ORIGINAL CONTRIBUTION

Chronotype Variability and Patterns of Light Exposure of a Large Cohort of United States Residents

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Chronotype (*i.e.,* disposition for activity early or late in the day) has traditionally been measured with questionnaires. A few studies with small sample sizes have also been conducted using actigraphy devices. In the present study, analysis was conducted of the daily pattern of activity of 1887 United States residents who wore actigraphy devices for a whole week. The devices also recorded the participants' exposure to light. As determined by cosinor analysis, the mean pattern of ambulatory activity exhibited robust 24-hour oscillation with a peak at 14:48. On average, participants went to sleep 2 minutes before midnight and woke up at 07:43. The distribution of chronotypes (defined as the midpoint of sleep) had a mean of 03:50, and 95% of all chronotypes were between 01:00 and 07:00. The mean duration of exposure to bright daylight was 3.57 hours per day. Duration of daily exposure to bright light was moderately but significantly correlated with chronotype (r = -0.18). The acrophase of the rhythm of exposure to bright light was significantly correlated with chronotype (r = 0.27) and with the acrophase of the activity rhythm (r = 0.36). Chronotype did not vary with the seasons, but exposure to bright light was longer in summer and spring than in winter and fall. These results confirmed chronotype findings from actigraphic studies with smaller sample sizes, endorsed their equivalence to the results of questionnaire studies, and confirmed and extended previous observations that urban dwellers have limited daily exposure to sunlight.

INTRODUCTION

The term "chronotype" refers to the variation of individual patterns of early or late beginning of daily activity, with extreme chronotypes often referred to as "morning types" (people who usually wake up early and are more productive in the morning) and "evening types" (people who usually wake up late and are more productive later in the day). Variations in chronotype are associated with variations in the timing of numerous physiological and behavioral variables that have consequences for overall health. For example, the rhythms of body temperature [1,2] and melatonin secretion [3,4] peak later in the day for late chronotypes than for early chronotypes. In terms of behavioral performance, early types are better at sentence recognition early in the day than late types [5] and are more alert than late types early in the day [6]. Among university students, early types tend to attain better course grades than late types, irrespective of class times [7,8]. Late types seem to have greater propensity

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for mental illness [9-12].

Measurement of chronotype has traditionally been conducted by questionnaires, such as the Morning-ness-Eveningness Questionnaire [13] and the Munich Chronotype Questionnaire [14]. Although early investigators attributed great importance to arbitrary break points between morning types, evening types, and intermediary types [13], more recent investigators with background in the study of biological rhythms have placed greater emphasis on the variability (and frequency distribution) of chronotypes [14], which is present in many species besides humans [15].

Because of the subjectivity involved in measurements obtained through questionnaires, some researchers have investigated the variation in the daily distribution of activity of human subjects using more objective acti-graphic devices. Unfortunately, the sample sizes in these studies have generally been quite small when compared with the sample size (over 55,000 participants) in the Central European implementation of the Munich Chronotype Questionnaire [16]. Three of the actigraphic studies, one in Canada [17], one in Italy [18], and one in Germany [19], had fewer than 70 participants. Another study in Canada [20] and two in the United States [21,22] had a few hundred participants. One study had more than 2000 participants, but the participants were from five different countries with very different daily distributions of activity [23]. To ensure the acquisition of a representative sample, the present study involved almost 2000 participants from the United States with approximately equal representation from California, Illinois, New York, and Florida.

Because chronotype is an expression of the phase angle of entrainment of the circadian system by the environmental light-dark cycle [15], the simultaneous study of the daily pattern of light exposure is very instructive. Current actigraphy devices include photic sensors, thus providing a convenient means for the monitoring of light exposure. Therefore, the current study included analyses of both the daily pattern of ambulatory activity and the daily pattern of light exposure of individuals studied under normal living conditions. The goal of the study was to evaluate the variability of chronotypes across the population and to relate this variability to an objective measure of light exposure.

MATERIALS AND METHODS

Data Collection

The data used in this study were collected as part of the Hispanic Community Health Study (HCHS) Study of Latinos (SOL), a multi-center epidemiological study of cardiovascular and metabolic health in Hispanic or Latino populations in the United States [24].

The full study involved over 16,000 male and female participants aged 18 to 74 years who represented various groups of origin, including Central Americans, Cubans, Mexicans, Puerto Ricans, and South Americans. Participants were studied at four centers affiliated with San Diego State University, University of Illinois at Chicago, Albert Einstein College of Medicine (in New York), and University of Miami. Participants who expressed willingness to be contacted about ancillary studies were invited to join an ambulatory sleep study using wrist-worn actigraphy devices (Actiwatch Spectrum, Philips Respironics, Murrysville, PA). Of 2252 individuals originally recruited, 1887 participants wore the actigraphs on the wrist of the nondominant arm continuously for seven or more days. Exclusion criteria included a physician's diagnosis of narcolepsy or sleep apnea and/or pregnancy. Different individuals were studied at different times of the year, with approximately the same number of participants in each of the four seasons.

Ambulatory activity counts and illumination levels (separately for white light, red light, green light, and blue light) were recorded in 30 second intervals. Scoring of sleep stage (simply "asleep" or "awake") was carried out by a trained technician at the Brigham Health Sleep Reading Center (Brigham and Women's Hospital, Harvard Medical School, Boston, MA). The data sets are stored in the publicly accessible database of the National Sleep Research Resource (https://www.sleepdata.org).

Data Analysis

The main analysis was conducted with a computer program in Visual Basic (Microsoft Corporation, Redmond, WA) written specifically for this study. The program sorted the 1887 individual files by season of the year and converted each file to 6-day-long time series with 6 minute (0.1 hour) resolution starting at midnight. Because different participants initiated and terminated data collection on different days of the week, no attempt was made to sort the files by day of the week. The files were not sorted by age or sex of the participants because the data sets were anonymized early on (including removal of sex and age) to preserve participant privacy, which effectively prevented the use of sex and age in the analysis of the data. There is no reason to suspect, however, that the distribution of ages in the sample of participants in this study differed from the distribution of ages in the general population, which means that the data analysis was not biased regarding age. Similarly, there is no reason to suspect a bias in the representation of males and females in the studied sample.

The acrophase (peak time) of each time series of ambulatory activity and of exposure to white light with illuminance (brightness) greater than 200 lux were cal-
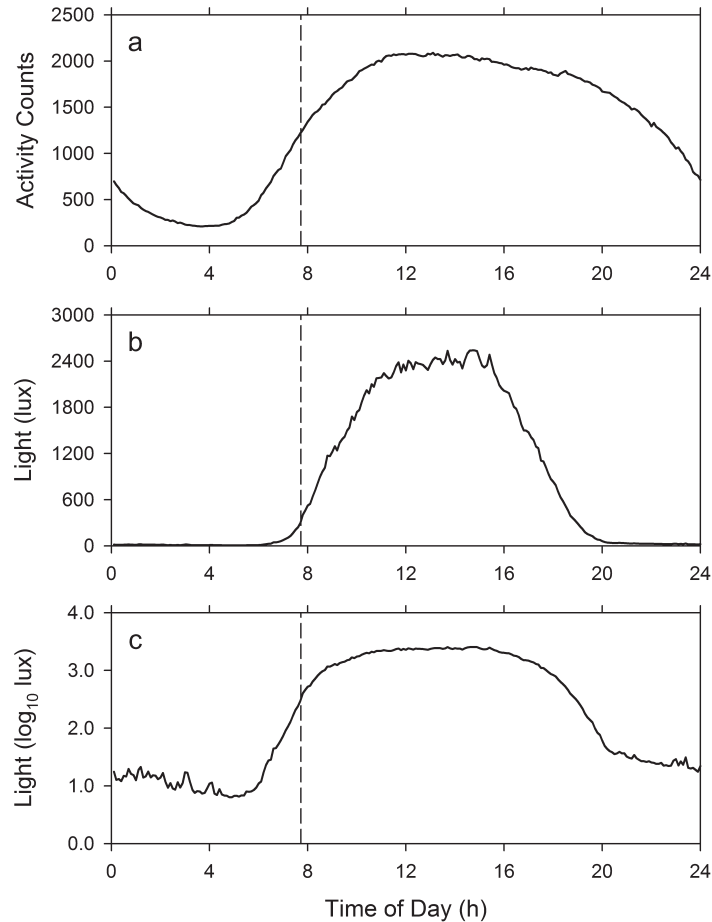
Figure 1. Mean daily patterns of ambulatory activity (**a**) and of exposure to light with intensity (illuminance) greater than 200 lux (**b**, **c**) of 1887 United States residents studied under normal living conditions. Illuminance is plotted both in natural (**b**) and logarithmic (**c**) units. In all three panels, the dashed vertical line indicates the mean wake-up time (07:43).

culated by cosinor rhythmometry [25,26]. A threshold of 200 lux was used because this is the average illuminance of indoor lighting [27], and exposure to greater brightness implies time spent outdoors. Cosinor rhythmometry was used also to calculate the robustness (rhythmic strength) of the time series.

The program further calculated the number of hours each day spent under white light with illuminance above 200 lux, under white light with illuminance above 5 lux, under red light with irradiance greater than 1 $\mu W \cdot cm^{-2}$, under green light with irradiance greater than 1 $\mu W \cdot cm^{-2}$, and under blue light with irradiance greater than 1 $\mu W \cdot cm^{-2}$.

Chronotype was computed as the midpoint between the time of initiation of sleep and the time of awakening the next day. Ideally, the computation of chronotype would be based only on non-work days and would include a correction for excess sleep on non-work days [16], but this type of computation was not possible because differ-

ent participants worked on different weekdays and started data collection at different times of the week and of the year.

Calculations of day length were based on the times of sunrise and sunset computed with basis on the local latitude, longitude, date, and geopolitical time zone. To account for the latitudinal differences in the four research sites, the program used the averages of the four locations, namely 10.0 hours of daylight in the winter, 13.1 hours in the spring, 14.4 hours in the summer, and 11.2 hours in the fall.

Comparisons of group means were conducted by analysis of variance (ANOVA), and bivariate correlations were computed by the principle of least squares, both procedures under OpenStat [28].

RESULTS

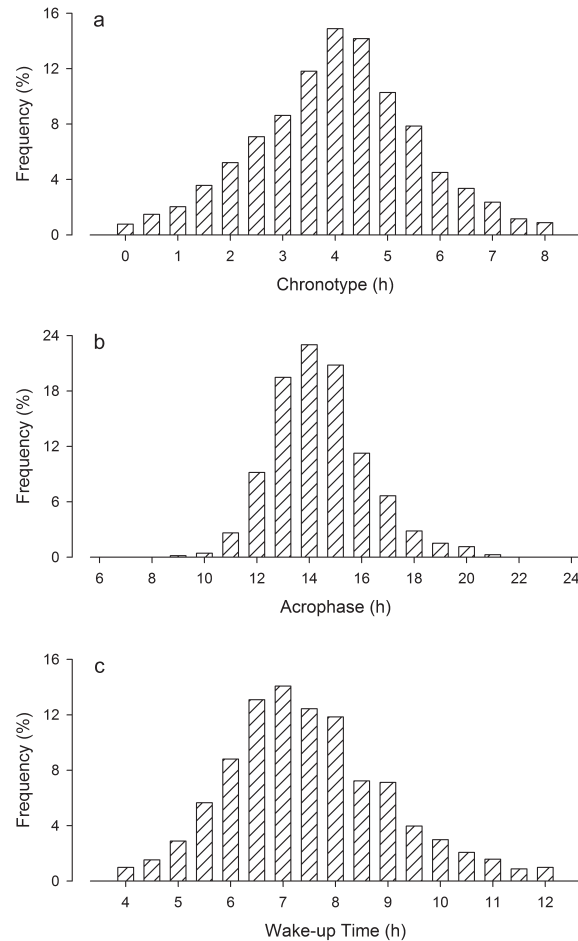The mean daily pattern of ambulatory activity of the

Figure 2. Frequency distributions of chronotype (**a**), acrophase of the activity rhythm (**b**), and wake-up time (**c**) of 1887 United States residents studied under normal living conditions.

1887 participants is shown in Figure 1a. On average, participants went to sleep 2 min before midnight and woke up at 07:43. The intensity of wrist movement started to grow about 2 hours before wake-up, reached a plateau around 10 o'clock in the morning and descended to the night-time level starting around 8 o'clock at night. As determined by cosinor rhythmometry, the mean daily pattern of ambulatory activity exhibited robust 24-hour variation (robustness = 92% of sinusoid signal) with acrophase (peak time) at 14:48. Individual activity rhythms were not as robust, with mean robustness being 26% and the strongest individual rhythm reaching 63%, but were still statistically significant.

Figure 1b indicates that exposure to outdoor light started shortly before wake-up, possibly as an artifact of averaging across many participants or because of sunlight coming through the bedroom window. Light intensity started to decrease at 4 o'clock in the afternoon and approached darkness at 20:00. The same light-exposure data are shown in Figure 1c with a logarithmic ordinate

to allow better visualization of low levels of illumination. The sleep-time illuminance of 1 log unit corresponds to 10 lux, which is possibly the result of the use of a night light by some participants, or the projection of streetlights through the bedroom window, or an artifact of the averaging procedure.

The frequency distributions of chronotype, acrophase, and wake-up time for all participants are shown in Figure 2. The distribution of chronotypes (Figure 2a) is fairly symmetrical with a mode of 4 and a mean ($\pm$ SEM) of 3.84 ± 0.04 hours and with 95% of all chronotypes situated within a 6-hour window between 1 o'clock and 7 o'clock. The distribution of acrophases (Figure 2b) has a mode of 14:00, or 10 hours after the midpoint between the time of initiation of sleep and the time of awakening. The distribution of wake-up times (Figure 2c) has a mode of 7 o'clock. The three variables are significantly correlated ($p < 0.00001$): $r = 0.45$ for acrophase and wake-up time, $r = 0.56$ for chronotype and acrophase, and $r = 0.82$ for chronotype and wake-up time.
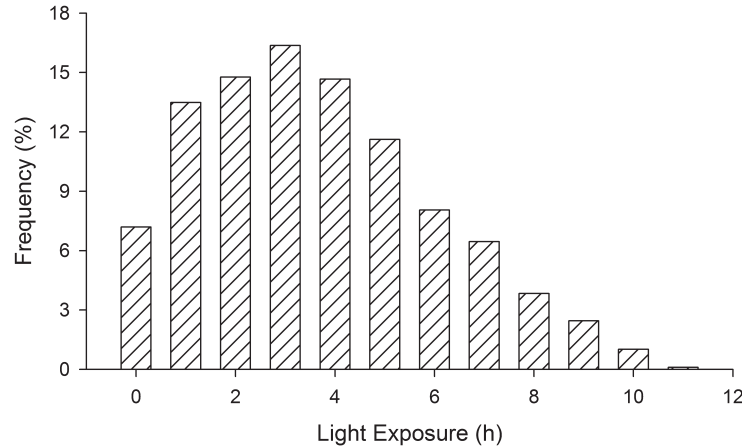
Figure 3. Frequency distribution of the duration of daily exposure to light with intensity (illuminance) greater than 200 lux of 1887 United States residents studied under normal living conditions.

The individual variation in the number of hours spent each day under illumination greater than 200 lux is shown in Figure 3. The mode of the distribution is at 3 hours, with 7% of the participants having had no exposure to outdoor brightness and 2% having had 10 or more hours of exposure. The mean ($\pm$ SEM) duration of daily exposure to outdoor brightness was 3.57 ± 0.05 hours. Duration of daily exposure to bright light was moderately but significantly correlated with chronotype ($r = -0.18$, $p < 0.00001$). The acrophase of the rhythm of exposure to bright light was significantly correlated with chronotype ($r = 0.27$, $p < 0.00001$) and with the acrophase of the activity rhythm ($r = 0.36$, $p < 0.00001$).

Not shown in Figure 3 is the breakdown of light exposure into color components. Whereas participants were exposed on average to 12.18 hours of white light above 5 lux each day, they were exposed to 10.58 hours of red light above 1 $\mu W \cdot cm^{-2}$, 10.04 hours of green light above 1 $\mu W \cdot cm^{-2}$, and 6.88 hours of blue light above 1 $\mu W \cdot cm^{-2}$. The bivariate correlations are shown in Table 1. All measures of light exposure were significantly correlated. The weakest correlation (but still strong at $r = 0.613$) was the one between white outdoor light (W>200) and total white light (W>5), the weaker correlation possibly being due to the fact that people are more consistent in the amount of time they spend indoors than in the amount of time they spent outdoors.

The analyses described so far involved the whole data set of 1887 individuals. Figure 4 breaks down the analyses by season of the year, with approximately 470 individuals per season. Chronotype did not vary with the seasons (Figure 4a, $F_{3, 1883} = 1.528$, $p = 0.205$), but exposure to bright light did (Figure 4b, $F_{3, 1883} = 63.011$, $p < 0.00001$). Because day length varies with the seasons, the seasonal variation in light exposure might be a simple consequence of the seasonal variation in day length.

To control for this extraneous factor, exposure to bright light was calculated also as a percentage of the number of bright sunlight hours available in a day and is plotted in Figure 4c. Under these conditions, there was still a significant seasonal variation in light exposure ($F_{3, 1883} = 7.315$, $p < 0.0001$), but the duration of light exposure was identical in the summer and spring, being slightly but significantly shorter in the winter and fall. In none of the seasons was mean exposure to bright light longer than 1/3 of the daily duration of sunlight.

DISCUSSION

The results of this study confirmed and expanded those of previous studies. In the large survey study by Roenneberg and colleagues [16], mean chronotype (defined as the midpoint of sleep) was approximately 4 o'clock in the morning, with the chronotypes of 95% of individuals contained within a 5 hour window around the mean. Two previous actigraphy studies identified mean chronotypes between 4 and 5 o'clock [20,21]. The mean chronotype in the present study was very close to 4 o'clock, which is particularly consistent with previous studies given the fact that weekdays and weekends were not differentiated in the present study. Other actigraphy studies used acrophase or wake-up time as measures of chronotype. Three of them identified mean acrophases between 14:37 and 15:48 [18,22,23], which is consistent with the acrophase in the present study (14:48). Another actigraphy study used wake-up time as the measure of chronotype, identifying a mean value of 07:46 [17], very close to the mean value of 07:43 obtained in the present study. The spread of individual chronotypes (95% window) found in the present study was 6 hours, which is the same as that found in a previous actigraphy study [23] although a little wider than the 5 hour spread found

Table 1. Bivariate correlations of durations of exposure to different color components of visible light.

	W>5	W>200	R	G	P
W>5	1				
W>200	0.613	1			
R	0.916	0.672	1		
G	0.917	0.726	0.936	1	
B	0.760	0.853	0.838	0.916	1

W>5: exposure to white light with intensity greater than 5 lux
W>200: exposure to white light with intensity greater than 200 lux
R: exposure to red light
G: exposure to green light
B: exposure to blue light
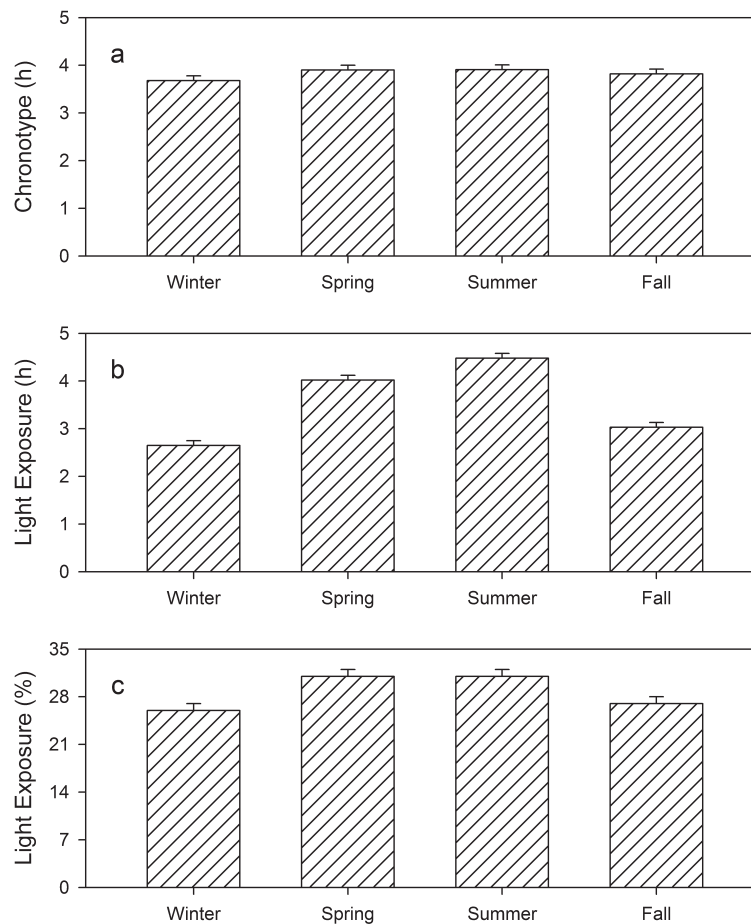All correlations are statistically significant (p < 0.00001)

Figure 4. Seasonal variation of chronotype (**a**) and light exposure (**b**, **c**) of United States residents studied under normal living conditions. Light exposure is expressed both in absolute hours per day (**b**) and as hours per day as a percentage of the number of sunlight hours in a day (**c**). In all panels, each bar is the mean (± SEM) of approximately 470 individuals. In panel **b**, all means are significantly different from each other as determined by pairwise *post hoc* Tukey tests. In panel **c**, winter and fall are not different from each other but are both different from spring and summer, spring and summer not being different from each other.

in the large questionnaire study [16]. In a study with 54 participants in Italy, measurements of chronotype with questionnaire and with actigraphy were correlated with a coefficient of r = 0.84 [18], a correlation actually stronger than that found between the scores of 2481 subjects in the two most commonly used questionnaires (r = 0.73) [29].

In previous studies of light exposure of urban dwellers, researchers have consistently found that most people are exposed to bright outdoor light for only a few hours each day [30-34]. In contrast, rural dwellers from pre-industrial societies are exposed to bright outdoor light during practically all hours of sunlight [35]. All the cited previous studies of light exposure of urban dwellers had fewer than 60 participants. The present study with 1887 participants concurred with the previous studies in indicating an average exposure of 3 ½ hours per day. Durations of exposure to red, green, and blue components of visual light correlated strongly with each other and with the duration of exposure to white light (when including as well as when excluding bright outdoor light), which does not suggest a differential effect of color components on chronotype.

As was the case in previous studies [31-34], the results of the present study indicated significant seasonal variation in the duration of exposure to outdoor light. Mean exposure time to bright outdoor light varied from a high of 4 ½ hours in the summer to 2 ½ hours in the winter. Some of the difference was due to the fact that there are more hours of sunlight in the summer, but a significant difference between spring/summer and fall/winter persisted when exposure time was calculated as a percentage of day length. More pleasant ambient temperatures in the spring/summer are likely one of the factors responsible for the greater amount of time spent outdoors.

Because the environmental light-dark cycle is a major synchronizer of circadian rhythms [36], variations in exposure to bright light might be associated with variations in chronotype. In this study, the acrophase of the rhythm of light exposure was moderately correlated with chronotype (r = 0.27) and with the acrophase of the activity rhythm (r = 0.36), although these associations could reflect a synchronizing effect of light just as much as an effect of chronotype on the timing of light exposure. If anything, the more modest correlation between chronotype and duration of exposure to bright sunlight (r = -0.18) suggests that interindividual variation in light exposure was not causally related to variation in chronotype. The physiological determinants of chronotype are still not fully understood [37].

In short, this actigraphic study of a large cohort of United States residents confirmed chronotype results from actigraphic studies with smaller sample sizes and their equivalence to the results of a questionnaire study of many thousands of individuals. Analysis of concomitant patterns of light exposure did not provide an explanation for the variation in chronotypes but confirmed previous observations of urban dwellers' limited daily exposure to sunlight.

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