REM contribution to sexual/reproductive function in the adult. For brevity, we call the view that REM contributes selectively to attachment and reproductive functions "the attachment hypothesis" of the function of REM sleep. Evidence for the attachment hypothesis with respect to the infant/juvenile comes from (1) the finding that REM is associated with selective and intense activation of the amygdala, (2) correlation of REM variables with "altriciality" variables, (3) data from studies of co-sleeping mother-infant pairs, (4) correlation of REM with nursing variables, (5) the role of REM in nursing behaviors, and (6) effects of maternal separation on REM. Evidence for the attachment hypothesis with respect to the adult comes from (1) effects of REM deprivation on sexual behavior, (2) attachment- and sexuality-related hormonal release during REM, (3) the REM-associated sexual excitation, and (4) correlations between REM and reproductive variables. In the final section of the paper we offer a speculative theory as to why the neurobiology of sleep states, and REM in particular, should be related to attachment and reproductive functions.

REM AND ATTACHMENT IN THE INFANT

To understand REM physiology in the infant it is important to know that its infant precursor state, "active sleep," appears first during fetal life. The fetus "sleeps" over 95% of the time, and the bulk of this sleep is active sleep. Quiet sleep does not appear until late in the gestational period. Authorities on REM (e.g., Zepelin 2000) have termed active/REM sleep a "fetal adaptation" as many of its adult properties (e.g., reduced thermoregulatory responses or poilkothermia) mimic the fetal state. Interestingly, fetal sleep states are not correlated with maternal sleep states (Curzi-Dascalova and Challamel 2000); while the fetus spends the bulk of its time in active/REM, the pregnant mother near term spends the bulk of her time in NREM sleep (Hertz et al. 1992).

Like the fetus, the typical mammalian neonate spends most of its immediate postnatal life asleep (Carskadon and Dement 2000; Davis et al. 1999), and REM constitutes the bulk of this sleep. In the human, for example, a REM-like state emerges from "active sleep" at about the first 1–2

postnatal weeks, becomes the predominant sleep state in the infant for several weeks, and then starts a slow decline relative to NREM until adult values are reached in late adolescence. This phenomenon of abundant REM early in life holds across all mammalian species studied to date, and thus many authorities on REM assert that REM's primary function(s) must be developmental in nature (Mirmiran 1995; Roffwarg et al. 1966).

REM and Unconscious Appraisals of Ecologic Context via Activation of the Amygdala

Belsky and colleagues' (1991) and Chisholm's (1993) models of developmental attachment processes suggest that there must be a physiologic process by which "assessment of current life circumstances" is made early in life. REM is a viable candidate for such a process as it involves very high activation levels of the amygdala and associated structures (Maquet and Franck 1997) which are anatomically active in the neonate (Daenen et al. 2002). In addition, electrical stimulation of the amygdala produces pontogeniculo-occipital (PGO) waves characteristic of REM sleep (DeBoer et al. 1998). There is now abundant evidence that the amygdala specializes in processing of emotion, particularly negative emotions, and functions as the "decisional" or "appraisal organ" of the mind (Bechara et al. 1999; Davidson and Irwin 1999; LeDoux 1996). In addition, along with hippocampal sites, it apparently supports both emotional memory formation and reactivation of emotional memories during REM (Wagner et al. 2001; Wilson and McNaughton 1994). It also contributes to regulation of other brain structures such as the hypothalamus that, in turn, regulate ongoing neuroendocrine processes in the developing organism (LeDoux 2002; Davis and Whalen 2001). Finally, the amygdala is implicated in development of key cognitive components (e.g., "theory of Mind") of the attachment process in the child (Siegel and Varley 2002). Thus, early in life when REM predominates over NREM sleep, REM-related amygdalar activation may signal the processing of unconscious appraisals/assessments of current ecologic conditions (e.g., maternal sensitivity to the child). REM then takes these assessments and uses them to implement appropriate adjustments in somatic versus reproductive effort.

REM and Altriciality

Our attachment hypothesis of REM suggests that REM evolved, in part, to respond to local ecologic contingencies by supporting appraisal/adjustment processes which in turn eventuate in maternal/infant attachment. The need for such an appraisal/adjustment function would be greatest in species born in an extremely immature state (altricial species). Zepelin (2000) has shown that REM sleep "quotas," such as amount of

REM as a percent of total sleep time, correlate with life-history variables such as degree of altriciality ($r = -.45$),[1] neonatal brain weight ($r = -.55$), gestation period ($r = -.39$), and litter size ($r = .41$) across a large range of mammalian species. The greater the immaturity of the species, the longer the time spent in REM. Opossums and ferrets, for example, are born in an extremely immature state. These animals devote about 30% of their total sleep time to REM (Siegel 1993). In terms of altriciality humans and nonhuman primates are intermediate between opossums/ferrets and horses/elephants. Adult humans spend a little less time (24% of total sleep time) in REM sleep relative to opossums/ferrets, and a little more time in REM than precocial horses/elephants (who spend approximately 22% of their total sleep time in REM). In some extremely precocial species (e.g., the bottlenose dolphin) REM appears to have disappeared altogether (Mukhametov et al. 1977), at least in the adult.

Zepelin (2000) points out that altriciality evolved in mammals in conjunction with new methods to regulate body temperature. Altriciality may have reduced the energy requirements for maturation by reducing gestational periods and by enabling the young to rely on parental body heat for temperature regulation. But this innovation, of course, placed a premium on parental care of the infant for survival and thus on increasingly sophisticated infant attempts to elicit care from an adult (i.e., attachment). The need for an infant to attach to a caregiver is linked not only to its need for food and protection but also to its need for warmth. The altricial infant uses the body heat of the mother to begin to regulate its own body temperature. This is particularly important during REM because REM is a partially poilkothermic state. For the neonate to benefit from its mother's thermal and other resources during REM sleep it needs to be in close proximity to its mother. Mammalian maternal care is often associated with building a nest where the mother can suckle the young and sleep in close physical contact with the young. Thus mammalian maternal care usually takes the form of co-sleeping, with the neonate sleeping next to the mother and nursing during sleep. Interestingly, co-sleeping is a near universal mammalian practice and is practiced in virtually every human culture with the sole exception being twentieth-century industrialized cultures (McKenna 1993; McKenna et al. 1993).

REM and Co-sleeping

How does the *newborn* mammalian infant achieve attachment to the mother? Our short answer to this question is: via co-sleeping and nursing with the mother. It is through sleeping next to the mother that the helpless neonate can best elicit nutritional and thermal resources from the mother. As the infant grows it can add to its care-elicitation repertoire new and

emerging capacities and behaviors such as distress vocalizations in the rat and mutual gazing in humans. Nevertheless, a great deal of the attachment process will still take place during sleep as we explain below.

Attachment in the neonate can also be fruitfully understood as entrainment or attunement of physiologic and behavioral processes between mother and infant. These attunement processes may occur most optimally while the infant and mother sleep. Among the interactive processes that get executed during sleep are heat transfer, touch, grooming, suckling in the infant, milk ejection in the mother, gut filling in the infant, active sleep/REM activation in the infant, arousal overlaps, hormonal rhythm overlap, temperature cycle entrainment, breathing cycles, and so on. Hofer (1984) and others (e.g., Stern 1985) call these exquisitely timed sleep interactions between mother and infant "attunement behaviors" or examples of synchrony between behavioral and biological rhythms in the mother and infant.

The mammalian neonate is an open system that depends upon the mother to set regulatory values of internal physiologic rhythms and organization (Frank et al. 1998; Hofer 1984; Hrdy 1999; Reppert et al. 1987; Rosenblum and Moltz 1983; Stern 1985). These neonatal physiologic systems become organized through interaction with or attachment to the mother. As the work of McKenna and colleagues has shown (McKenna and Mosko 1994; McKenna et al. 1990), co-sleeping facilitates the development of infant physiologic systems as well as entrainment of biologic rhythms in the infant to the mother. The mother acts as a kind of *Zeitgeber* for the infant, and the mutual entrainment of rhythms occurs both during sleep and during waking behaviors. Synchrony and attunement of physiological variables such as autonomic indices and EEG waveforms may help each member of the attached pair to regulate their own internal physiological systems. Beebe et al. (1982) and Belsky and Nezoworski (1988), among others, have documented the role of synchrony in the attachment process (in humans) between mothers and infants. Several experts on the psychobiologic mechanisms of attachment (Field 1985; Hofer 1987a, 1987b; Reite and Capitanio 1985; Stern 1985) have argued that attachment can be understood as psychobiological attunement or synchrony between individuals. From this perspective attachment *is* synchrony of behavioral and biological rhythms between individuals. Field (1985) cites a long list of behavioral and biologic variables that have been documented to display synchrony of one kind or another in organisms undergoing attachment. Among these variables are sleep states and EEG waveforms.

If the physiologic basis of attachment involves mechanisms of behavioral and physiological synchrony, then attachment in the neonate and the child can plausibly occur while the infant is sleeping next to the mother. If so, we would expect to find that REM variables would vary systematically as a

function of co-sleeping status. Fortunately, data are available on sleep variables as a function of co-sleeping status, and they tend to confirm the prediction. McKenna et al. (1990, 1993) and McKenna and Mosko (1994) studied both routinely co-sleeping mother infant pairs and mother infant pairs who do not routinely co-sleep. A number of physiologic parameters were measured in both mothers and their infants when they co-slept and when they slept alone. McKenna and colleagues found that *(a)* bed-sharing mothers and infants exhibited high levels of "arousal overlap," meaning, presumably, that arousal times were synchronized; *(b)* infants exhibited more frequent stage shifts (i.e., they moved from one stage of sleep to another more frequently) when bed-sharing; *(c)* they spent more time in the same sleep stage as their mother when bed-sharing—possibly another example of synchrony; and *(d)* they spent less time in stages 3 and 4 and more time in active or REM when bed-sharing, as the attachment hypothesis predicts. In addition, infants faced toward the mother during most of the bed-sharing night (between 72% and 100% of the time) and they almost doubled their number of breast-feeding episodes (relative to the solitary-sleeping night when mothers were presumably available in the next room for breast-feeding if the infant cried).

Sleep Quotas and Nursing Variables

Nursing is the primary setting in which the mammalian infant receives resources from its mother (Clutton-Brock 1991; Gubernick and Klopfer 1981). In addition, potential conflict over attachment becomes acute during the periods of peak lactation and weaning. If the mother or some other caretaker fails to nurse the young it will typically die. What is the relation, if any, between nursing and sleep states? Our review finds that *(a)* both REM and NREM quotas are correlated with nursing-related variables across a range of mammalian species and *(b)* in a number of altricial species both the mother and the infant are typically asleep (with the mother in NREM and the infant in REM) when nursing occurs.

To our knowledge no one has yet examined the relation between sleep quotas and attachment-related nursing variables across a range of mammalian species. We extracted data on milk content, milk yield (amount of milk transferred to the infant), and milk yield at peak lactation (a measure of maternal energetic investment in the infant) from Oftedal (1984), who has tabulated the relevant nursing data for 54 mammalian species. After fitting his data to various models, Oftedal (1984) suggested that maternal energetic investment in the infant at peak lactation can be calculated as: $y = 236x - 4.9$ where y is maternal energy yield per $kg^{0.75}$ and x is the "metabolic mass ratio" (i.e., the litter metabolic mass/maternal metabolic mass or weight). We suggest that milk yield at peak lactation reflects the mother's

inclination to invest in offspring and thus may be considered an indirect measure of parent-offspring conflict and attachment.

For REM and NREM quotas (where "quotas" = percent of total sleep time spent in REM vs. NREM) we used most recently available data tabulated in Elgar et al. (1988). The cross-tabulation between the two datasets yielded 10 species with complete data. These 10 species represented a fairly broad range of species in terms of the altriciality–precociality dimension. The associated correlation matrix is displayed in Table 1. Note that virtually every measure of milk composition correlated significantly with quiet sleep time but not with active sleep time. Sugar content was negatively correlated with quiet sleep time. Conversely, maternal energetic investment at peak lactation correlated significantly with active sleep time (.65, explaining 42% of the shared variance) but not with quiet sleep time. The only milk content measure that correlated significantly (.48) with active sleep time was protein. The significant correlation between active sleep and maternal milk yield/energetic investment in the infant is consistent with the attachment hypothesis.

Nursing and Sleep States

Hofer (1987a, 1987b; Hofer and Shair 1982) and his colleagues have shown that nursing (the paradigmatic attachment behavior) in the rat is controlled by an elaborate set of cues all embedded in sleep. Infants sleep while they are nursing and suck while they are asleep. Their sucking induces milk ejections (via oxytocin release) in the mother. However, oxytocin release in the mother cannot occur unless she is in slow wave sleep or SWS (Hofer 1984; Lincoln et al. 1980; Voloscin and Tramezzani 1979). The infant, on the other hand, must be in active sleep at the point of milk ejection since it begins a pattern of rapid rhythmic sucking once the teat is engorged with milk. Lorenz (1985) and Lorenz et al. (1998) find that the suckling rat pup responds to receiving the milk by displaying paradoxical sleep (PS). Indeed, the amount of PS displayed increases as the volume of milk increases to 4% of the pup's body weight. Gut loads of milk and a

Table 1. Correlations between Sleep Quotas and Nursing Measures (with Allometric Corrections) for 10 Mammalian Species

	Quiet sleep time	*Active sleep time*
Dry matter	.54 (p = .036)	.35 (p = .19)
Fat	.34 (p = .17)	.35 (p = .16)
Protein	.62 (p = .007)	.48 (p = .047)
Sugar	−.45 (p = .070)	−.34 (p = .17)
Milk yield/energetic output at peak lactation	.50 (p = .13)	.65 (p = .039)

warm ambient temperature (from a co-sleeping mother or litter-mates) appear to work in an additive manner to enhance PS duration.

Effects of Maternal Separation on Sleep

Benoit et al. (1992) have documented an association between sleep disorders in childhood and insecure maternal attachment. Other authors have pointed to this relation between sleep problems and failure to achieve "secure" attachment between mother and child (Anders 1994; Scher 2000). The animal literature suggests a deep relation between sleep states and attachment. Separation of an infant rat or monkey from an attachment object (typically the mother) results in decreased REM sleep with little or no effect on NREM sleep (see studies summarized in Table 2).[2]

In order to explicate the role of sleep states in attachment we reviewed maternal deprivation studies that measured *both REM and SWS* so that selective effects on REM could be definitively documented. Results are displayed in Table 2. Virtually all controlled studies show a selective effect on REM: REM was severely inhibited during the despair phase of the separation experiment. SWS indices were never significantly affected. Sometimes the REM inhibition effect was especially severe, as in the case of its complete disappearance in the infant pigtail monkey in the Reite et al. (1978a) study. The selective effects on REM were particularly striking in the Reite and Short (1978) studies. In these studies 10 infant pigtail monkeys were separated from their mothers at 26 weeks. Sleep measures were taken at baseline (pre-separation) and then prospectively during a 4-day separation period and a 4-day reunion period with the mother. REM duration decreased from a baseline of 90 minutes to a mean of 37.7 minutes during the separation period (Table 2), indicating a profound inhibition of REM. Upon reunion with the attachment object, however, REM rebounded rapidly back to baseline. REM latency increased from a baseline of 64 to a mean of 172.7 minutes during the separation period. Interestingly REM latency rapidly returned to baseline during the reunion period—even falling below baseline average on reunion day 4. Notice however that the effect of maternal deprivation on sleep is selective: SWS values during the separation period (mean 463.7) did not differ from the baseline value of 469 minutes.

REM AND REPRODUCTIVE STRATEGIES IN ADULTS

Although all of the above evidence suggests a strong relation between REM and attachment for juveniles, REM persists into adulthood. Does it have any attachment- or pair-bonding-related functions in adulthood? Evidence suggesting that it does comes from (1) effects of REM deprivation

Table 2. Effects of Maternal Separation on Infant Sleep: REM vs. NREM

Study	*Design*	*Findings*
Hofer 1975b	Two-week-old infant rats; half stayed with mother, half alone	"Active" or REM sleep decreased markedly in separated infants compared with controls 4 hours after separation
Hofer 1975a	Two-week-old infant rats separated from mothers for 24 hours	Reduction of PS sleep Body movements increased and nonnutritive suckling decreased during separation Total time in SWS variably affected REM showed constant reduction
Reite et al. 1974	Four infant pigtail (*M. nemestrina)* monkeys; mother removed at 33 weeks after baseline measurements	Average % REM decreased from 16.4 (± 3.7) (baseline) to 3.5 (± 2.3) on the night following separation
Reite et al. 1978a	One infant pigtail (*M. nemestrina)* monkey; mother removed at ~14 weeks post birth for 3 weeks, juvenile adopted by another adult female	The night immediately following separation the infant showed a total absence of REM sleep REM returned after adoption
Reite et al. 1989	Five infant bonnet (*M. radiata)* monkeys; mothers removed at ~173 days post birth for four days. Each infant adopted and slept with another adult female	Infants showed significantly longer REM latency, fewer REM periods, shorter REM periods on the night following separation REM sleep decreased while no change in NREM sleep Changes in REM rebounded toward baseline values in the 2–4 days following separation from mother

			LENGTH IN MINUTES							
				Separation				*Reunion*		
		Sleep Stage	*Baseline*	S_1	S_2	S_3	S_4	R_1	R_2	R_3
Reite and Short 1978	Ten infant *M. nemestrina* monkeys removed from mother at 26 weeks. Baseline, 4-day separation from and 4-day reunion with mother	REM sleep	90.4 ± 4.6	21	36	48	46	88	95	89
		REM latency	64 ± 6.4	212	163	197	119	102	80	77
		SWS	469 ± 4.6	442	463	466	484	487	478	469
Reite et al. 1978b	Three infant pigtail (*M. nemestrina)* monkeys removed from mother at birth, raised by cloth surrogate. 4-day separation, 3-day reunion with surrogate	REM sleep	91 ± 14	36	60	78	84	89	93	108
		REM latency	68 ± 21	219	108	180	83	49	79	34
		SWS	495 ± 34	465	495	493	471	497	487	490
Reite et al. 1981	Three infant pigtail (*M. nemestrina)* monkeys separated from mothers for 10 days while infants remained with social groups	SWS showed a ~10% decrease on the night following separation and returned to baseline First night of separation produced decreases in REM time, number of REM periods, and mean REM length, and increases in REM latency and inter-REM intervals REM period length returned to normal during rest of 10 days REM time, number of REM periods, and REM latency appeared changed throughout duration of separation and rebounded with reunion								

on social and sexual behavior, (2) release of oxytocin and sex hormones during REM, (3) REM-associated sexual excitation, and (4) correlations between REM and reproductive variables.

Effects of REM Deprivation on Psychologic and Biologic Function

After sleep deprivation, SWS and then REM evidence a compensatory rebound on subsequent recovery nights. Aside from the REM rebound effect, and according to recent extensive reviews of the literature on REM deprivation (REMD), no significant psychologic or biologic effects are noted with REMD—at least short-term REMD. With prolonged (16 to 54 days) REM deprivation (at least in the rat) death may ensue (Kushida et al. 1989; Rechtschaffen and Bergmann 1995). But it is questionable whether death is due to selective REM deprivation since SWS deprivation results in death as well (in 23 to 66 days). In addition, in these studies of prolonged REMD, experimenters noted substantial leakage of both REM and SWS into the REMD period and vice versa. It is very difficult to selectively deprive an animal of a given sleep type over a long period of time. Death in the prolonged SWS/REMD studies is believed to be due to a significant decline in core body temperature (as much as 2°C) with compensatory attempts to increase temperature through increased energy expenditure.

The attachment hypothesis predicts impairment of sexual and attachment functions after REMD. With respect to sexual functions Velazquez-Moctezuma and colleagues (1996) have shown that even when effects of the stress associated with the REMD procedure in rats are controlled, sexual behavior is radically impaired in male rats after selective REMD. Compared with control rats, REMD rats evidenced an increase in mount, intromission, and ejaculation latencies and in mount frequency as well. There was also a decrease in ejaculation frequency. Thus, while sexual drive (mount frequency) might increase after REMD, sexual *function* (intromission and ejaculations) declines and is, in fact, impaired.

We know of no studies in either animals or humans of effects of REMD on attachment. There is, however, indirect evidence of such effects in the human studies: After review of some 35 studies of selective REM versus NREM deprivation, Pearleman (1982) concluded that the only consistent psychologic effect of REM deprivation was impairment in interpersonal relationships—participants were found to be "less interpersonally effective." For example, Hartmann (1973) noted that dream-sleep deprivation in humans reliably produced "poor social presence," poor social interaction, and impaired ego-defensive functioning. Finally, hundreds of patients given antidepressants such as the selective serotonin reuptake inhibitors have undergone prolonged pharmacologic suppression of REM with no effects on memory or cognition and no obvious effects on attach-

ment functions. There are, however, well-known deleterious "side-effects" of these REM suppressant antidepressants on sexual function (Fava and Rankin 2002).

Hormonal Effects: Oxytocin, Vasopressin, and Arginine Vasotocin

Attachment processes in both the infant and the adult appear to be mediated by specialized neurohormonal systems. Neurohypophysial hormones like oxytocin and vasopressin, as well as arginine vasotocin, seem to be especially important for attachment and other social and sexual behaviors (see papers in Pedersen et al. 1992). REM contributes to recruitment and activation of complex attachment and sexual behavioral strategies via its regulation of key neuroendocrine systems (Van Cauter and Spiegel 1999). It is through activation and inhibition of these neuroendocrine circuits that REM can regulate adjustment of relevant waking behavioral strategies in response to limbic appraisals. For example, prolactin (PRL) is known to be crucial, not only for development of mammaries and synthesis of maternal milk proteins, but for development of reproductive and sexual behaviors as well (Bole-Feysot et al. 1998). It stimulates an array of testicular functions in males and ovarian functions in females. Its release is dependent on REM, with its levels rising rapidly at sleep onset and peaking around 3–5 A.M. when REM predominates. Similarly, growth hormone (GH) release is sleep-dependent and tightly coupled to slow wave sleep. GH is known to stimulate a host of growth factors as well as sexual and brain functions (Van Cauter and Spiegel 1999). Deconvolution and pharmacologic analyses of nocturnal GH secretion rates demonstrate maximal GH release within minutes of the onset of (NREM) slow wave sleep. GH levels and effects, however, are modulated by somatostatin levels, which are, in turn, REM sleep dependent. Thus, NREM stimulates GH release while REM regulates its levels. Neuroendocrine systems more directly implicated in maternal-infant attachment processes are also REM dependent. Oxytocin, for example, displays a sleep-sensitive pattern of release in humans, with peak levels occurring at about 4 o'clock in the morning when REM sleep begins to predominate over NREM (Forsling 1993). When injected centrally, oxytocin induces several of the behaviors associated with social bond formation in mammals including maternal-infant contact, nursing in infants, care-taking behaviors in the mother, and species-typical reproductive behaviors in adults (Argiolas and Gessa 1991; Insel 1992).

Arginine vasotocin (AVT) is considered to be the evolutionary precursor to vasopressin (Pedersen et al. 1992). Both vasopressin and oxytocin promote various types of bonding behaviors in a range of mammalian species. Vasotocin promotes sexual behaviors in various non-mammalian

species. Subcutaneous injection of AVT in human subjects causes a selective increase in REM sleep. Intranasal administration causes a dramatic enhancement of REM sleep indices. Lumbar CSF (cerebrospinal fluid) levels of AVT vary with REM sleep indices and AVT levels are abnormally high during REM sleep in narcoleptics (Pavel et al. 1979; Popoviciu et al. 1979).

Sexual Excitation and REM

Although it has been known for some time that every REM cycle is associated with penile erections in males and clitoral engorgement in females, it is not known why this sexual excitation occurs. Oddly enough, REM-related erections have generally been considered as mere epiphenomena of REM-related physiologic changes. Schmidt (2000), however, has now provided convincing evidence that REM-related penile erections are dependent on an oxytocinergic mechanism and hypothesizes that regular sleep-related erections confer reproductive advantages in obvious ways.

Sex-related hormones have been selectively associated with REM. Prolactin (PRL) release is dependent on sleep states—specifically, its levels rise rapidly at sleep onset but peak around 3–5 A.M. when REM predominates. Its release can be blocked by sleep deprivation. Testosterone levels in males are highest at the transition from NREM stages to REM (see Borbely and Tobler 1989 for review and critique of the literature on REM-sleep-associated endogenous substances).

REM and Reproductive Functions

We have already mentioned work on sleep quota correlations with maturational and reproductive variables such as gestational length and degree of maturity at birth (Elgar et al. 1988; Meddis 1983; Zepelin 2000). To our knowledge, no data yet exist on possible relations of sleep quotas with other reproductive indices such as pair-bonding status in the adult, age at sexual maturation, timing and length of the estrous cycle, and so on. The attachment hypothesis would predict significant correlations between REM and all of these variables. We attempted to collate data on sleep quotas (Elgar et al. 1988) and life history and reproductive indices for primates (Harvey et al. 1987). We could find appropriate data for 16 species but complete data for some analyses was available for only 10 species. Analysis showed that there were no significant correlations between quiet sleep and any of the reproductive indices. By contrast, active sleep times were significantly related to length of the estrous cycle in days ($r = -.73$, $p = .016$; $N = 10$ species); age (in months) at sexual maturation in the female ($r = .89$, $p = .001$; explaining 79% of the shared variance, $N = 9$ species) and age at

sexual maturation in the male ($r = .95$ but this was based on only 4 species). The correlation between estrous cycle length and REM suggests that the longer the cycle the shorter the REM, while the correlation between REM and sexual maturation in females suggests that the longer it takes to reach sexual maturation the longer the REM duration in that species.

REM Anatomy

Evidence from brain activation and brain lesion studies suggests that REM is associated with selective rather than widespread brain activation (see reviews in Gillin et al. 1993; Hobson et al. 1998a, 1998b). The sites most consistently activated during REM are (1) the pontine reticular formation; (2) extrastriate (visual) regions (as well as other sensory association sites), but not primary sensory strips; and (3) limbic and paralimbic regions, including the lateral hypothalamus, the amygdala and anterior cingulate, parahippocampal, and possibly medial and orbitofrontal cortices, but not the dorsolateral prefrontal cortex (Braun et al. 1997, 1998; Maquet et al. 1996; Nofzinger et al. 1997). This configuration represents intense activity in emotional and appraisal functions with reductions in activity of executive and reflective functions.

In a careful review of the neuropsychological literature, Solms (1997) has pointed to a role for activation of a "motivational circuit," presumably involving activation of the amygdala, limbic, and basal forebrain during REM. It has been known for some time that lesions in the region of the basal forebrain (which is interconnected with both the amygdala and the orbitofrontal cortex) are associated with REM sleep fragmentation and loss of dream recall (Solms 1997).

We have seen that the amygdala undergoes intense activation in REM. Given its apparent role in emotional appraisal and emotional memory it should not be surprising to find that the amygdala is also involved in attachment. In their review of the neuroanatomic structures that mediate early attachment, Steklis and Kling (1985) concluded that limbic system sites (especially the amygdala), the anterior temporal cortex, and the orbitofrontal cortex were critical for attachment. Lesioning any of these three sites produces profound disruption in attachment processes.

Conclusions: REM, Attachment, and Reproductive Strategies

Our review of the literature on REM sleep and attachment suggests that one function of REM sleep could be to promote or support early attachment in service of development of optimal long-term reproductive strategies. REM values, such as duration of REM as a percent of total sleep time, vary significantly with life-history traits such as length of the estrous cycle

and age at first reproduction. REM duration is greatest during development and in altricial species. REM is associated with selective activation of the amygdala—the neural instantiation of the emotional "appraisal" process—so it is positioned to mediate decisions about behavioral responses to local environmental conditions. In the juvenile those decisions are focused primarily on attachment strategies that later become reproductive strategies. REM is also associated with release of the attachment-related hormones prolactin and oxytocin. Many mammalian infants nurse while they are asleep, and there are indications that they are in active sleep when they nurse. REM values vary systematically with milk yield/transfer to the infant in a range of mammalian species and with co-sleeping status in human infants. REM deprivation in adult humans and in rats leads to decreased competence in sexual functions. REM is associated with anatomic activation of brain sites that are also implicated in attachment processes—namely the amygdala and the limbic cortex. Finally disruption of the attachment bond leads to a selective effect on REM: REM processes are inhibited or even lost altogether whereas no significant changes occur in NREM/SWS values.

Having established that REM is significantly associated with attachment and reproductive functions, we turn to the final task for this paper. That task is to suggest why an association between REM and attachment/reproductive strategies exists at all and thus to strengthen the claim that REM evolved to facilitate development of attachment and reproductive strategies.

WHY REM?

Guided by the Belsky et al. and Chisholm models of the links between developmental processes of attachment and adult reproductive strategies, our original hypothesis was that REM evolved to promote development of attachment and reproductive strategies. We have presented a substantial amount of evidence to support the fundamental claim of the existence of physiologically significant links among REM, attachment, and sexual processes. But aside from the demonstration that REM is, in fact, associated with attachment/reproductive variables, we have not yet provided an evolutionary argument as to *why* REM should be so associated. We, in fact, do not know why. We nevertheless offer the following brief speculation in hopes that it might eventually lead to a more definitive answer of the *why* question.

We begin by recalling that for most mammalian species, REM alternates with NREM sleep states across each sleep period, with NREM predominating in the first third of the sleep cycle and REM in the last third. Simi-

larly, while REM predominates in the fetus, NREM predominates in the pregnant mother. At term, REM promotes nutritive suckling in the neonate, but the mother must be in NREM for milk ejection to occur. REM values increase in the infant when the infant co-sleeps with the mother, but NREM values increase in the mother with co-sleeping. In the infant, REM undergoes a profound inhibition during the despair phase after maternal separation. There is, on the other hand, no significant change in NREM values in the infant after this catastrophic separation. REM is associated with release and high levels of attachment promoting hormones such as prolactin and oxytocin, while NREM is not. Conversely, growth hormone (GH) release is under the control of NREM. On the other hand, REM, via its control of somatostatin—the GH inhibitory factor—modulates these NREM GH levels. Similarly, muscle tone, thermoregulatory responses, and autonomic responsivity are all variable in REM but stable in NREM. Finally, brain activation patterns are significantly different and even opposing for the two sleep states, with REM demonstrating high activation levels in limbic sites and *deactivation* of dorsolateral prefrontal cortex sites, while regional cerebral blood flow studies for NREM/SWS indicate deactivation of thalamic functions and activation in secondary association areas in temporal and parietal lobes, including the language-related planum temporale and the inferior parietal lobule areas (Hofle et al. 1997). The list could go on, but the trend is clear. Indeed, our review of the literature suggests that REM and NREM sleep states may functionally complement one another in some respects and oppose one another's actions in other respects.

Recently, Keverne and colleagues (1996) have pointed out that functionally distinct regions of the brain may reflect the distinct contributions of the maternal and paternal genomes. These genomes contribute differentially (through genomic imprinting) to brain development, with the maternal complement influencing primarily neocortical sites and the paternal complement, hypothalamic/limbic sites. Imprinted genes display parent-of-origin-dependent monoallelic expression that apparently regulates complex mammalian traits, including brain function, growth, and behavior. Recent human genetic studies have directed attention to the role of genetic imprinting in a number of syndromes involving sleep dysfunction, including the Prader-Willi and Angelman syndromes. The Prader-Willi syndrome is associated with maternal additions/paternal deletions on chromosome 15 and is characterized by poor sucking response, obesity, temperature control abnormalities, islands of spared cognitive abilities, and excessive sleepiness with enhanced NREM values. Angelman syndrome, on the other hand, is associated with paternal additions/maternal deletions on chromosome 15 and is characterized by prolonged sucking, frequent crying, severe mental retardation, and *sleeplessness* due to sleep-onset REM and enhanced REM values (i.e., reduced deep NREM sleep).

These data suggest that the paternal genome may differentially influence REM and those brain sites (hypothalamus, limbic, amygdala, etc.) implicated in REM, while the maternal genome may differentially influence NREM brain functions.

If the paternal genome does in fact disproportionately influence REM, then it is possible that REM evolved in service to these paternal genes. Haig (2000) has argued that the father's genes in the developing fetus function to promote the greatest possible extraction of resources from the mother and thus are more prominent in placental function. Haig sees much of the pregnancy/gestational periods as a conflict between maternal/paternal genes over extraction of resources from the mother, with paternal genes selected to extract as much as possible from the mother and the mother producing mechanisms (e.g., spontaneous abortion) to "protect" herself from overexploitation. We have seen that the fetus spends virtually all of its time in active/REM sleep (it is never "awake"). Thus, it seems reasonable to suggest that REM may contribute to the effort to extract resources from the mother. This role for REM then continues postnatally when the goal becomes "attachment." Recall, for example, that REM values vary with nursing/sucking rates and with maternal investment. In service to paternal genes, REM facilitates extraction of resources (milk, warmth, nearness, protection, attachment, etc.) from the mother. NREM, in turn, may have evolved after REM in order to modulate REM's "demands." Recall that in the pregnant mother REM is decreased and NREM enhanced. In addition, she must be in SWS (NREM) for milk ejection to occur.

We cannot here provide a detailed defense of the above speculation concerning the evolutionary "why" of REM sleep. We note only that it is consistent with the facts concerning associations of REM sleep that we reviewed in this article. Those facts, of course, stand whether or not our speculation turns out to be correct.

Patrick McNamara, Ph.D., is an assistant professor of neurology at Boston University School of Medicine and a member of the Department of Neurology at the Boston VA Medical Center. He specializes in study of catecholaminergic mechanisms of cognitive disorders in Parkinson's and related disorders. He has a longstanding interest in anthropological and evolutionary approaches to medicine and to human cognition. His recent book *Mind and Variability* applied Darwinian models to problems of memory and identity. He is currently writing a book on the evolutionary psychology of sleep and dreams.

Sanford Auerbach, M.D., is an associate professor of neurology and psychiatry at Boston University School of Medicine and medical director of the Neurophysiology Laboratories at the Boston Medical Center. He is a behavioral neurologist and a board-certified sleep specialist. He is also director of the Sleep Disorders Center

at Boston Medical Center. He has been associated with the NIH-sponsored Sleep Heart Health Study and other sleep-related research. He has been a member of the executive committee of the Sleep Section of the American Academy of Neurology and a past chair of the Neurology section of the American Sleep Disorders Association.

Jayme Dowdall is a medical student at Boston University School of Medicine who plans to specialize in molecular approaches to sleep disorders.

NOTES

1. For these comparative analyses Zepelin (2000) had an expert mammalian biologist rate each species for which Zepelin had sleep data ($N = 65$) along an altricial–precocial scale for neonates with 1 = eyes closed, naked, sometimes can cling . . . to 4 = eyes open, furred, can walk and follow or swim.
2. The inhibiting effect of maternal separation on REM sleep appears to be qualitatively different from the so-called first night effect that typically occurs in subjects during their first night of sleep in a novel environment such as a sleep lab. The *first night effect* refers to the fact that very few subjects sleep normally when forced to sleep in an unfamiliar environment or when hooked up to special recording equipment. Most subjects, however, habituate quickly (usually in one day) to the new environment.

Although the first night effect is typically associated with "disrupted REM" and to a certain extent disrupted NREM sleep states, the effect disappears after the first night as the subject habituates to the novel lab environment (Webb and Campbell 1979). REM inhibition after maternal separation, on the other hand, persists (although in a slightly attenuated form) into the despair phase of the "protest"-then-"despair" separation sequence (Hofer 1987a, 1987b; Hofer and Shair 1982).

In monkeys this inhibition may last for days. Indeed REM may never fully normalize unless the abandoned infant is adopted by some other individual or is reunited with the mother. If re-adoption fails to occur the infant may, in fact, die. While REM is resistant to normalization after separation, NREM values quickly renormalize after separation (often after the first night of separation—see the Reite and Short 1978 and Reite et al. 1978b studies in Table 2). In addition, REM inhibition occurs even when the infant is not placed in a new environment. The crucial ingredient is the disappearance of the mother—not the appearance of a novel environment, as with the first night effect. Hinde (1974) has shown that the effects of maternal separation on the infant are more severe when the mother is separated from the infant than when the infant is separated from the mother—even though the infant, in the latter case, is placed in a novel environment (without the mother of course) and thus should be experiencing the first night effect.

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