Meta-Analysis of Quantitative Sleep Parameters From Childhood to Old Age in Healthy Individuals: Developing Normative Sleep Values Across the Human Lifespan

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Objectives: The purposes of this study were to identify age-related changes in objectively recorded sleep patterns across the human life span in healthy individuals and to clarify whether sleep latency and percentages of stage 1, stage 2, and rapid eye movement (REM) sleep significantly change with age.

Design: Review of literature of articles published between 1960 and 2003 in peer-reviewed journals and meta-analysis.

Participants: 65 studies representing 3,577 subjects aged 5 years to 102 years.

Measurement: The research reports included in this meta-analysis met the following criteria: (1) included nonclinical participants aged 5 years or older; (2) included measures of sleep characteristics by "all night" polysomnography or actigraphy on sleep latency, sleep efficiency, total sleep time, stage 1 sleep, stage 2 sleep, slow-wave sleep, REM sleep, REM latency, or minutes awake after sleep onset; (3) included numeric presentation of the data; and (4) were published between 1960 and 2003 in peer-reviewed journals.

Results: In children and adolescents, total sleep time decreased with age only in studies performed on school days. Percentage of slow-wave sleep was significantly negatively correlated with age. Percentages of stage 2 and REM sleep significantly changed with age. In adults, total sleep time, sleep efficiency, percentage of slow-wave sleep, percentage of REM sleep, and REM latency all significantly decreased with age, while sleep latency, percentage of stage 1 sleep, percentage of stage 2 sleep, and wake after sleep onset significantly increased with age. However, only sleep efficiency continued to significantly decrease after 60 years of age. The magnitudes of the effect sizes noted changed depending on whether or not studied participants were screened for mental disorders, organic diseases, use of drug or alcohol, obstructive sleep apnea syndrome, or other sleep disorders.

Conclusions: In adults, it appeared that sleep latency, percentages of stage 1 and stage 2 significantly increased with age while percentage of REM sleep decreased. However, effect sizes for the different sleep parameters were greatly modified by the quality of subject screening, diminishing or even masking age associations with different sleep parameters. The number of studies that examined the evolution of sleep parameters with age are scant among school-aged children, adolescents, and middle-aged adults. There are also very few studies that examined the effect of race on polysomnographic sleep parameters.

Key Words: meta-analysis, PSG, psychiatric disorders, sleep disorders, moderator analysis

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INTRODUCTION

SLEEP PATTERNS EVOLVE ACROSS THE NORMAL AGING PROCESS IN COMPLEX WAYS. Changes in sleep patterns across childhood and adolescence, for example, are related not only to chronologic age but also to maturation stage. Few studies, however, have made comprehensive analyses of these 2 aspects in adolescents.[1] Similarly, chronologic age in elderly people does not always match physiologic age. Therefore, changes in sleep patterns may happen earlier, ie, at a younger age, for some individuals or at an older age for others. Further, epidemiologic and other studies suggest that much of the sleep disturbance typically seen in old age is likely the result of medical comorbidities than age per se.[2-6]

Nevertheless, 4 age-related changes have been consistently demonstrated in polysomnographic (PSG) studies of sleep architecture: total sleep time (TST),[7-29] sleep efficiency,[7,9-14,17-23,25-29,30-36] and slow-wave sleep (SWS)[7,8,10,12-18,21-28,31,33,35,37-39] all decrease, while wake after sleep onset (WASO)[12-14,16,17,19,21,23,28,29, 32,33,36,37,40] increases with age.

However, a number of PSG sleep characteristics remain uncertain as regard their evolution with age: (1) sleep latency has been reported to increase with age in some studies,[10,13,26,31,40] while several other studies have found no significant changes with age.[8,9,12,14,16,17,20-23,28,29,32,33,35-37,39,41] Likewise, a number of studies have found no significant differences with age for (2) percentage of stage 1[9,25,26,35,39,42] and (3) stage 2 sleep[9,13,20,22,23,25,33,35,36,42,43] while many others have reported an increase with age of these stages.[7,8,12,17,27,28,31] (4) Similarly, rapid eye movement (REM) sleep has been reported to decrease with age in several stud-

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ies[7,8,10-12,14,16-18,20,21,23-26,28,31,33,37,38,44] while many other studies have found no such association with age.[9,13,15,19,22,27,34-36,39-43]

Why such discrepancies between the studies? Several factors may be responsible for the difficulties identifying age trends in sleep architecture of apparently healthy subjects, including for example, small sample sizes; inconsistency in controlling factors that may influence sleep, such as mental or physical illness; uncontrolled use of alcohol, drugs, or medications; or insufficient screening for sleep disorders.

The purposes of this study were to better define normative sleep across the human life span by identifying age-related changes in objectively recorded sleep patterns in healthy individuals using meta-analyses. More specifically, this study aimed to clarify whether sleep latency, percentages of stage 1 and stage 2 sleep, and percentage of REM sleep change with age and in which direction. It also aimed to verify to what extent lack of control over key variables modify the observed age changes in sleep patterns.

METHODS

The target population studies for these meta-analyses included all studies that met the following criteria:

1. Included nonclinical participants aged 5 years or older; the lower limit of 5 years was chosen to include only school-aged children
2. Included measures of sleep characteristics by "all-night" PSG or actigraphy on 1 or more of the following variables: sleep latency, sleep efficiency, TST, stage 1 sleep, stage 2 sleep, SWS, REM sleep, REM latency, and minutes of WASO
3. Included data presented numerically
4. Was published between 1960 and 2003 in peer-reviewed journals (unpublished works, dissertations, chapters, and abstracts were not included)

Databases searched were PubMed, PsyInfo, and Science Citation Index. Search terms were *sleep* with *normal*, *normative*, and *healthy*. In addition, references cited in retrieved reports were screened for additional reports. More than 4,000 reports were first screened for inclusion criteria and reduced to 585 reports. Subsequently, if a research report referred to the same data, only the most complete data set was taken, and the other papers were discarded.

Overall, 65 studies met all inclusion criteria. These studies represented 3,577 subjects aged 5 years to 102 years. The research reports devoted to children and adolescents totaled 1,186 subjects aged between 5 years and 19 years. The research reports on adults included 2,391 participants aged 19 years or older.

Procedures

Each accepted research report was reviewed and coded according to 6 criteria

1. At least 1 target variable (TST, sleep latency, sleep efficiency, WASO, REM sleep, stage 1 sleep, stage 2 sleep, SWS) was present
2. The sample was well described (number of subjects, recruitment procedure, etc)
3. Statistical analytic results were reported for at least 1 target variable (for example, F value, *r* value, etc);
4. Central tendency measures (eg, mean) and measures of variability were reported for at least 1 target variable;
5. Sexes were identified, and data summarized for each
6. Age was identified, and data summarized for age groups

Research reports with positive answers to criteria 1 to 4 and positive answers on criteria 5 or 6 were analyzed with a detailed checklist composed of 15 items summarizing the key elements of the articles: background, participants, intervention, selection criteria, objectives, outcomes, sample size, composition of the sample, variables assessed, statistical methods, and key results. As a rule, when the studies included 2 or more nights of PSG recording, the first-night results were discarded from the meta-analysis. When the results for each night were presented, night-1 results were discarded, and the data were averaged for all the other nights.

Statistical Analyses

Calculation of Effect Sizes

Effect sizes are indices that measure the magnitude of the differences between 2 groups. Effect sizes can be measured in 2 ways: (1) as the standardized differences between 2 groups or (2) as the correlation between an independent variable classification and individual scores on the dependent variable (effect size correlation). For this study, we measured standardized differences between 2 groups by calculating Cohen's d.[45] The simplest formula of Cohen's d is defined as the difference between means (M1 – M2) divided by the SD of either group. Furthermore, since the different groups in the selected studies are presumed to come from the same population (healthy individuals), pooled SD was used instead.[46] The pooled SD is the root mean square of the 2 SD. The formula is then: $d = M_1 - M_2 / \sigma_{pooled}$ where $\sigma_{pooled} = \sqrt{[(\sigma_1^2 + \sigma_2^2) / 2]}$.

Some studies did not provide means and SD for the key variables; therefore, effect size had to be calculated from other statistical tests reported, such as correlation coefficients, *t* tests, or analyses of variance.

Analyses of Effect Sizes

Effect sizes for each study were analyzed using Comprehensive Meta Analysis, a software package developed by Biostat (Englewood, NJ). The software provides a correction of effect sizes for sampling errors,[47] particularly important since most studies had small sample sizes. The formula given by Hedges and Olkin[47] was used: unbiased estimate of $d = d \times (1 - [3 / \{4 (M_1 + M_2)-9\}])$. Values of d are interpreted according to Cohen guidelines:[45] effect sizes at .2 are considered small, at .5 are considered medium, and are large at .8. In the text, as a general rule, a positive value of the effect size indicates an *increase with age* of the studied variable while a negative value indicates a *decrease with age*. The closer an effect size is to 0, the smaller is the age difference.

The *Q* statistic, a homogeneity test, was calculated to assess the dispersion of individual outcomes vis-à-vis the combined effect. The *Q* statistic has an approximate χ^2 distribution with *k*-1 degrees of freedom where *k* is the number of effect sizes. When *Q* is significant, it indicates that the variation is greater than expected by sampling error and that analyses of moderators should be done. Therefore, 7 moderator variables that might influence sleep parameters were also collected: mental illness, physical illness, drugs or alcohol use, sleep apnea, other sleep

disorders, sex, and polysomnographic recordings performed according a fixed sleep-wake schedule or based on habitual sleep patterns. For children and adolescents, the time of the recording (school day vs nonschool day) was also collected. These moderators were used to calculate to what extent their presence (or absence) modified the different effect sizes. Alpha was set to .05 for all analyses, and the confidence intervals to 95%.

RESULTS

Only 10.8% of the studies were conducted in 1975 or earlier; 16.9% were performed between 1976 and 1985; 33.8% of studies were carried out between 1986 and 1995; and 38.5% between 1996 and 2003. Table 1 presents the number of studies and subjects involved for each moderator variables.

Studies in Children and Adolescents

Data collection of objective sleep parameters was relatively infrequent in children and adolescents. A total of 18 studies presenting numeric data on TST and sleep stages were found from 1972 to 2003 (Table 2). In addition, the instrumentation used to collect sleep data varied. Eleven studies used in-laboratory PSG recording. Two studies used an ambulatory monitoring system,[55,58] and 5 studies used actigraphy, 1 of them using both in-laboratory polysomnographic recording and actigraphy.[57,60-62,64] The 18 studies were performed in different contexts. Five studies were done only on school days,[53,58,60-62] 3 studies were performed on week ends or during summer time,[54,52,59] and 2 studies included both school days and nonschool days.[57,64] Eight studies did not specify the time of the year.

Studies in Adults

Forty-seven studies using either PSG or actigraphy recording of sleep parameters in healthy adults were retained. A listing of these studies can be found in Table 3. In these studies, 17 (36.2%) compared sleep parameters of elderly adults to those observed in young adults (mostly subjects in their 20s). Seven (14.9%) compared young, middle-aged, and elderly subjects, 3 studies compared middle-aged subjects to elderly, 11 other studies were limited to young and middle-aged adults, and 9 included only elderly subjects. Most of the studies included both men and women but rarely reported values for each sex. Thirteen studies included only men and 1 study only women.

Six studies reported results based on a single night of polysomnographic recording (Table 3). In the other studies, the first night was for habituation to the laboratory, and the analyses were carried on the other nights. All but 5 of the PSG studies used the Rechtschaffen and Kales criteria[75] for sleep-stage scoring.

Overall Age-Related Trends

To describe age-related changes, we plotted mean values of each of sleep variables (TST; sleep latency; sleep efficiency; percentage of S1, S2, SWS, and REM sleep; and REM latency) as a function of age. The method of least squares was used to fit exponential equations to the data. Figure 1 presents the data and Table 4 the details of the equations. As is seen, sleep latency and percentage of S1, S2, and REM sleep had a low proportion of variance explained by age only (11% or less).

As can be observed, TST (r = -.76, P < .0001), sleep efficiency (r = -.82, P < .0001), percentage of SWS (r = -.56, P < .0001), and percentage of REM sleep (r = -.34, P < .0001) each showed a significant decrease with age. On the other hand, sleep latency (r = .16, P < .0001), percentage of stage 1 sleep (r = .16, P < .0001), percentage of stage 2 sleep (r = .34, P < .0001), and WASO (r = .75, P < .0001) each increased with age.

Magnitude of Effect Sizes

Table 5 and 6 provide information about the effect sizes calculated for each of the 9 sleep variables studied, the number of studies and subjects involved, the mean weighted effect sizes with 95% confidence intervals, and the Q values of homogeneity tests.

Age Trends for Children and Adolescents

In children and adolescents, TST (n = 1360), percentage of SWS (n = 585), and REM latency (n = 447) were negatively correlated with age, which indicated that as the children are aging, these sleep variables are decreasing (Table 5). Percentage of stage 2 sleep (n = 572) was positively related to age, indicating that percentage of stage 2 increases with age. The effect size was in the small range for percentage of REM sleep, indicating that the differences between children and adolescents, although significant, were not so large (about 2%). Effect sizes were in the medium range for TST, percentage stage 2 sleep, REM latency, and SWS. The decrease in SWS and the increase in percentage of stage 2 were about 7% per 5-year period between 5 and 15 years of age. Sleep latency, sleep efficiency, and percentage of stage 1 sleep had nonsignificant effect sizes.

Table 1—Number of Studies and Subjects Involved for Each Moderator in Adult Samples

	Studies, no.	Subjects, no.		
		Total	Men	Women
Total	47	2391	1474	917
Sex comparison	17	1045	506	539
Use of habitual sleep patterns for polysomnography	26	1382	849	533
Participants screened for				
Mental illness	28	1801	1059	742
Physical illness	38	1913	1113	800
Drugs or alcohol use	31	1622	961	661
Sleep apnea	15	670	368	302
Other sleep disorders	29	1382	849	533

Age Trends for Adults

In adults, all sleep parameters had effect sizes significantly different from 0. The effect size was in the large range for TST, sleep efficiency, percentage of SWS, and WASO; medium for REM percentage; and small for percentage of stage 1 sleep and REM latency. Total sleep time, sleep efficiency, percentage of SWS, percentage of REM sleep, and REM latency were negatively correlated with age. This pattern indicates an age-related decrease in these sleep variables.

As seen in Figure 1a, TST (n = 2009) linearly decreased with age with a loss of about 10 minutes per decade of age. Similarly, percentage of SWS (n = 1544) linearly decreased at a rate of about 2% per decade of age. The decrease in sleep efficiency (n = 1738) was more evident from 40 years of age: a 3% decrease per decade of age can be observed until very old age. The decrease in percentage of REM sleep (n = 1986) was subtler and was more obvious when young adults were compared to individuals 60 years of age or older, where a 4% discrepancy can be observed between these 2 groups.

On the other hand, sleep latency (n = 1436), percentages of stage 1 (n = 1072) and stage 2 sleep (n = 1133), and WASO (n = 1012) increased with age, as indicated by significant positive effect-size values. As illustrated in Figure 1a, and showing a small effect size, sleep latency increased very progressively with age and became more obvious after 65 years of age. The same observations can be made for percentages of stage 1 and stage 2

Table 2—Studies Using Polysomnography or Actigraphy to Assess Sleep Parameters in Normal Healthy Children and Adolescents

First author, year	Country	Sample	Measures	Variables Provided
Williams, 1972[48]	USA	28 boys 8-15 years	PSG, 3 nights	S1, S2, S3, S4, REM
Karacan, 1975[49]	USA	7 boys & 10 girls 12.5-15.8 years	PSG, 3 nights	TST, SL, SE, S1, S2, S3, S4, REM
Orr, 1977[50]	USA	13 children 6-16 years	PSG, 3 nights	TST, S1, S2, S3, S4, REM
Benoit, 1978[51]	France	13 boys & 8 girls 5-12 years	PSG, 2 nights	TST, S1, S2, S3, S4, REM
Carskadon, 1980[52]	USA	11 boys 10.2-15.7 years 8 girls 10.9-15.8 years Recorded 3 summers	PSG, 3 nights, MSLT	TST, SL, S2, SWS, REM
Coble, 1984 [53]	USA	42 boys & 45 girls 6.0-15.11 years	PSG, 3 nights during school year	TST, TSA, SL, SE, S1, S2, S3, S4, REM
Goetz, 1987[54]	USA	24 boys & 16 girls mean age 15.6 ± 1.5 years	PSG, 3 Nights	TST, TSA, SL, SE, S1, S2, S3, S4, REM
Palm, 1989[55]	Sweden	9 boys & 9 girls 8-12 years	AMS, 50 hours	TST, TSA, SL, SE, S1, S2, S3, S4, REM, NNW
Acebo, 1996[56]	USA	23 boys 13.3 ± 2.1 years 22 girls 13.8 ± 1.8 years	PSG, 1 night	TST, TSA, SL, SE, S1, S2, S3, S4, REM
Carskadon, 1998[57]	USA	15 boys & 25 girls 14-16.2 years	Actigraphy, 2 weeks + PSG, 1 night	TST, TSA, SL, S1, S2, S3, S4, REM, bedtime, wake-up time
Stores, 1998[58]	UK	30 boys & 30 girls 5-16 years	AMS, 1 night	TST, SL, SE, S1, S2, S3, S4, REM, NNW
Laberge, 2000[59]	Canada	19 boys 13.9-17 years	PSG, 2 nights	TST, SL, SE, S1, S2, SWS, REM
Sadeh, 2000[60]	Israel	72 boys & 68 girls 7.2-11.8 years	Actigraphy, 5 school nights	TST, TSA, SL, SE, MWT, NNW
Aronen, 2001[61]	Finland	33 boys & 33 girls 5-12 years	Actigraphy, 5 school nights	TSA, SL, SE
Gaudreau, 2001[26]	Canada	16 boys & 8 girls 6-16 years	PSG, 1 night	TST, SL, SE, S1, S2, S3, S4, REM
Paavonen, 2002[62]	Finland	6 boys & 14 girls 7.3-13.3 years	Actigraphy, 3 school nights	TSA, SL, SE
Bruni, 2002[63]	Italy	6 boys & 4 girls 6-10 years	PSG, 2 nights	TST, TSA, SL, SE, S1, S2, S3, S4, REM
Wolfson, 2003[64]	USA	106 boys & 196 girls 13.8-19.9 years	Actigraphy, sleep questionnaire, sleep diary	TSA, bedtime, wake-up time (school-days, weekends)

PSG refers to polysomnography; MSLT, Multiple Sleep Latency Test; AMS, ambulatory monitoring system; S1, stage 1 sleep; S2, stage 2 sleep; S3, stage 3 sleep; S4, stage 4 sleep; REM, rapid eye movement; TST, total sleep time; TSA, time spent asleep; SL, sleep latency; SE, sleep efficiency; SWS, slow-wave sleep; MWT, morning wake time; NNW, number of night awakenings

Table 3—Studies Using Polysomnography or Actigraphy to Assess Sleep Parameters in Normal Healthy Adults

First author, year	Country	Sample	Measures	Variables provided
Feinberg, 1967[40]	USA	9 men and 6 women mean age 77.0 years 9 men and 6 women mean age 26.6 years	PSG, 1 night	TST, SL, SE, REM, WASO
Kahn, 1969[44]	USA	16 men, 71-95 years	PSG, 4-5 nights	TST, SE, S1, S2, S3, S4, REM
Kahn, 1970[30]	USA	10 women, 66-87 years	PSG, 4-5 nights	TST, SE, S1, S2, S3, S4, REM
Williams, 1972[7]	USA	10 men, 41-46 years 11 men, 60-69 years 10 men, 13-15 years	PSG, 3 nights	TST, SE, S2, S3, S4, REM
Brezinova, 1975[8]	Scotland	5 men and 9 women mean age 55 years 6 men and 4 women mean age 22 years	PSG, 10 nights	TST, SL, S1,S2,SWS, REM
Gaillard, 1978[9]	Switzerland	18 men and 22 women 19-30 years	PSG, 3 nights	TST, SL, SE, S1, S2, S3, S4, REM
Gillin 1981[10]	USA	21 men & 15 women 15-64 years	PSG, 3 nights	TST, SL, SE, SWS, REM
Hayashi, 1982[31]	Japan	5 men and 10 women 73-92 years 13 men, 19-22 years	PSG, 3 nights	SL, SE, S1, S2, S3, S4, REM
Webb, 1982[42]	USA	40 men & 40 women 50-60 years 16 men & 16 women 20-30 years	PSG, 3 nights	S1, S2, S3, S4, REM
Krieger, 1983[65]	USA	10 men & 10 women 20-30 years 11 men & 9 women 53-76 years	PSG, 2 nights	SWS, REM
Bixler, 1984[32]	USA	40 men and 60 women mean age 45.4 years	PSG, 4 nights	TST, SL, SE, WASO
Berry, 1985[66]	USA	55 men & 64 women 50-70 years	PSG, 5 nights	TST, SE, S1, S2, S3, S4, RM
Naifeh, 1987[33]	USA	5 men and 6 women 61-81 years 6 men and 6 women 30-39 years	PSG, 4 nights	TST, SL, SE, S1, S2, SWS, REM, WASO
Zeplin, 1987[37]	USA	9 men and 9 women 57-71 years 9 men and 9 women 18-23 years	PSG, 3 nights	SL, SWS, REM, WASO
Hoch, 1988[41]	USA	9 men and 10 women 60-82 years	PSG, 2 x 3 nights	TST, SL, SE, REM, WASO
Schiavi, 1988[11]	USA	40 men, 23-73 years	PSG, 3 nights	TST, SE, REM
Bonnet, 1989[67]	USA	12 men, 55-70 years 12 men, 18-28 years	PSG, 4 nights (data from baseline night after 1 night habituation)	TST, SL, S1, S2, S3, S4, REM, WASO
Dijk, 1989[68]	Netherland	13 men & 15 women 19-28 years	PSG, 2 nights	TST, S1, S2, S3, S4, REM
Brendel, 1990[12]	USA	6 men and 4 women mean age 83.0 years 10 men and 4 women mean age 23.9 years	PSG, 3 nights	TST, SL, SE, S1, S2, S3, S4, SWS, REM, WASO
Hoch, 1990[34]	USA	49 men and 56 women 60-91 years	PSG, 3 nights	TST, SE, REM
Vitiello, 1990[69]	USA	11 men and 13 women mean age 63.6 years	PSG, 3 nights	TST, SL, SE, S1, S2, SWS, REM, WASO
Van Coevorden, 1991[38]	Belgium	8 men, 67-84 years 8 men, 20-27 years	PSG, 3 nights	TST, SWS, REM
Lauer, 1991[13]	Germany	26 men and 25 women mean age 38.3 years	PSG, 3 nights	TST, SL, SE, S1, S2, SWS, REM, WASO

Table 3 continued

Monk, 1991[14]	USA	16 men and 18 women mean age 83.1 years 21 men and 9 women mean age 25.5 years	PSG, 2 nights	TST, SL, SE, SWS, REM, WASO
Burger, 1992[15]	USA	30 men, 20-79 years	PSG, 1 night	TST, SWS, REM
Buysse, 1992[16]	USA	16 men and 18 women mean age 83.1 years 21 men and 9 women mean age 25.5 years	PSG, 2 nights	TST, SL, SWS, REM, WASO
Hirshkowitz, 1992 [17]	USA	186 men 20 years or older	PSG, 2 nights	TST, SL, SE, S1, S2, SWS, REM, WASO
Monk, 1992[18]	USA	20 men and 25 women 71-91 years 10 men and 11 women 19-28 years	PSG, 2 nights	TST, SE, SWS, REM
Schiavi, 1992[19]	USA	67 men 45-74 years	PSG, 4 nights	TST, SE, REM, WASO
Wauquier 1992[70]	Netherland	7 men & 7 women 88-102 years	AMS, 48 hours	TST, SE, SL, REM
Hoch, 1994[20]	USA	21 men and 29 women 61.1-89.2 years	PSG, 3 nights	TST, SL, SE, S1, S2, SWS, REM, WASO
Frank, 1995[21]	USA	8 men, mean age 65 years 8 men, mean age 25 years	PSG, 1 night	TST, SL, SE, SWS, REM, WASO
Landolt, 1996[22]	Switzerland	8 men, 20-26 years 8 men, 57-64 years	PSG, 1 night	TST, SL, SE, S1, S2, SWS, REM
Vitiello, 1996[71]	USA	45 men and 68 women mean age 69.1 years	PSG, 3 nights	TST, SL, SE, SWS, REM, WASO
Ehlers, 1997[39]	USA	33 men & 28 women 20-40 years	PSG, 3 nights	TST, SL, SE, S1, S2, SWS, REM, WASO
Haimov, 1997[35]	Israel	17 men, 65-78 years 8 men, 19-26 years	PSG, 1 night	TST, SL, SE, S1, S2, SWS, REM
Martin, 1997[72]	UK	7 men and 5 women mean age 25 years	PSG, 2 x 2 nights	TST, SE, S1, S2, SWS, REM
Parrino, 1998[23]	Italy	20 men and 20 women ≥ 10 years	PSG, 2 nights	TST, SL, SE, S1, S2, S3, S4, REM, WASO
Rao, 1999[36]	USA	35 men and 38 women mean age between 24.2 and 42 years	PSG, 2 nights	TST, SL, SE, S1, S2, S3, S4, REM, WASO
Spiegel, 1999[73]	Switzerland	20 men and 10 women T1: 63.1 years T2: 77.1 years	PSG, 2 nights	SL, S1, S2, SWS, REM, WASO
Armitage, 2000[74]	USA	15 men & 8 women 22-40 years	PSG, 2 nights	TST, SL, S1, S2, SWS, REM
Van Cauter, 2000[24]	USA	149 men 16-93 years	PSG, 2 nights	TST, SWS, REM
Murphy, 2000[43]	USA	5 men & 9 women 19-28 years 6 men & 5 women 60-82 years	PSG, 5 nights	S1, S2, SWS, REM
Carrier, 2001[25]	USA	53 men & 47 women 20-60 years	PSG, 3 nights	TST, SE, S1, S2, SWS, REM
Gaudreau, 2001[26]	Canada	20 men & 10 women 19-60 years	PSG, 1 night	TST, SL, SE, S1, S2, SWS, REM
Nicolas, 2001[27]	France	17 men and 19 women 10-69 years	PSG, 2 night	TST, SE, S1, S2, SWS, REM
Crowley, 2002[28]	Australia	8 men and 6 women mean age 21.4 years 11 men and 9 women mean age 75.5 years	PSG, 2 nights	TST, SL, SE, S1, S2, SWS, REM, WASO
Yoon, 2003[29]	USA	22 men and 38 women mean age 66.2 years 26 men and 47 women mean age 23.5 years	Actigraphy, 1 week	TST, SL, SE, WASO

PSG refers to polysomnography; AMS, ambulatory monitoring system; TST, total sleep time; SL, sleep latency; SE, sleep efficiency; REM, rapid eye movement; WASO, wake after sleep onset; S1, stage 1 sleep; S2, stage 2 sleep; S3, stage 3 sleep; S4, stage 4 sleep; SWS, slow-wave sleep.

sleep. In both cases, there was an increase of about 5% between 20 and 70 years, which translated into small effect sizes. On the other hand, the effect size was large for WASO. It can be seen in Figure 1e that WASO consistently increased about 10 minutes per decade of age from 30 years.

All the homogeneity statistics (Q statistic) were significant (Table 6), indicating that factors other than aging may be responsible for the observed differences. Results of the moderator analyses are reported in Tables 7, 8, and 9.

Table 4—Equations Relating Sleep Variables to Age in Studies Using In-laboratory Recordings

Variables	N	EEG b	PVE
TST	2890	-0.004	59
Sleep latency	2465	0.002	2
SE %	2843	-0.003	63
Stage 1 %	2140	0.003	2
Stage 2 %	2185	0.003	11
SWS %	2907	-0.016	34
REM %	3063	-0.003	10
REM latency	2220	-0.008	50
WASO	1698	0.029	60

EEG refers to electroencephalogram; TST, total sleep time; REM, rapid eye movement; WASO, wake after sleep onset; PVE, proportion of variance explained

Impact of Moderator Variables

Total Sleep Time

In children and adolescents, the relation between age and TST was moderated by the recording methods; studies that used in-laboratory PSG found significantly larger correlations than those using actigraphy (z statistic for contrast: -7.92; $P < .0001$). Similarly, the relation between age and TST was moderated by the time of recording. Studies that took place during school days (z statistic for contrast: -7.60; $P < .0001$) had larger correlations than those that were done on nonschool days. The results showed that TST decreased with age only when recordings took place on school days. On nonschool days, TST remained the same from childhood to the end of adolescence.

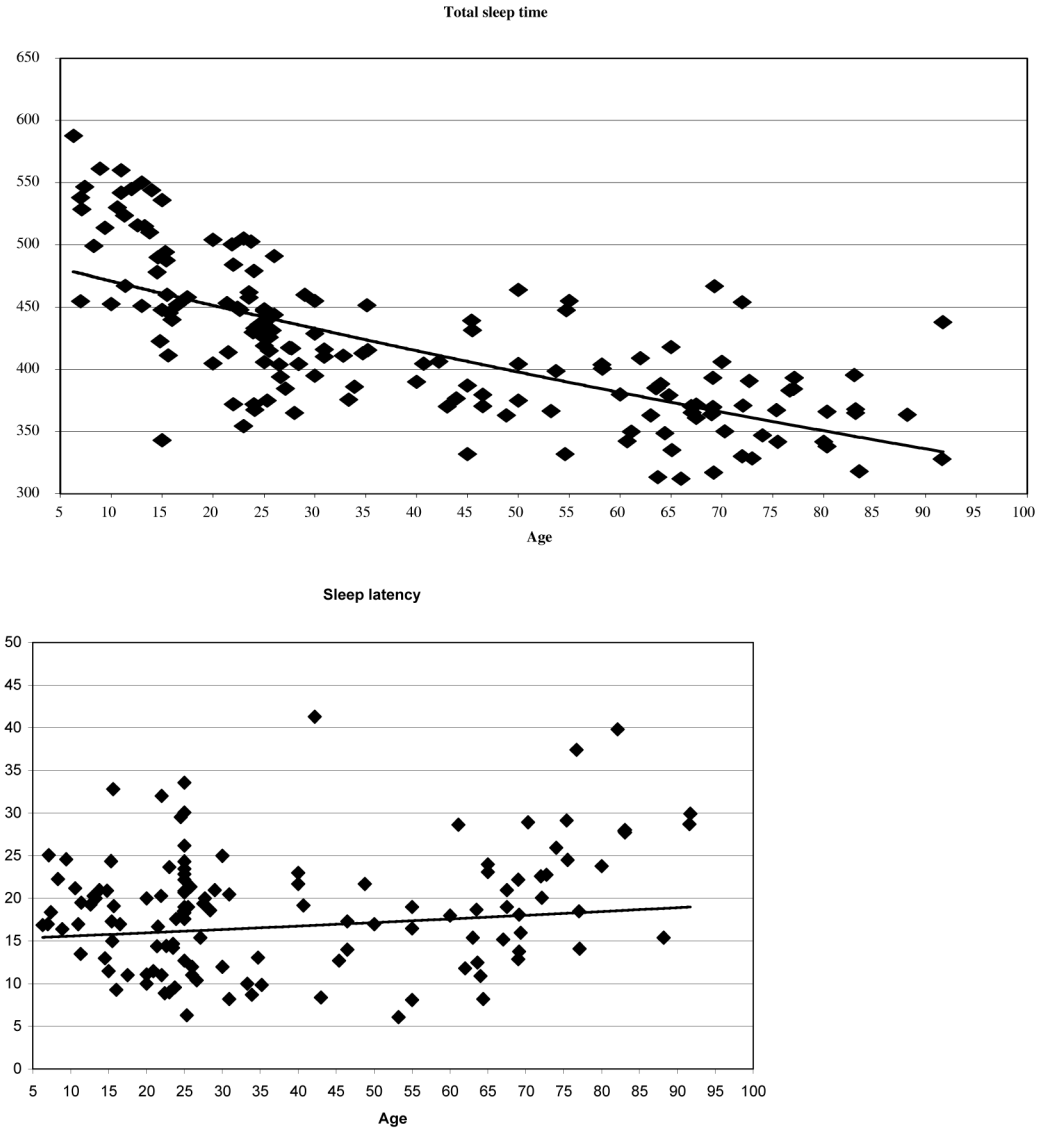


Figure 1a—Age-related trends for total sleep time (minutes) and sleep latency (minutes). Lines represent the exponential equations fitted for data from samples

In adults, exclusion of subjects with mental disorders produced a larger effect size, indicating a greater association between TST and aging when researchers excluded participants with a mental disorder compared to studies that kept such participants. The same effect on TST was observed when researchers excluded participants with physical illnesses, drug or alcohol use, or sleep apnea, or other sleep disorders (Table 7). Studies that kept habitual sleep patterns for the night of the PSG recording also produced a larger effect size than when researchers imposed the schedule for lights off and on. Effect size was larger in women than in men, indicating a greater association between declining TST and aging among women.

We also verified that the sample composition in terms of age—ie, elderly only (60 years or older); young, middle-aged, and elderly subjects; or samples composed of young adults and elderly subjects—produced different results. The association between TST and age was higher in studies that compared young adults with middle-aged and young adults with elderly subjects. The association was nonsignificant when the researchers included only participants 60 years or older. This indicates that TST did not continue to significantly decline among older subjects.

Sleep Efficiency

Similar to the pattern seen for TST, adult studies that excluded participants with mental disorders, physical illnesses, sleep apnea, or other sleep disorders obtained a greater association between sleep efficiency and age compared to studies that included these participants. Inclusion or exclusion of drugs or alcohol had no appreciable influence on effect sizes. Again, effect size was larger in women than in men, indicating a greater association between declining sleep efficiency and aging among women. The examination of sample composition showed that, once again, a larger effect size was found in studies that compared young with elderly adults and young with middle-aged subjects; however, in contrast to what was observed for TST, sleep efficiency continued to significantly decrease with age in the "elderly only" samples where a medium effect size was observed.

Sleep Latency

As seen in Table 7, adult studies that included participants with physical illnesses or with other sleep disorders had nonsignificant effect size for sleep latency, indicating that sleep latency did not

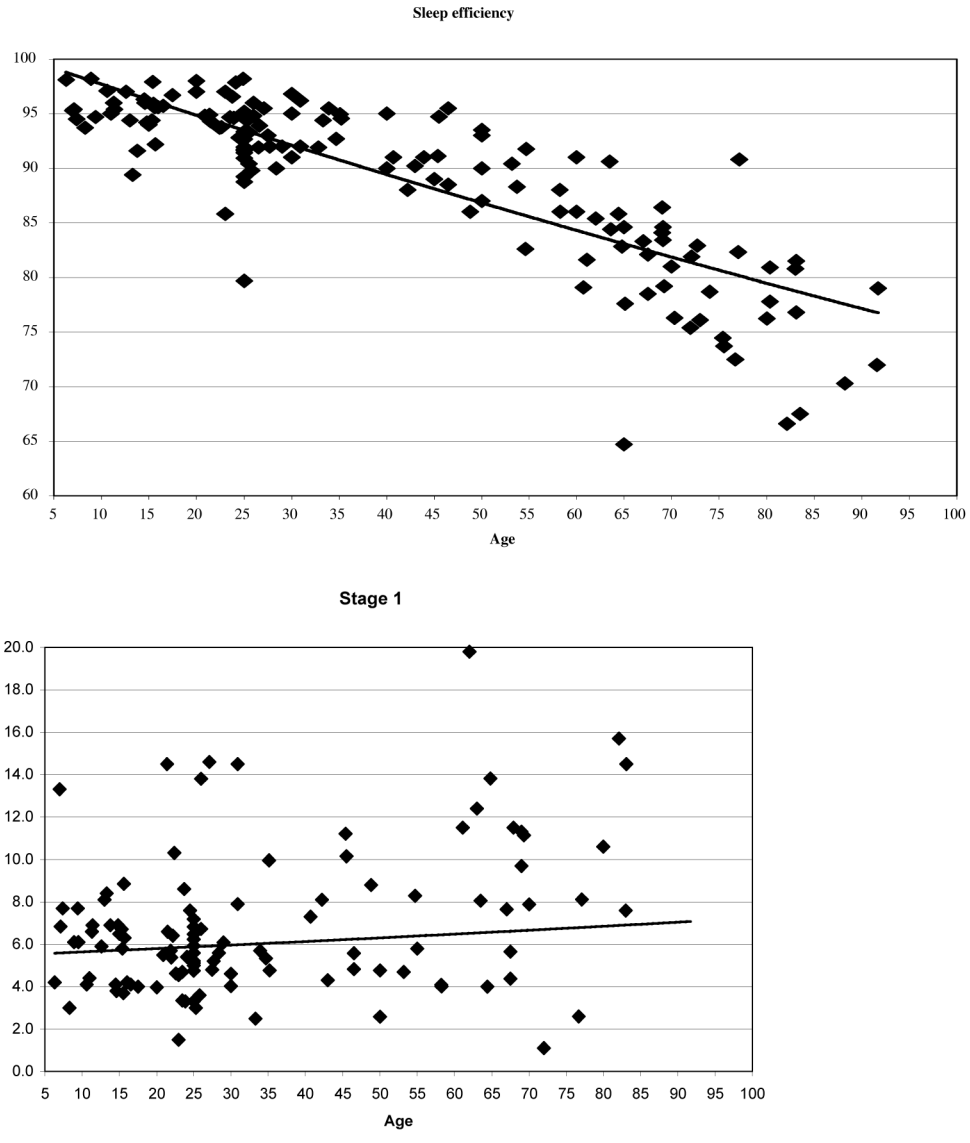


Figure 1b—Age-related trends for sleep efficiency and percentage of stage 1 sleep. Lines represent the exponential equations fitted for data from samples.

change with age. In contrast, studies that took care to exclude such participants had medium positive effect sizes, indicating that sleep latency increased with age. Studies that included subjects with sleep apnea had significant positive effect sizes, while those that excluded them had nonsignificant effect sizes. Again, sample composition in terms of participants' ages produced different effect sizes: studies that included only elderly subjects and those that included young, middle-aged, and elderly subjects had nonsignificant effect sizes. Only when researchers compared very young adults to elderly participants was a positive association observed between sleep latency and getting older.

Percentage of Stage 1 Sleep

Moderator analyses in adults showed that the association between percentage of stage 1 sleep and age is greater when researchers excluded participants with a mental disorder, sleep apnea or other sleep disorders or taking drugs or alcohol (Table 8). On the other hand, inclusion or exclusion of participants with a physical illness had no impact on effect size. Larger effect size was obtained when the association between increasing percentage of stage 1 sleep and aging was limited to women compared to when it was limited to men. Again, larger effect sizes were obtained when studies included only young and middle-aged participants or young and elderly participants.

Percentage of Stage 2 Sleep

In children and adolescents studies, as well as in adult studies, percentage of stage 2 sleep significantly increased with age.

The relation between age and percentage of stage 2 sleep in children and adolescents was somewhat influenced by the day of recording (Table 5). Studies that took place during school days (z statistic for contrast: 3.05; $P < .0001$) had smaller effect sizes than those that were done on nonschool days (z statistic for contrast: 2.83; $P < .01$) or those for which there was no indication for the time of the year (z statistic for contrast: 4.39; $P < .0001$).

In adult samples, studies that excluded participants with mental disorders, physical illnesses, drug or alcohol use, sleep apnea, or other sleep disorders obtained larger effect sizes between aging and percentage of stage 2 sleep, while studies that kept those participants had nonsignificant effect sizes. Similarly, stud-

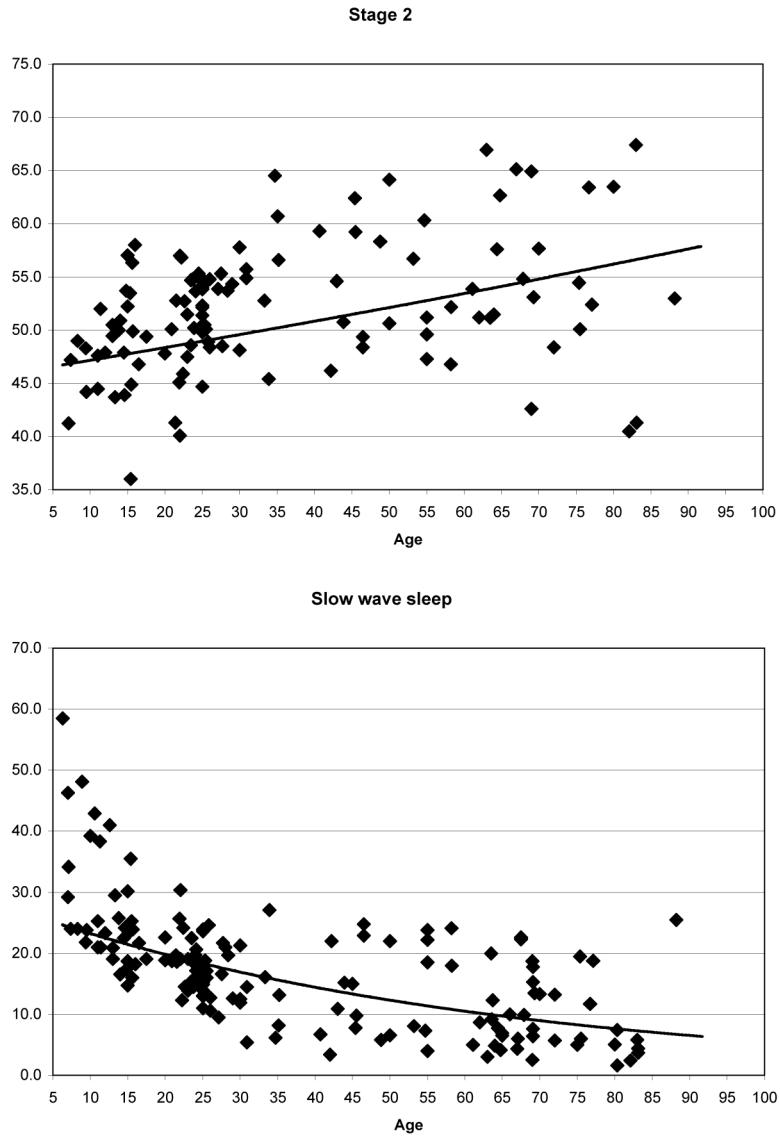
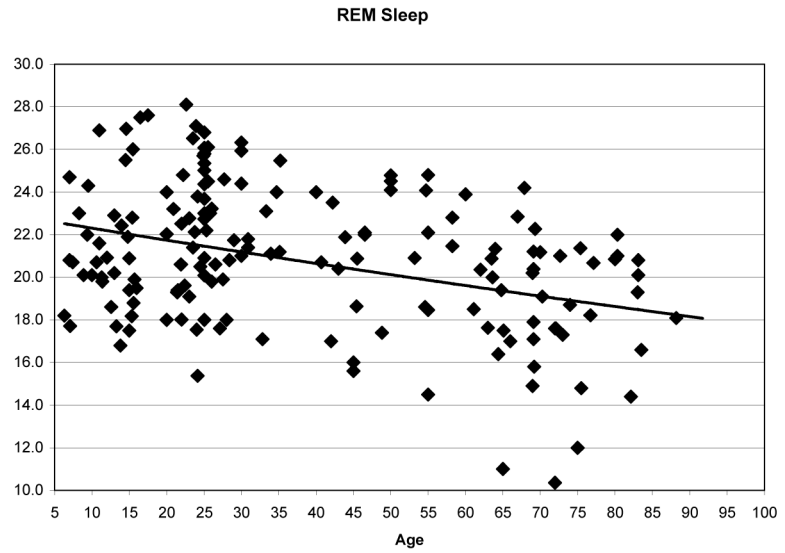


Figure 1c—Age-related trends for percentage of stage 2 sleep and percentage of slow wave sleep. Lines represent the exponential equations fitted for data from samples.



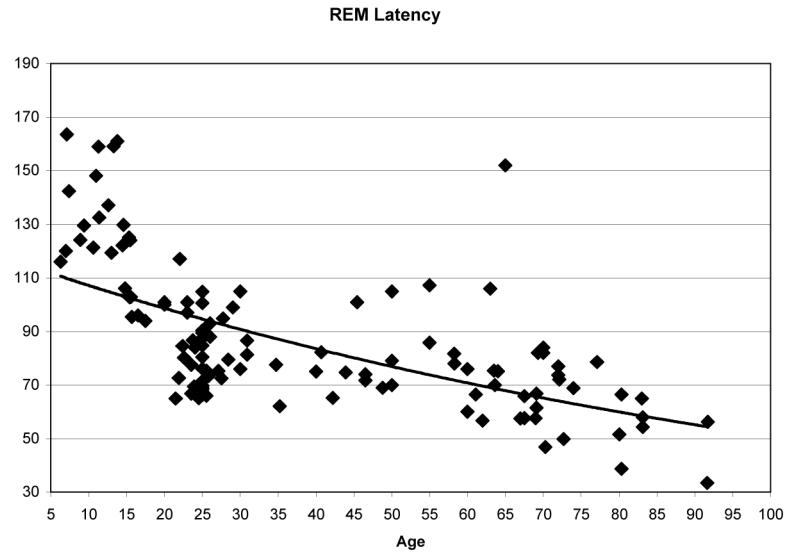


Figure 1d—Age-related trends for percentage of rapid eye movement (REM) sleep and REM sleep latency (minutes). Lines represent the exponential equations fitted for data from samples.

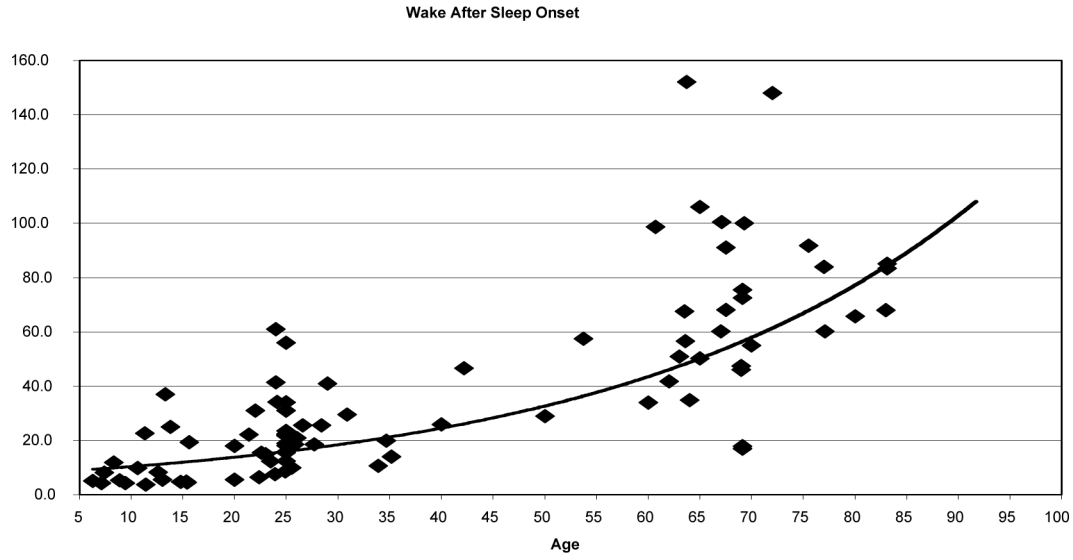


Figure 1e—Age-related trends for wake after sleep onset. Lines represent the exponential equations fitted for data from samples.

ies that used the habitual sleep patterns of the participants to set the PSG recording obtained larger effect sizes than did studies that imposed a fixed schedule for lights off and lights on (Table 8).

Percentage of SWS

In children and adolescents studies, moderator analyses showed a large effect size in studies performed on nonschool days and a small effect size for studies performed on school days.

In adults, as seen in Table 8, analyses of moderator variables did not produce different results: the exclusion or inclusion of participants with a mental disorder, physical illness, drug or alcohol use, sleep apnea, or other sleep disorders gave large effect sizes in all cases. However, it was noted that effect sizes were much larger when participants with a mental disorder, sleep apnea, or other sleep disorders were excluded. Furthermore, the use of habitual sleep patterns to set the PSG recording gave a larger size effect than in studies that imposed a fixed schedule for lights off and lights on (Table 8).

Effect sizes were similar in men and in women. When examining the sample composition, studies that included only elderly participants did not find changes in percentage of SWS.

Table 5—Effect Sizes and Homogeneity Statistics for Sleep Variables in Children and Adolescent Samples

	Effect sizes, no.	Studies, no.	Subjects, no.	Effect size (95% CI)	*Q*
Total sleep time					
All studies	37	15	1360	-0.48 (-0.59. -0.38)*	114.75 (27 *df*)*
Electroencephalogram	20	9	501	-0.65 (-0.82, -0.49)*	70.92 (19 *df*)*
Actigraphy	13	5	836	-0.33 (-0.49, -0.18)†	76.39 (12 *df*)*
School days	18	7	843	-0.57 (-0.72, -0.43)*	60.17 (17 *df*)*
Nonschool days	10	5	607	-0.04 (-0.23, 0.15)	11.75 (9 *df*)
Unknown	9	4	199	-1.05 (-1.32, -0.78)*	44.69 (8 *df*)*
Sleep latency	17	8	513	0.09 (-0.06, 0.25)	22.09 (16 *df*)
Sleep efficiency	21	9	653	0.01 (-0.13, 0.15)	32.74 (20 dif)†
Stage 1 %	17	8	455	-0.09 (-0.25, 0.08)	52.46 (17 *df*)*
Stage 2 %					
All studies	23	10	572	0.45 (0.30, 0.60)*	82.61 (22 *df*)†
School days	9	3	194	0.37 (0.13, 0.61)*	12.64 (8 *df*)
Nonschool days	6	3	164	0.44 (0.13, 0.74)‡	36.13 (5 *df*)
Unknown	8	4	214	0.55 (0.30, 0.80)*	32.80 (7 *df*)*
SWS %					
All studies	25	11	585	-0.57 (-0.71, -0.42)*	88.95 (24 *df*)*
School days	9	3	194	-0.37 (-0.60, -0.13)*	6.40 (8 *df*)
Nonschool days	6	3	164	-0.93 (-1.24, -0.61)*	29.36 (5 *df*)*
Unknown	10	5	227	-0.56 (-0.80, -0.32)*	45.34 (9 *df*)*
REM %	25	11	585	0.21 (0.07, 0.35)‡	30.49 (24 *df*)
REM latency	17	7	447	-0.68 (-0.86, -0.51)*	130.49 (16 *df*)*
WASO	12	5	318	-0.30 (-0.50, -0.11)*	36.64 (11 *df*)*

CI refers to confidence interval; SWS, slow-wave sleep; REM, rapid eye movement; WASO, wake after sleep onset.
*$P < .0001$
†$P < .05$
‡$P < .01$

Table 6—Effect Sizes Related to Age And Homogeneity Statistics for Sleep Variables in Adult Samples

	Effect sizes, no.	Studies, no.	Subjects, no.	Effect size (95% CI)	*Q*
Total sleep time	62	38	2009	-0.60 (-0.69, -0.51)*	343.63 (61 *df*)*
Sleep latency	42	27	1436	0.27 (0.17, 0.37)*	92.25 (41 *df*)*
Sleep efficiency	54	32	1738	-0.71 (-0.81, -0.61)*	372.28 (54 *df*)*
Stage 1%	37	21	1072	0.38 (0.26, 0.49)*	179.20 (36 *df*)*
Stage 2 %	40	24	1133	0.28 (0.17, 0.40)*	310.53 (39 *df*)*
SWS %	51	31	1544	-0.85 (-0.96, -0.75)*	406.03 (50 *df*)*
REM %	63	38	1986	-0.46 (-0.55, -0.37)*	234.88 (62 *df*)*
REM latency	32	21	933	-0.15 (-0.28, -0.03)†	56.85 (31 *df*)*
WASO	27	20	1012	0.89 (0.75, 1.202)*	177.07 (26 *df*)*

CI refers to confidence interval; SWS, slow-wave sleep; REM, rapid eye movement; WASO, wake after sleep onset.
*$P < .0001$
†$P < .05$

Percentage of REM Sleep

As seen with percentage of SWS, exclusion of participants with any of the moderator variables did not produce major changes in the effect sizes for mental disorder, drug or alcohol use, habitual sleep patterns, and sex. The most notable effect was observed in studies that excluded participants with other sleep disorders compared to those that kept them (Table 9). Once more, the effect size was not significant for studies that included only elderly individuals. Studies that compared young to elderly subjects and young to middle-aged subjects found greater effect sizes.

REM Latency

The relationship between REM latency and age was modified by the exclusion of subjects with sleep apnea or other sleep disorders (Table 9). In both cases, a negative association was observed between REM latency and age. Effect sizes were also larger in women than in men and in studies that kept the habitual sleep patterns of the participants. Similarly, studies that compared young to elderly participants obtained the largest effect sizes between REM latency and age; however, those studies that included only elderly participants or broader age ranges had nonsignificant effect sizes.

Wake After Sleep Onset

The exclusion of participants with a mental disorder, a physical illness, or sleep apnea or those using drugs or alcohol decreased the effect sizes, while the exclusion of participants with other sleep disorders increased the effect sizes (Table 9). This pattern indicates that when sleep disorders were possibly present, the association of WASO and age was weakened.

Sex Trends

Table 10 provides information about effect sizes and homogeneity tests calculated for comparisons between men and women. Negative effect sizes indicated that women had higher means than men on the sleep measures, while positive effect sizes indicated that men had higher means than women on the sleep measures. As can be seen, TST, sleep latency, percentage of SWS, percentage of REM sleep, and REM latency had negative effect sizes, indicating that men had higher means on these variables. On the other hand, percentage of stage 2 sleep and WASO

Table 7—Moderator Analyses for Total Sleep Time, Sleep Efficiency, Sleep Latency, and Age in Adult Samples

	Total sleep time		Sleep efficiency		Sleep latency	
Moderators & Levels	Effect size (95%CI)	*z* value	Effect size (95%CI)	*z* value	Effect size (95%CI)	*z* value
Mental disorders						
Included	-0.24 (-0.42, -0.06)	-2.66‡	-0.34 (-0.53, -0.14)	-3.38*	0.23 (-0.05, 0.40)	2.59‡
Excluded	-0.72 (-0.82, -0.62)	-13.78*	-0.83 (-0.94, -0.72)	-14.70*	0.29 (0.17, 0.41)	4.59*
Physical illness						
Included	-0.20 (-0.37, -0.03)	-2.34†	-0.32 (-0.50, -0.14)	-3.55*	0.15 (-0.05, 0.35)	1.45
Excluded	-0.75 (-0.86, -0.65)	-14.15*	-0.87 (-0.99, -0.76)	-14.94*	0.30 (0.19, 0.42)	5.19*
Drugs/alcohol						
Included	-0.46 (-0.60, -0.32)	-6.51*	-0.71 (-0.86, -0.56)	-9.18*	0.27 (0.12, 0.41)	3.63*
Excluded	-0.71 (-0.83, -0.59)	-8.18*	-0.71 (-0.83, -0.58)	-11.18*	0.27 (0.13, 0.41)	3.77*
Sleep apnea						
Included	-0.47 (-0.57, -0.37)	-9.26*	-0.68 (-0.78, -0.57)	-12.45*	0.29 (0.18, 0.40)	5.22*
Excluded	-1.17 (-1.38, -0.97)	-11.33*	-0.85 (-1.07, -0.63)	-7.50*	0.14 (-0.10, 0.38)	1.16
Other sleep disorders						
Included	-0.24 (-0.37, -0.11)	-3.55*	-0.35 (-0.49, -0.21)	-4.97*	0.12 (-0.03, 0.27)	1.55
Excluded	-0.91 (-1.03, -0.79)	-14.80*	-1.04 (-1.71, -0.91)	-15.30*	0.38 (0.24, 0.51)	5.59*
Habitual sleep time						
Unknown	-0.27 (-0.48, -0.06)	-2.49†	-0.44 (-0.67, -0.21)	-3.71*	0.22 (-0.02, 0.46)	1.78
No	-0.43 (-0.64, -0.22)	-4.08*	-0.86 (-1.07, -0.64)	-7.77*	0.33 (0.14, 0.52)	3.35*
Yes	-0.75 (-0.86, -0.64)	-13.16*	-0.74 (-0.86, -0.62)	-11.93*	0.25 (0.12, 0.39)	3.69*
Sex						
Both	-0.72 (-0.83, -060)	-11.82*	-0.92 (-1.04, -0.79)	-14.83*	0.36 (0.24, 0.48)	5.72*
Men	-0.37 (-0.51, -0.23)	-5.09*	-0.30 (-0.48, -0.13)	-3.45*	0.08 (-0.11, 0.26)	0.84
Women	-1.18 (-1.59, -0.77)	-5.73*	-0.64 (-1.04, -0.24)	-3.17*	0.16 (-0.30, 0.62)	0.70
Sample composition						
E	-0.13 (-0.35, 0.08)	-1.21	-0.41 (-0.63, -0.19)	-3.72*	0.10 (-0.20, 0.40)	0.67
YM	-0.77 (-1.01, -0.53)	-6.43*	-1.12 (-1.42, -0.82)	-7.41*	0.22 (-0.03, 0.46)	1.75
YME	-0.28 (-0.45, -0.10)	-3.13*	-0.20 (-0.38, -0.02)	-2.16†	0.19 (-0.01, 0.39)	1.87
YE	-0.60 (-0.69, -0.51)	-13.29*	-1.58 (-1.77, -1.40)	-16.47*	0.51 (0.34, 0.68)	5.85*

CI refers to confidence interval; Included, no screening for the condition; Excluded, exclusion of subjects with the condition; E, samples including groups of elderly only; YME, samples including groups of young, middle-aged, and elderly subjects; YE, samples including groups of young and elderly subjects.
*$P < .0001$
‡$P < .01$
†$P < .05$

had positive effect sizes, indicating higher means for women than for men. Effect sizes were in the small range for most variables (TST, sleep latency, percentage REM sleep, REM latency, and WASO), indicating that the differences between men and women on these variables were modest.

DISCUSSION

This study aimed to describe age-related changes in the macrostructure of sleep and to clarify the issues regarding earlier contradictory results regarding the evolution of sleep latency and percentages of stage 1, stage 2, and REM sleep. Indeed, about half of the studies that analyzed age-related changes for percentages of REM and stage 1 sleep reported that these parameters changed with age, while the other half found no change. Similarly, about 2 of 3 studies reported that sleep latency and percentage of stage 2 sleep did not change with age, while the others found that these 2 parameters increased with age. One of the problems was that these studies based their conclusions on a small number of subjects. Therefore, it is very difficult to identify age-related trends when the changes are subtle. To summarize all this information, we decided to perform meta-analyses on 65 studies, which represented 3,577 subjects aged 5 years or older. This method allowed quantifying conclusions, which cannot be done with traditional literature reviews. We also performed the analyses in relationship with several moderators that can have a significant impact on any potential associations between sleep and aging.

In relationship with the objectives of the study, the following conclusions can be drawn from our meta-analytic results.

(1) Sleep latency increases with age. Overall, it appeared that sleep latency modestly but significantly increased with age. However, the change is very subtle: when young adults were compared to middle-aged individuals, and middle-aged compared to elderly individuals, sleep latencies were comparable. The significant difference appeared only when very young adults were compared to elderly individuals. The overall increase in sleep latency between 20 and 80 years was less than 10 minutes.

(2) Percentage of stage 1 sleep increases with age. The significant increase in stage 1 sleep was found between young and middle-aged adults and between middle-aged and elderly individuals, which means that percentage of stage 1 sleep significantly increased across all adulthood.

(3) Percentage of stage 2 sleep increases with age. This increase was present across the full age range studied, from childhood (5 years and older) until age 60.

Table 8—Moderator Analyses for Stages 1, 2, and Slow-Wave Sleep and Age in Adult Samples.

	Stage 1 sleep, %		Stage 2 sleep, %		Slow-wave sleep, %	
Moderators & Levels	Effect size (95%CI)	*z* value	Effect size (95%CI)	*z* value	Effect size (95%CI)	*z* value
Mental disorders						
Included	0.30 (0.12, 0.48)	3.25*	0.15 (-0.02, 0.32)	1.74	-0.67 (-0.85, -0.50)	-7.60*
Excluded	0.43 (0.28, 0.58)	5.57*	0.40 (0.24, 0.56)	4.93*	-0.96 (-1.09, -0.83)	-14.25*
Physical illness						
Included	0.35 (0.13, 0.57)	3.10*	0.23 (0.02, 0.44)	2.17†	-0.85 (-1.06, -0.64)	-8.12*
Excluded	0.39 (0.25, 0.52)	5.56*	0.31 (0.17, 0.45)	4.31*	-0.86 (-0.98, -0.73)	-13.72*
Drugs/alcohol						
Included	0.05 (-0.14, 0.24)	0.55	0.01 (-0.17, 0.19)	0.10	-0.96 (-1.12, -0.80)	-11.55*
Excluded	0.57 (0.42, 0.72)	7.61*	0.49 (0.34, 0.64)	6.24*	-0.78 (-0.92, -0.64)	-11.12*
Sleep apnea						
Included	0.18 (0.04, 0.32)	2.46‡	0.07 (-0.07, 0.21)	1.01	-0.78 (-0.90, -0.66)	-12.76*
Excluded	0.77 (0.57, 0.97)	7.53*	0.83 (0.61, 1.05)	7.43*	-1.11 (-1.33, -0.89)	-9.91*
Other sleep disorders						
Included	0.23 (0.07, 0.39)	2.78‡	0.11 (-0.04, 0.27)	1.49	-0.55 (-0.70, -0.39)	-7.06*
Excluded	0.55 (0.38, 0.72)	6.34*	0.53 (0.34, 0.71)	5.69*	-1.14 (-1.29, -1.00)	-15.34*
Habitual sleep time						
Unknown	0.11 (-0.22, 0.45)	0.67	0.20 (-0.11, 0.52)	1.28	-0.62 (-0.85, -0.40)	-5.44*
No	0.35 (0.16, 0.55)	3.54*	0.11 (-0.08, 0.30)	1.12	-0.50 (-0.69, -0.31)	-5.07*
Yes	0.45 (0.29, 0.61)	5.55*	0.44 (0.27, 0.60)	5.17*	-1.17 (-1.32, -1.02)	-15.27*
Gender						
Both	0.44 (0.29, 0.59)	5.75*	0.25 (0.10, 0.40)	3.22*	-0.85 (-1.00, -0.70)	-11.20*
Men	0.23 (0.04, 0.43)	2.33†	0.31 (0.12, 0.51)	3.19*	-0.85 (-1.02, -0.69)	-10.37*
Women	0.60 (0.09, 1.10)	2.33†	0.45 (-0.06, 0.96)	1.77	-0.87 (-1.24, -0.50)	-4.60*
Sample composition						
E	0.15 (-0.20, 0.50)	0.85	0.02 (-0.31, 0.35)	0.12	-0.08 (-0.41, 0.25)	-0.48
YM	0.59 (0.36, 0.83)	4.96*	0.60 (0.35, 0.85)	4.66*	-0.69 (-0.90, -0.48)	-6.42*
YME	0.21 (0.02, 0.40)	2.12†	0.20 (0.01, 0.39)	2.11†	-0.61 (-0.80, -0.43)	-6.46*
YE	0.46 (0.18, 0.74)	3.28*	0.00 (-0.27, 0.26)	-0.03	-1.71 (-1.93, -1.48)	-14.96*

CI refers to confidence interval; Included, no screening for the condition; Excluded, exclusion of subjects with the condition; E, samples including groups of elderly only; YME, samples including groups of young, middle-aged, and elderly subjects; YE, samples including groups of young and elderly subjects.

*$P < .0001$

‡$P < .01$

†$P < .05$

(4) Percentage of REM sleep decreases with age in adults. Percentage of REM sleep first increased from childhood to adolescence, than decreased between young and middle-aged adults, and remained unchanged in subjects older than 60 years of age.

(5) In adults, the increase in the percentage of stage 2 sleep with age and the decrease of REM latency with age appeared to be very sensitive to psychiatric disorders, use of drugs or alcohol, sleep apnea, or other sleep disorders; failure to exclude individuals with these conditions resulted in the confounding of their significant associations with age.

(6) In children 5 years and older and in adolescents, the apparent decrease in TST with age appears to be related to environmental factors rather than to biologic changes. As we showed in Table 5, the studies analyzed indicated a significant decrease of TST with age but only when recordings were performed during school days.

(7) While almost all studies in children 5 years of age or older and adolescents did not find significant changes in REM sleep with age, it appeared that there actually is a modest but significant increase in the percentage of REM sleep from childhood to the end of adolescence. After that age, percentage of REM sleep remains relatively stable until 60 years of age, when it again begins to decrease.

Sleep in Children and Adolescents

Studies that examined the normal sleep in children aged 5 years or older and adolescents using PSG recordings are still scant, making it difficult to impossible to effectively perform moderator analyses and to analyze all the sleep variables examinable in the older population.

Results of the meta-analysis suggested that different recording techniques are likely to give different results. Although the conclusion for TST was the same for in-laboratory recordings and actigraphy, the association between TST and age was weaker with actigraphy (-0.33) than with in-laboratory recordings (-0.69). Furthermore, the discrepancy for TST between the different methods was large among the younger children: more than 60 minutes for children aged between 8 and 12 years.

Importantly, the timing of the recording influenced the age-related change for several sleep variables. Thus, the reduction in TST with age was significant only when recordings were made during school days; TST was unassociated with age when studied on nonschool days. This pattern suggests that, in children and adolescents, the decrease in TST is not related to maturation but to other factors such as school schedules. Several North American studies have reported the difficulties adolescents have

Table 9—Moderator Analyses for REM Sleep, REM Latency, Wake After Sleep Onset, and Age in Adult Samples

	REM%		REM latency		Wake after sleep onset	
Moderators & Levels	Effect size (95%CI)	*z* value	Effect size (95%CI)	*z* value	Effect size (95%CI)	*z* value
Mental disorders						
Included	-0.36 (-0.52, -0.19)	-4.30*	-0.09 (-0.51, 0.33)	-0.42	0.98 (0.64, 1.32)	5.69*
Excluded	-0.50 (-0.60, -0.40)	-9.54*	-0.16 (-0.29, -0.03)	-2.34†	0.87 (0.73, 1.01)	11.81*
Physical illness						
Included	-0.29 (-0.46, -0.12)	-3.32*	-0.22 (-0.63, 0.20)	-1.04	1.28 (0.55, 2.01)	3.54*
Excluded	-0.52 (-0.62, -0.42)	-10.08*	-0.15 (-0.28, -0.01)	-2.14†	0.87 (0.74, 1.01)	12.66*
Drugs or alcohol						
Included	-0.42 (-0.56, -0.29)	-6.07*	-0.19 (-0.41, 0.03)	-1.68	1.26 (1.03, 1.49)	10.96*
Excluded	-0.48 (-0.60, -0.37)	-8.42*	-0.13 (-0.29, 0.02)	-1.71	0.69 (0.52, 0.85)	8.22*
Sleep apnea						
Included	-0.40 (-0.50, -0.30)	-8.04*	-0.10 (-0.25, 0.05)	-1.34	0.92 (0.77, 1.07)	12.21*
Excluded	-0.69 (-0.88, -0.50)	-7.05*	-0.31 (-0.56, -0.05)	-2.39†	0.74 (0.44, 1.04)	4.85*
Other sleep disorders						
Included	-0.22 (-0.34, -0.09)	-3.45*	0.02 (-0.20, 0.23)	0.16	0.14 (-0.13, 0.42)	1.02
Excluded	-0.70 (-0.82, -0.57)	-11.16*	-0.25 (-0.41, -0.09)	-3.06*	1.12 (0.97, 1.27)	14.43*
Habitual sleep time						
Unknown	-0.16 (-0.36, 0.05)	-1.47	0.12 (-0.19, 0.43)	0.74	0.29 (0.05, 0.53)	2.34†
No	-0.50 (-0.69, -0.31)	-5.19*	-0.07 (-0.32, 0.18)	-0.55	0.89 (0.57, 1.20)	5.55*
Yes	-0.53 (-0.64, -0.42)	-9.40*	-0.27 (-0.44, -0.10)	-3.17*	1.24 (1.06, 1.43)	13.16*
Gender						
Both	-0.55 (-0.67, -0.43)	-8.92*	-0.12 (-0.28, 0.04)	-1.46	0.89 (0.74, 1.04)	11.68*
Men	-0.34 (-0.48, -0.21)	-4.91*	-0.14 (-0.39, 0.11)	-1.13	0.86 (0.54, 1.19)	5.26*
Women	-0.46 (-0.76, -0.15)	-2.92*	-0.44 (-0.87, -0.01)	-2.02†	0.87 (0.23, 1.51)	2.72‡
Sample composition						
E	-0.13 (-0.35, 0.08)	-1.21	-0.04 (-0.34, 0.27)	-0.24	-0.08 (-0.43, 0.27)	-0.46
YM	-0.52 (-0.71, -0.32)	-5.12*	-0.27 (-0.59, 0.05)	-1.68	0.39 (-0.02, 0.81)	1.87
YME	-0.17 (-0.34, -0.00)	-1.97†	0.06 (-0.31, 0.42)	0.31		
YE	-0.85 (-1.02, -0.69)	-9.95*	-0.35 (-0.57, -0.13)	-3.13*	1.52 (1.32, 1.71)	15.32*

REM refers to rapid eye movement; CI, confidence interval; Included, no screening for the condition; Excluded, exclusion of subjects with the condition; E, samples including groups of elderly only; YME, samples including groups of young, middle-aged, and elderly subjects; YE, samples including groups of young and elderly subjects.

*$P < .0001$

‡$P < .01$

†$P < .05$

in adjusting to early school days, which occurs for older rather than younger children.[76]

Sleep latency and sleep efficiency remained largely unchanged from childhood to adolescence, and none of the studies in the meta-analysis reported significant age-related changes for these 2 sleep parameters.

Percentage of stage 2 sleep was found to increase with age, while percentage of SWS decreased. These 2 results were also found individually in the 5 studies that examined these 2 parameters. Of note, however, is a very large difference between results using the ambulatory monitoring system and in-laboratory recording, which may be attributed to methodologic differences in the studies.

The results of the meta-analysis suggested that the percentage of REM sleep significantly (but modestly) increased with age, an unexpected finding since the studies that examined this parameter did not find this association.[26,49,52,53,58,59] Since the effect size is small, it would have been difficult to identify this association without the quantitative assessment provided by the meta-analysis.

Sleep in Adults

As expected, TST and sleep efficiency consistently decreased with age. WASO obtained the largest effect size, showing the important increase with age of time awake after sleep onset. Sleep latency and percentage of stage 2 sleep increased with age, but the associations were small (.27 and 0.28, respectively). Percentage of SWS and REM sleep both also decreased. In addition, small effect sizes were obtained for percentage of stage 1 sleep and REM latency; the first increasing with age, and the other decreasing with age. From the results of this meta-analysis, it is clear that all studied sleep parameters significantly change with age across the adult lifespan.

Roles of Moderator Variables

A great advantage of meta-analyses includes its potential to explore the role of different moderators on the association between aging and different sleep variables.

The analyses of potential moderators brought to light a number of noteworthy observations. Failure to exclude participants with a mental disorder had several significant consequences on the results: (1) it diminished the associations of TST and sleep efficiency with age, that is, the decreases observed in TST and sleep efficiency were less pronounced when participants were not screened for mental disorders; (2) it hid the age-related increase of percentage of stage 2 sleep; and (3) it hid the age-related diminution of REM latency.

A similar pattern was observed with medical illness. Failure to

Table 10—Effect Sizes Related to Sex and Homogeneity Statistics for Sleep Variables in Adult Samples

	Effect sizes, no.	Studies, no.	Subjects, no.	Effect size (95% CI)	*Q*
Total sleep time	24	17	996	-0.26 (-0.39, -0.13)*	180.55 (23 *df*)*
Sleep latency	18	13	699	-0.35 (-0.51, -0.19)*	113.22 (17 *df*)*
Sleep efficiency	21	15	928	0.04 (-0.09, 0.17)	84.72 (20 *df*)*
Stage 1%	13	10	615	0.10 (-0.07, 0.26)	88.70 (12 *df*)*
Stage 2 %	13	10	615	0.43 (0.26, 0.60)*	74.69 (12 *df*)*
SWS %	23	16	1030	-0.49 (-0.63, -0.36)*	197.51 (22 *df*)*
REM %	24	16	1034	-0.16 (-0.28, -0.03)†	68.89 (23 *df*)*
REM latency	17	13	706	-0.30 (-0.46, -0.15)*	112.73 (16 *df*)*
WASO	13	8	487	0.38 (0.20, 0.57)*	28.92 (12 *df*)*

CI refers to confidence interval; SWS, slow-wave sleep; REM, rapid eye movement; WASO, wake after sleep onset
*$P < .0001$
†$P < .05$

Table 11—Summary of findings from the meta-analysis

	Direction of the Evaluation		
	C -> A	YA -> MA -> E	E -> OE
Total sleep time	⇔	⇓	⇔
Sleep latency	⇔	⇔	⇔
Sleep efficiency	⇔	⇓	⇓
Stage 1%	⇔	⇑	⇔
Stage 2 %	⇑	⇑	⇔
SWS %	⇓	⇓	⇔
REM %	⇑	⇓	⇔
REM latency	⇓	⇔	⇔
WASO	⇓	⇑	⇔

C refers to children (5-12 years old); A, adolescents (13-18 years old); YA, young adults (18-40 years old); MA, middle-aged adults (40-60 years old); E, elderly (60-70 years old); OE, old elderly (≥70 years old); SWS, slow-wave sleep; REM, rapid eye movement; WASO, wake after sleep onset;
⇔ Unchanged; ⇓ Decrease; ⇑ Increase

exclude participants with medical illness resulted in considerably diminished associations of TST and sleep efficiency with age and also obscured the relationship between aging and increased sleep latency.

Exclusion of participants with sleep apnea had important modifications on effect sizes for the TST; percentages of stage 1, stage 2, and REM sleep; and REM latency. Indeed, studies that did not screen participants for sleep apnea had smaller effect sizes on these variables, which indicated that age-related changes were less pronounced.

Using predetermined light off and light on time instead of the habitual sleep schedule of the participants also had consequences for the results: the observed decrease in TST with age was smaller and the significant increase of percentage of stage 2 sleep and the significant decrease in REM latency with age disappeared.

Why are the age effects less obvious with the inclusion of these disorders? There is no simple explanation for this fact. First, it is impossible to determine how many subjects were suffering from 1 or several of the diseases included in the moderator analyses. However, in small samples, the inclusion of some not perfectly healthy subjects creates a heterogeneous group, and it is enough to influence the results in unexpected ways. This is a very different situation than when the purpose of the research is to measure the effects of a disease on sleep architecture; in this case the subjects of the experimental group all have the disease, and some conclusions can be drawn. Second, the evolution of sleep architecture with age in specific diseases is not well known: studies usually used age-matched controls to measure the effect of the disease on sleep architecture—which is a methodologically sound; however, this does not provide information on the evolution of sleep architecture with age. Furthermore, participants in the studies included in the meta-analysis were all from nonclinical populations. It is unlikely that individuals with a severe mental disorder were included in the studies even when no screening was done to exclude mental disorders. It has been repeatedly demonstrated, however, that mild or moderate mental disorders such as anxiety or depression are often accompanied by sleep complaints. It is therefore reasonable to assume that the presence of such low-grade mental disorders may have adversely impacted sleep-age relationships. The same conjecture can be made about medical illnesses.

The sex analyses showed that the associations between sleep variables and aging were generally the same for both sexes; however, larger effect sizes were observed in women for TST, sleep efficiency, percentage of stage 1 sleep, and REM latency, indicating that the age effect on these variables were more important in women. On the other hand, effect sizes calculated for sex indicated that women have longer TST and sleep latency than similarly aged men. They also have less percentage of stage 2 sleep and greater percentage of SWS than age-matched men.

Interestingly, Figures 1c and 1d clearly illustrate that percentages of SWS and REM sleep that were based on in-laboratory studies decrease with age. The diminution in the percentage of SWS can be readily observed in childhood and continues steadily until old age. Conversely, for REM sleep, the overall data pattern (see Figure 1d) may explain disagreements among previous studies concerning the evolution of this sleep stage with age. Meta-analytic results indicated that the percentage of REM sleep decreased with age from young adulthood to late middle age, but the decrease is not significant in individuals over 60 years of age.

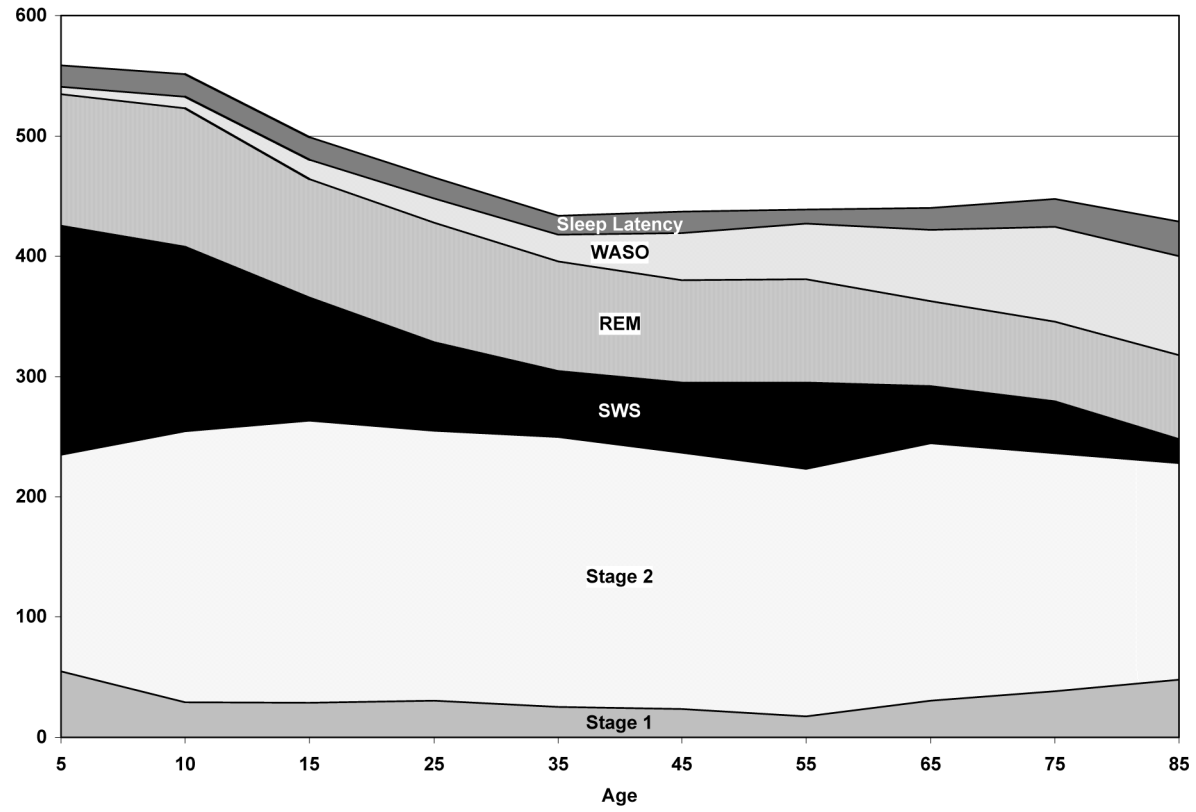


Figure 2—Age-related trends for stage 1 sleep, stage 2 sleep, slow wave sleep (SWS), rapid eye movement (REM) sleep, wake after sleep onset (WASO) and sleep latency (in minutes).

Limitations

This meta-analysis is not without limitations. For many studies, it was impossible to calculate effect sizes related to age and sex because no information was given in relation with the presence or absence of sex differences. Therefore, we had to discard several studies with otherwise usable data. Effect sizes can be calculated from different statistical information, but a minimum is needed. The same can be said for race. Most of the studies did not include information about the race composition of the sample. It was therefore impossible to include race as a moderator variable, as had been originally planned.

Several studies did not include middle-aged subjects. This is quite obvious in the Figures, where a concentration of information can be observed at both extremes: young adults and elderly participants. One of the consequences of this was to maximize the effect sizes related to age. In the sample composition moderator, we wanted to measure the effect size for the progression between young and middle-aged and between middle-aged and elderly subjects. This more-complex analysis showed that age progressions for all of the sleep variables were much more subtle than when a simple comparison of young to elderly subjects was made.

Another limitation may have come from our decision to limit our sample to peer-reviewed studies. It is known that, for clinical trials, the limitation to peer-reviewed reports might introduce a small bias on effect sizes because published studies often favor significant findings. On the other hand, this issue is less likely to have played a role in our study, since the reports used in the meta-analysis were mostly purely descriptive, aimed at describing age-related changes of sleep in the population.

Conclusions and Recommendations

Accurate normative data on the evolution of sleep architecture across the human life span are important to better understand exactly what type of changes in sleep patterns can be expected as individuals are aging. The main findings of this study are summarized in Table 11. The evolution with age of the different sleep stages, REM sleep, and WASO is shown in Figure 2. In summary, and in contrast to what was generally suggested in several small studies, the TST in children 5 years of age or older and adolescents did not really change with age. It appeared to be related to environmental factors rather than to biologic changes. There was a modest but significant increase in the percentage of REM sleep from childhood to the end of adolescence. After that age, percentage of REM sleep remained relatively stable until 60 years of age, when the percentage again began to decline. Sleep latency modestly but significantly increased with age. However, the change was very subtle and was apparent when very young adults were compared to elderly individuals. Percentage of stage 1 sleep increased with age through all adulthood. Percentage of stage 2 sleep increased with age from childhood (5 years and older) until old age. After 60 years of age, only sleep efficiency continued to significantly decrease, with all the other sleep parameters remaining unchanged.

The results of the meta-analysis clearly illustrated the importance of strict screening methods for the study of sleep parameters in healthy individuals, as it maximizes the emergence of age-related changes in sleep. As was demonstrated, inclusion of individuals with sleep, organic, or psychiatric disorders, as well as the modification of habitual sleep time, substantially obliterated the importance of changes in sleep patterns with aging.

There are several aspects of normal sleep that need to be further investigated: racial comparisons of sleep patterns are still poorly documented; polysomnographic data in healthy children and adolescents, and to a somewhat lesser degree in middle-aged adults, are still scant. Any future studies aimed at examining age-related changes in sleep should utilize carefully screened subjects and take into account subjects' habitual sleep schedules, as well as whether PSG recording occurs on weekday or weekend nights.

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