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# Patterns of Decline in Sleep Efficiency over the Adult Lifespan: Clarification via Use of Smoothing Splines -

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## ABSTRACT

**Purpose:** To further explicate age-related changes in sleep efficiency by pinpointing when change over the adult lifespan occurs in related sleep parameters: Sleep latency, waking after sleep onset, total sleep, and time in bed. Accurate information about sleep-parameter decline with age before the age of electronics is useful as baseline knowledge for understanding modern environmental factors' impact on sleep efficiency.

**Methods:** A research synthesis approach specifically designed to detect nonlinear developmental changes was used. Specifically, Cubic B smoothing splines were fit to scatter plots generated using descriptive study results. English-language research reports produced over 45 years provided data from thousands of subjects for each sleep parameter. All subjects were described in research reports as normal or healthy. Mean ages of samples used ranged from 18.0 to 91.7 years (SD < 4 years). Two coders extracted information; formal reliability testing showed excellent coder reliability.

**Results:** No nonlinearity was detected in the relationship between age and sleep efficiency, which decreased 2.2% per decade. Similarly, no nonlinearity was detected in total sleep, which decreased 12.2 minutes per decade. Significant nonlinearity was detected for three relationships: Sleep latency increased more rapidly after age 32; waking duration increased more rapidly after age 49; and the relationship between age and time-in-bed was curvilinear with adults spending the least amount of time in bed around age 50.

**Conclusions:** Sleep efficiency declines with age, not only because sleep latency and waking duration increase, but also because total sleep decreases while time in bed first decreases and then increases. Increased TIB after age 50 may be an attempt to increase amount of sleep despite increasing sleep latencies and more waking after sleep onset. Ability to detect nonlinearity in rates of change in sleep parameters using smoothing splines improves precision for understanding the decline in sleep efficiency over the adult lifespan.

**Keywords:** Meta-Analysis; Smoothing Splines; Sleep Efficiency (SE); Sleep Latency (SL); Waking After Sleep Onset (WASO); Total Sleep Time (TST); Time In Bed (TIB)

## INTRODUCTION

One way to quantify sleep quality is to calculate Sleep Efficiency (SE), i.e., the ratio of time spent in sleep to time spent in bed. Sleep efficiency is decreased by two factors that may limit total sleep: (a) difficulty falling asleep and (b) difficulty staying asleep. Calculated sleep efficiency values may also be decreased if adults attempt to compensate for lost sleep by extending time in bed. As the interest in how much hand-held electronic devices and other sources of bright light impact sleep quality increases, availability of accurate baseline norms for sleep parameters prior to the electronic age are essential [1-3].

The desire to describe typical changes is sleep quality over the adult lifespan and to differentiate changes due to normal aging from changes due to pathology or non-conducive sleep environments has generated an extensive body of sleep research, which makes secondary research studies feasible. In 1994, Floyd began to create a database for use in meta-analytic studies of sleep change over the adult lifespan [4]. The age-range covered by studies included in the database was from the late teens to over 100 years of age, with sample means ranging from 18.0 to 92.7 years. The database was used to identify mean weighted correlations and 95% confidence intervals for the magnitude of linear change in objectively-measured sleep parameters over the adult life span [5-8].

With regard to how SE and related sleep parameters were correlated with age during adulthood, the Floyd research team reported: (a) significant decreases in SE, (b) significant increases in time taken to fall asleep, i.e., Sleep Latency (SL), (c) significant increases in Waking After Sleep Onset (WASO), (d) significant decreases in Total Sleep Time (TST), and (e) significant increases in Time In Bed (TIB) [5-8].

In 2004, Ohayon and his colleagues confirmed Floyd's findings regarding adults, i.e., they also reported significant linear relationships between age and objectively-measured SL, WASO, TST, and SE values, respectively; however, they did not report correlational results for age and TIB [9]. The oldest adults in Ohayon's meta-analysis were in their early 90s, with mean ages of samples ranging from 22.0 to 83.1 years. Ohayon and his colleagues used Cohen's d to capture group differences whenever researchers reported sleep values for a younger versus an older group, rather than using Pearson's *r* to more precisely identify correlations between the continuous values for age and sleep characteristics. Nevertheless, both research teams found significant linear relationships between age and each sleep parameter examined and reported effects sizes as small, medium or large.

The cut off values for small, medium, and large effects are .1, .3, and .5 for *r*, while the comparable cut off values for *d* are .2, .5, and .8 [10]. Both Floyd [5-8] and Ohayon [9] reported small, but statistically significant effects sizes for age-related change in SL and large effect sizes for age-related sleep change in WASO. Estimates of magnitude of linear change differed somewhat between the two research teams for TST and SE, but both teams agreed linear trends were statistically significant and were medium or large in size, see table 1.

Both the Floyd and Ohayon research teams recognized that changes in sleep characteristics over the adult lifespan did not appear purely linear, i.e., there appeared to be inflection points at which rates of change in a sleep parameters accelerated or decelerated. Beginning in 2000, Floyd's team described a new analytic approach for detecting these inflection points and the nature of resultant non-linear change in sleep characteristics over the lifespan [11,12]. The method developed was statistical in nature and utilized descriptive sleep results from studies homogeneous on age to create scatter plots representing sleep values for each decade of the lifespan. The methods were piloted using SL data from 258 adult subjects clustered within 15 samples. These 15 studies were known to the Floyd team because of their earlier meta-analysis of linear changes in sleep with age [5-7].

For the pilot work by Floyd, two mathematical models were tested. One model suggested inflection points for SL may exist around ages 30 and 50, respectively. Using this model, SL was shown to increase from the late teen years to age 30, remain unchanged from ages 30 to 50, and then decline steadily after age 50 thru old age. The

**Table 1:** Magnitudes of Linear Relationships between Age and Sleep Characteristics Estimated Using Meta-Analysis.

| Researchers: Sleep Variables: | Floyd Team [8] | | | Ohayon Team [9] | | |
|---|---|---|---|---|---|---|
| | N | *r* (95% CI) | Effect Size | N | d (95%CI) | Effect Size |
| SE | 1,192 | *r* = -.65(-.68;-.61) | Lg | 1,738 | d = -.71(.81; -.61) | Md |
| SL | 1,092 | *r* = .20(.11; .28) | Sm | 1,436 | d = .27(.17;.37) | Sm |
| WASO | 2,469 | *r* =.73 (.71;.75) | Lg | 1,012 | d = .89(.75;1.20) | Lg |
| TST | 4,043 | *r* = -.31(-.37; -.25) | Md | 2,009 | d = -.60(-.69;-.51) | Lg |
| TIB | 2,306 | *r* = .18 (.13;.23) | Sm | n.r. | n.r. | n.r. |

Note: SE = Sleep Efficiency; SL = Sleep Latency; WASO = Waking After Sleep Onset; TST = Total Sleep Time; TIB = Time In Bed; N = Sample Size; CI = Confidence Interval; *r* = Mean Weighted Correlation; d = Standardized Mean Difference; Sm = Small; Md = Medium; Lg = Large; n.r. = Not Reported.

second model showed an increase in SL with age, but lacked adequate power to identify a significant non-linear trend. Floyd concluded that SL may not increase at a steady rate over the adult life-span, but that further refinement in research synthesis methods and an extensive dataset would be needed to perfect an analytic approach that could pinpoint thresholds of change in SL and other sleep parameters if they exist [11,12].

Methods for identification of inflection points in rates of change across the lifespan were perfected and finalized by Floyd's team in 2004 [8] and their use was demonstrated for clarifying disparate descriptions in the sleep literature regarding when REM% declines with age [13,14].

In 2004, the Ohayon research team also attempted to shed light on possible non-linear changes in sleep parameters over the lifespan, proposing an alternate approach that used least squares to fit exponential equations directly to the mean values of samples. For SE and sleep parameters related to the calculation of SE, they reported the following regarding possible inflection points when rates of change in adult sleep parameters may increase or decrease:

1. SE decreases over the adult lifespan, becoming more evident after age 40;
2. SL increases over the adult lifespan becoming more evident after age 65;
3. After age 30, WASO increases over the adult lifespan; and,
4. TST decreases linearly over the adult lifespan with no inflection points observed [9].

In summarizing sleep change over the adult lifespan, Ohayon also reported that "after 60 years of age, only sleep efficiency continued to significantly decrease, with all the other sleep parameters remaining unchanged [9]. This statement suggests a second inflection point for both WASO and TST, respectively, at age 60 with WASO and TST values then holding steady in the 60s and thru old age. In addition, this statement contradicts results reported earlier in paper indicating that SL increases even more rapidly after age 65 [9].

## PURPOSE

The purposes of this study were to: (a) Clarify and extend knowledge about the nature and magnitude of sleep efficiency decline over the adult lifespan and (b) show more precisely how changes in SL, WASO, TST, and TIB during adulthood account for the observed decline in SE with age. Based on Ohayon's replication [9] of Floyd's reports of significant age-related linear trends for SE and sleep parameters related to the calculation of SE [5-8], significant linear trends were hypothesized for age and SE, SL, WASO, and TST, respectively. A significant linear trend was also hypothesized for age and TIB based on Floyd's early reports [7,8].

Due to the pilot nature of the Floyd team's exploration of non-linearity in SL values [11,12] and the contradictory reporting of the Ohayon team's exploration of non-linearity in SL, WASO, and TST values [9], research questions were posed in lieu of stating hypotheses regarding nonlinearity.

## MAJOR RESEARCH QUESTIONS

1. Are there changes in the rate at which SE decreases over the adult lifespan? If so, does the rate of change increase after age 40 and continue in a linear fashion into old age as stated by Ohayon [9]?
2. Are there changes in the rate at which SL increases over the adult lifespan? If so, does the rate of change (a) level off after age 60 as stated by Ohayon [9], (b) increase after age 65 as stated by Ohayon [9] , (c) decline from 17-30, hold steady from 30-50, and resume decline after age 50 as suggested by one of two models tested in the early pilot work of Floyd's team [11,12] or (d) decline in a linear fashion with no significant nonlinearity as suggested by a second model applied to Floyd's pilot data [11,12]?
3. Are there changes in the rate at which WASO increases over the adult lifespan? If so, does the rate increase after age 30 and level off after age 60 as stated by Ohayon's [9] team?
4. Are there changes in the rate at which TST decreases over the adult lifespan? If so, does the rate of change level off after age 60 as stated by Ohayon's [9] team?
5. Are there changes in the rate at which TIB increases over the adult lifespan? If so, at what ages do increases or decreases occur?

## METHODS

This study of SE decline over the adult lifespan was conducted using a subset of studies in an existing dataset originally created for an NIH-funded program of research that focused on the development of various research synthesis methods to describe how sleep parameters and other activities of daily living change over the adult life-span [1,8]. For the analyses presented, the subset of studies used was comprised of all research reports published from 1960 thru 2004 that met the following criteria: (a) Subjects were adults healthy adults of a similar age, i.e., standard deviation for sample ages was ≤ 4.0 years, and (b) researchers reported descriptive statistics for one or more of the following sleep parameters: SE, SL, WASO, TST, TIB.

### Search and retrieval of studies

Most studies were identified by searching the following databases electronically or by searching paper copies of these same indexes by hand whenever electronic databases did not include early work: PubMed, CINAHL, Psyc INFO, and Dissertation Abstracts. In addition, sleep journals were hand-searched. Finally, ancestry searching was completed for all included papers and inquiries were sent to sleep center directors and chairs of graduate research departments to help assure inclusion of unpublished works. Approximately 3500 papers were retrieved and examined, with only 17% yielding useable data [8]. Over-retrieval was necessary given existing literature indexing practices did not facilitate efficient targeting of sleep studies that contained descriptive sleep results for samples homogeneous on age [15]. Papers that contained usable data for healthy subjects typically belonged to one of the following categories: (a) Observational studies of normal sleep, (b) experimental studies of the effect of various interventions or other experimental conditions on normal sleep, and (c) observational studies of sleep in populations with various physical or psychological conditions that also included groups of healthy subjects used for comparison.

### Coder reliability

Attention to inter-coder reliability has been described elsewhere [4,8,16]. In summary, continual training and periodic testing were completed to maintain excellent coder reliability over the decade required to create the extensive database. Kappa values never dipped below the .75 cutoff that is considered excellent for inter- and intra-coder reliability. Also, no linear trends were found that would indicate coder drift over time [8].

### Analytic Procedures

The development of the analytic approach including formula and computer software used for analyses have been described in detail previously [8,11,14]. Briefly, the following steps were taken: First, previously reported univariate sleep results for similarly-aged subjects in samples of varying mean ages were used to simulate five scatter plots (one for SE values and one each for the four sleep parameters that may help explain decline in SE over the adult lifespan, i.e., SL, WASO, TST, and TIB). Once scatter plots were generated, smoothers (Cubic B smoothing splines) were fit to the data. Statistically significant smoothers ($p < .05$) were inspected to determine the kind of function that best fit the data for each sleep parameter.

## RESULTS

Three different types of statistically significant functions were identified among the five sleep parameters examined during this study: Linear, quadratic, and linear-quadratic. For two purely linear functions, slopes were identified to facilitate description of change in sleep parameters per decade. For one quadratic function the age at which the minimum value occurred was identified, and for two linear-quadratic functions, the ages at which the rate of linear change in the sleep parameter accelerated were identified using segmented regression.

### Sleep Efficiency

The scatter plot generated using previously reported SE values from 339 samples represented 4,269 subjects. The functional relationship was essentially linear with no identifiable inflection points. The slope of the function was -0.22: thus, for each decade in age from the late teens through the early 90s, SE decreased approximately 2.2%. Average SE was estimated at 97% for subjects in their late teens and 79% for subjects in their early 90s.

### Sleep Latency

The scatter plot generated using previously reported SL values from 446 samples represented 5,332 subjects. A significant non-linear trend was detected that was linear-quadratic in nature. Segmented regression showed an inflection point at age 32: After age 32 the rate of change in SL values began to slowly accelerate from an average SL of 21 minutes at age 32 to an average SL of 33 minutes for subjects in their early 90s. No other inflection points were identified.

### Waking after Sleep Onset

The scatter plot generated using previously reported WASO values was based on data representing 3,032 subjects clustered in 234 samples. A significant non-linear trend was detected that was linear-quadratic in nature. Segmented regression showed an inflection point at age 49: After age 49, the rate of change in WASO values began to noticeably accelerate from an average of 29 minutes at age 49 to an average of nearly 90 minutes for subjects in their early 90s. No other inflection points were identified.

### Total Sleep Time

The scatter plot generated using previously reported TST values was based on data representing 5,061 subjects clustered in 428 samples. The functional relationship was essentially linear in nature with no identifiable inflection points. The slope of the function was -1.22: thus, for each decade in age from the late teens through the early 90s, TST decreased approximately 12.2 minutes. The mean amount of sleep for subjects in their late teens was 7.6 hours, but TST had decreased to 6.0 hours for subjects in their early 90s.

### Time in Bed

The scatter plot generated using previously reported TIB values from 209 samples represented 2,610 subjects. A significant non-linear trend was detected, which was quadratic in nature: Time in bed declined from the late teens until age 50; after a low-point at age 50, time in bed steadily increased into old age. The mean TIB for subjects at age 50 was 7.1 hours. For subjects in their early 90s, TIB averaged 8.3 hours.

## DISCUSSION

As expected, an inverse relationship (negative correlation) between age and SE, as well as between age and TST were observed in healthy adults along with direct relationships (positive correlations) between age and SL and age and WASO, respectively. While a direct relationship was observed between age and TIB after age 50, an inverse relationship between age and TIB from the late teens to age 50 also was detected when the smoother was fit. Thus, a quadratic function was identified, i.e., a curvilinear relationship was found to exist between age and TIB, which had not been hypothesized. This unexpected finding suggests that TIB contributes to the magnitude of computed decline in SE differentially over the adult lifespan. Before age 50, TIB may mask decline in sleep quality (as measured by SE) as SL and WASO increase and TST decreases. After age 50, TIB may exaggerate decline in sleep quality as SL slowly increases, WASO rapidly increases and TST continues to decrease.

While Ohayon and his colleagues [9] described some nonlinearity in SE, Sl, WASO, and TST, no nonlinearity for SE or TST decreases across the adult lifespan were detected. The slope obtained in this study and used to describe the purely linear change in SE over the adult lifespan was similar to that reported by Ohayon and his colleagues. For SE, Ohayon's team reported a 3% decline in SE per decade compared to the estimate of 2.2% obtained in the current study. Ohayon's team reported that the 3% decline per decade was an accelerated rate commencing around age 40, but a steady rate of decline in SE from the late teens to old age was observed in this study. Similarly, a purely linear relationship between age and TST was observed in this study. Ohayon reported a decrease of 10 minutes per decade that ceased after age 60 compared to the estimate of 12.2 minutes per decade that extended over the entire adult lifespan shown in this study.

Regarding SL and WASO, significant non-linear relationships were detected. Ohayon's research team had identified non-linearity for both SL and WASO, although their descriptions of possible inflection points were contradictory [9], while Floyd's team had predicted possible inflection points for SL, but questioned their statistical significance [11,12]. Results of this study failed to replicate any of the previous descriptions of non-linearity by either Ohayon or Floyd regarding the points along the adult lifespan when rates of change accelerate or decelerate for SL. Similarly, for WASO, the results of this study failed to replicate the inflection points identified by Ohayon as ages when rates of change accelerate or decelerate for WASO.

These new findings for aging-related changes in SE and sleep parameters related to the calculation of SE, suggest that the consistently reported decline in SE observed during adulthood likely results from additive factors including: (a) Increasing SL in young adulthood followed by a small, but continuous acceleration in the rate of increase in SL beginning in the early 30s, (b) increasing WASO in young adulthood followed by a moderate and continuous acceleration in the rate of change in WASO beginning in the late 40s, (c) moderate decreases in TST across the entire adult lifespan, and (d) increasingly less time spent in bed from young adulthood to age 50 and increasing more time spent in bed after age 50.

Identifying the reasons why sleep parameters change over the normal adult lifespan is beyond the scope of this study, which focused solely on use of research synthesis methods that increase the precision of describing sleep norms. Specially, for the new and unexpected curvilinear relationship observed between age and TIB, why TIB declines from the late teenage years to midlife and then reverses course can only be speculated upon. Perhaps employment and/or social and family demands leave little time to remain in bed if not asleep, thus leading to declining TIB as TST declines during young and middle adulthood. There is some empirical evidence that staying in bed is a widely used strategy among older adults who are coping with sleep loss as they age [17].

## Strengths and Limitations

A major general limitation of the methods employed for this study is related to resource intensiveness. Building the extensive dataset required to generate scatter plots was very time consuming and would not have been feasible without substantial external funding over several years [4]. Also, producing scatter plots and fitting smoothers to data requires computer-time intensive renderings.

More specifically, for examination of nonlinearity in the relationship between age and SE as well as other sleep parameters related to the calculation of SE, one strength of the research synthesis method employed is its ability to estimate the functional relationship between ages and sleep parameters without imposing any a priori relationship. The approach can be considered grounded given that empirical data are used to develop the functions, which facilitates the detection of any existing nonlinearity in the relationship without having to know a priori how the nonlinearity will be manifested. This was particularly useful for clarifying SL and WASO inflection points along the adult lifespan and for detecting the unexpected quadratic function for age and TIB.

A second strength of the research synthesis method employed is its precision in comparison to methods employed by the Ohayon team [9]. Both means and variance estimates along with sample sizes for samples homogeneous on age were used in the generation of scatter plots. This is in contrast to Ohayon's methods for detecting nonlinearity, which appear to use only mean values from samples with much wider variances on age, while also failing to weight sample influence by sample-size [8,9,11,14].

The availability of an exceptionally large database of sleep values is a third strength of the study. In addition to the coding of data from studies with a primary purpose of examining normal adult sleep as used by Ohayon [9], the inclusion criteria allow for coding of additional baseline data from healthy subjects used in control groups for experiments, as well as data used in comparison groups for observational studies of clinical populations. These procedures often doubled or tripled the amount of data available in this study compared with the Ohayon study, see table 2.

Limitations regarding the dataset have been discussed at length in earlier publications [8,11,14]. Two relevant issues are summarized here. First, although the dataset includes data collected over several decades it does not include data from the current era. It does, however, represent normative sleep values for the era preceding the advent of handheld devices widely believed to be changing the physical sleep environment in ways that decrease sleep quality. As such, clarification of how sleep parameters have declined with age historically has been shown to be feasible and should be useful as a baseline for understanding the impact of emerging environmental factors believed to impact sleep quality.

A second major issue relates to how well populated scatter plots were for sleep parameters for each decade of life. For this study, more samples existed for younger subjects, followed by samples of older subjects; thus average sleep parameter values for young adults and older adults are considered more precise than for middle-aged adults. Also, gaps in the age ranges where inflection points are located can result in unstable point estimates due to the lack of information within these gaps. Fortunately, the extensive body of experimental

**Table 2:** Samples Sizes Available for Identification of Nonlinear Relationships of Sleep with Age.

| Researchers:<br>Sleep Variables: | Ohayon Team [8]<br>N | Floyd Team [9]<br>N |
|---|---|---|
| SE | 1,738 | 4,269 |
| SL | 1,436 | 5,332 |
| WASO | 1,012 | 3,032 |
| TST | 2,009 | 5,061 |
| TIB | n.r. | 2,610 |

Note: SE = Sleep Efficiency; SL = Sleep Latency; WASO = Waking After Sleep Onset; TST = Total Sleep Time; TIB = Time In Bed; N = Sample Size; n.r. = Not Reported.

sleep research as well as research comparing various clinical groups to normal controls generated a wealth of data about normal adult sleep, including adequate samples of middle-aged subjects needed to identify non-linearity and pinpoint the ages at which rates of change in SL, WASO, and TIB accelerated or decelerated during the middle-aged years.

Finally, it is important to note that no results regarding gender differences were presented in this paper. Many of the sample values used in this study were from mixed-gender samples because researchers did not provide descriptive statistics separately for males and females. However, enough data appears to exist in the dataset for smoothers to be fit to samples composed solely of women versus samples composed solely of men for additional publications in the future [8].

## CONCLUSIONS

It is important to establish accurate sleep norms for use in the modern era as baseline knowledge for future research regarding the possible impact of changing environmental conditions on sleep quality. Both the Ohayon research team and the Floyd research team have contributed to foundational knowledge about how various sleep parameters change over the lifespan, replicating much of each other's findings, but leaving a legacy of some inconsistencies as each team attempted to go beyond estimating magnitudes of linear trends to describing non-linearity in sleep change.

This study contributes to a more precise description of when SE, and sleep parameters related to the calculation of SE, change over the adult lifespan. It shows that there are accelerations and decelerations in the rates of linear change over the adult lifespan for some, but not all sleep parameters. It also challenges Ohayon and his colleagues' generalization that all sleep parameters other than SE cease to decline around age 60 [9]. Instead, sleep parameter changes were shown to continue to change into old age and to interact to produce the often observed linear decline in SE with aging.

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