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ORIGINAL ARTICLE

Circadian analysis of large human populations: Inferences from the power grid

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Few, if any studies have focused on the daily rhythmic nature of modern industrialized populations. The present study utilized real-time load data from the U.S. Pacific Northwest electrical power grid as a reflection of human operative household activity. This approach involved actigraphic analyses of continuously streaming internet data (provided in 5 min bins) from a human subject pool of approximately 43 million primarily residential users. Rhythm analyses reveal striking seasonal and intra-week differences in human activity patterns, largely devoid of manufacturing and automated load interference. Length of the diurnal activity period (alpha) is longer during the spring than the summer (16.64 h versus 15.98 h, respectively; $p < 0.01$). As expected, significantly more activity occurs in the solar dark phase during the winter than during the summer (6.29 h versus 2.03 h, respectively; $p < 0.01$). Interestingly, throughout the year a ''weekend effect'' is evident, where morning activity onset occurs approximately 1 h later than during the work week (5:54 am versus 6:52 am, respectively; $p < 0.01$). This indicates a general phase-delaying response to the absence of job-related or other weekday morning arousal cues, substantiating a preference or need to sleep longer on weekends. Finally, a shift in onset time can be seen during the transition to Day Light Saving Time, but not the transition back to Standard Time. The use of grid power load as a means for human actimetry assessment thus offers new insights into the collective diurnal activity patterns of large human populations.

Keywords: Circadian, human, population activity analysis, power grid

INTRODUCTION

Stable circadian rhythmicity in humans is a recognized hallmark of health and well-being (Kelly et al., 2012; Mormont et al., 2000; Roenneberg et al., 2012), and disruptions of these rhythms have been linked to increased pathology and mortality (Arntz et al., 1999; Monsees et al., 2012; 1991; Willich et al., 1987; Witte et al., 2005; Witting et al., 1990). It is notable, therefore, that although the nature of circadian rhythms in physiology and sleep has been extensively characterized at the individual level, and an increasing effort has been made to study circadian related pathophysiology at the population level (Levandovski et al., 2011; Roenneberg et al., 2012), little is known of basic circadian rhythmic patterns of large human populations. Definition of such basic processes is critical to understanding human chronobiology in modern society, which may prove important for understanding and preventing health outcomes associated with disorders linked to circadian disruption.

Biological rhythms have been well documented in humans. There is circadian variation in core body temperature (Aschoff et al., 1967), plasma cortisol (Orth et al., 1967), testosterone (Rose et al., 1972), and waste excretion (Lewis et al., 1956; Lewis & Lobban, 1957). There is also evidence of circadian modulation in mood disorders (Levandovski et al., 2011) as well as mortality of cardiac incidence (Willech et al., 1987). When kept in isolation without external cues human activity rhythms, while highly variable, display an approximate 25 h period (Aschoff, 1965; Mills et al., 1974). Under conventional living conditions, human activity rhythms are tightly entrained to a 24-h circadian cycle (Ortiz-Tudela et al., 2010), though evidence of social influence (masking) can be observed, such as delayed activity onset of weekend days (Oliver et al., 2012 supplemental) and shifts associated with Daylight Saving Time (Kantermann et al., 2007).

A major challenge in the study of human chronobiology is the collection of circadian data representative of large human populations in natural settings. Medical records have been utilized to retrospectively assess circadian variations in the daily timing of cardiac related mortality (Arntz et al., 1999; Willich et al., 1987), and

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relatively large surveys have been used to self-report sleep-wake times (Kantermann et al., 2007) and to determine chronotype (Adan et al., 2012; Roenneberg et al., 2003). However, there remains a large gap in our understanding of human biological rhythms expressed at the population level, and how those rhythms are affected by seasonality, work constraints, and imposed advance and delay shifts of the light:dark cycle (LD). In the present study, electrical power grid utilization from a largely residential area of the Pacific Northwestern United States comprising approximately 43 million people in nine different states was used as a reflection of human operative activity patterns. Data were analyzed over the 2012 calendar year for the core circadian parameters of activity onset, offset and duration of the diurnal activity period (alpha) as well as intra-week and seasonal effects. The present results revealed the first-ever actographic portrayal of mass human circadian activity patterns that are significantly modulated by seasonal and intra-week influences. Our data suggest that power grid utilization could contribute to studies of the circadian structure of large industrialized human populations.

MATERIALS AND METHODS

Data collection

Streaming internet power consumption data was obtained in 5 min bins from a public online database from the Bonneville Power Administration (BPA; http://transmission.bpa.gov/Business/Operations/Wind/) for the Pacific Northwestern United States (approximately between 42 and 50° N). All data was entered into Excel (Microsoft; Redmond, CA) and imported into ClockLab actimetry software (Coulborune Instruments, White Hall, PA) to create actograms and perform circadian analyses of the times of activity onset and offset used for estimating alpha.

Activity onset/offset determination

Activity onsets and offsets were standardized using the sum of the daily minimum load value and 50% of the difference between the maximum morning (onset) or evening peak load (offset) and minimum load each day. This value was designated the onset and offset load value, respectively. The onset time was defined as the earliest time between 12 a.m. and 12 p.m. at which the actual load value first exceeded the calculated onset load (Figure 1). Activity offset was defined as the first actual load time that fell below the calculated offset load between 5 p.m. and 12 a.m. Onset/offset times are reported as clock time ± minutes. Alpha was calculated as the offset time subtracted from the onset time, and is reported in hours ± fractions of an hour (decimal).

Activity under seasonal solar darkness

Activity during solar darkness was calculated as the sum of the difference between sunrise and onset time, and the difference between offset time and sunset. The daily sunrise and sunset times were obtained for The Dulles, Oregon (approximate geographical center of the data collection region). For 2012, the date ranges for each season are as follows: winter, Dec. 21-Mar. 19; spring, Mar. 20-Jun. 19; summer, Jun. 20-Sept. 21; fall, Sept. 22-Dec. 20. Length of activity under solar darkness is reported as hour ± fraction of an hour (decimal).

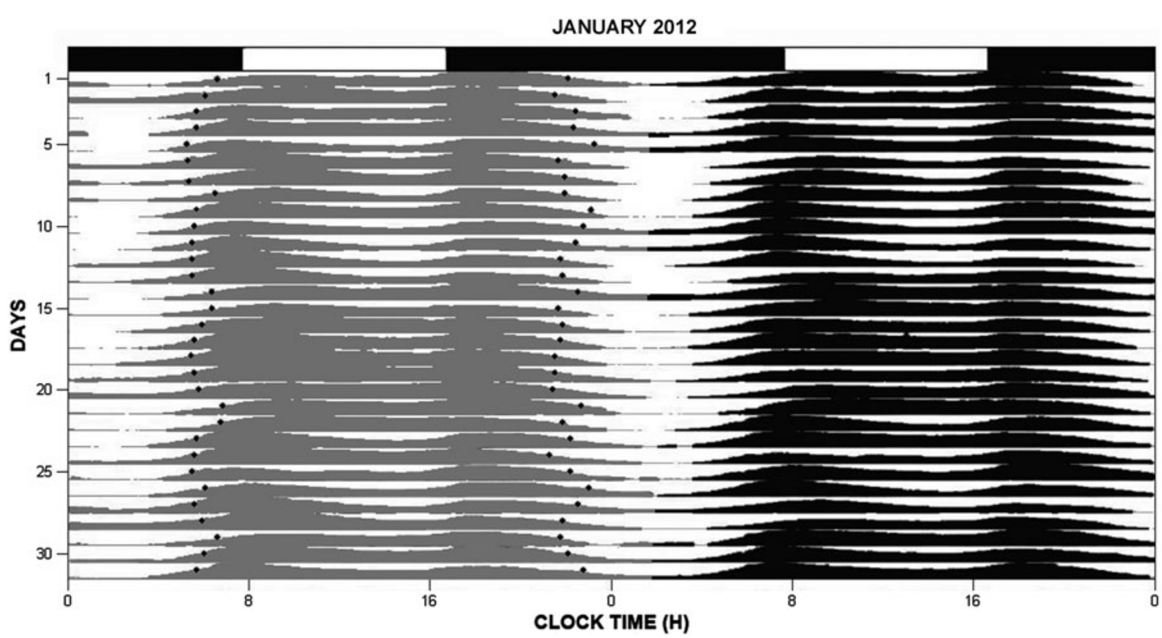

FIGURE 1. Double plotted actogram illustrating electrical load for the month of January. Dots indicate calculated time of activity onset (left) and offset (right). Coloration on the left was changed to grey to increase visibility of the points. Dark bars on top represent the average solar dark period for the month of January.

Shifts between standard and daylight saving time

To determine the effects of daylight saving time changes, data from 2007–2014 was analyzed. For each year, the onset time for the Sunday before, the Sunday of, and the Monday immediately following the clock change in both spring and fall were used.

Statistics

All analysis was performed using Sigma Plot (v12.0, SYSTAT Software, Chicago, IL). One-way or Two-way analysis of variance (ANOVA) was used for all statistical assessment. Significant differences were assessed utilizing Student Newman–Keuls *post hoc* testing. All statistics are reported as a mean ± S.E.M. In all cases, level of significance was set at $p < 0.05$.

RESULTS

Length of the daily activity period (alpha) varies seasonally and by week day

Two-way analysis of variance reveals that there is are main effects of day of week, with alpha being approximately 1 hour longer on week days than on the weekends (16.71 ± 0.04 h versus 15.72 ± 0.06 h, respectively; $F_{1,388} = 186.52$; $p < 0.01$; Figure 2) as well as season, with alpha being longest in the spring and shortest in the summer (16.64 ± 0.07 versus 15.98 ± 0.07 respectively; $F_{3,388} = 16.07$; $p < 0.01$). Additionally, there is an interaction between day of the week and season ($F_{3,388} = 3.28$; $p = 0.02$). Notice the relatively constant weekday alpha compared to the high variability of weekend alpha.

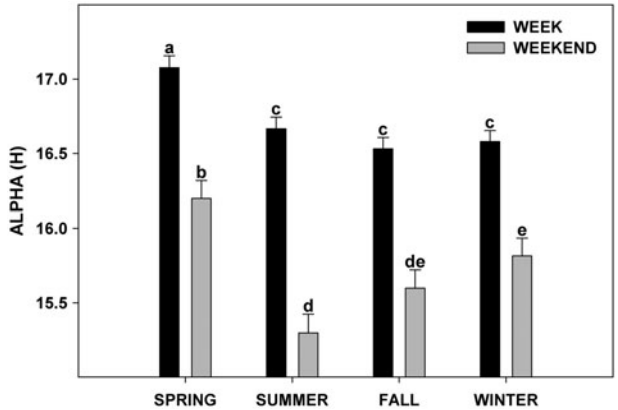

FIGURE 2. Bar graph illustrating seasonal variation in alpha for week- and weekend- days. Bars represent mean weekday or weekend values ± S.E.M.

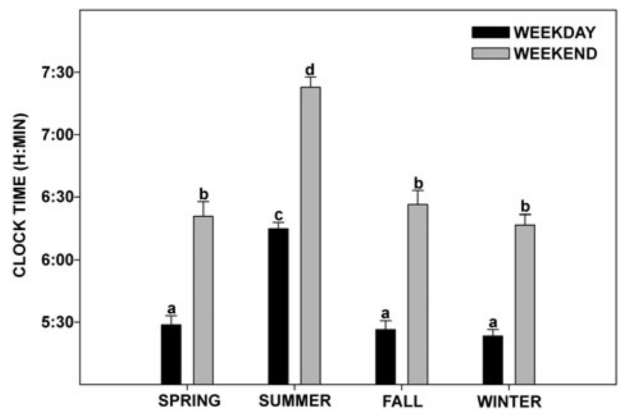

FIGURE 3. Bar graph illustrating seasonal variation in activity onset time for week- and weekend- days. Bars represent mean weekday or weekend values ± S.E.M. Letters represent significant differences between means.

Daily onsets and offsets of activity on weekdays versus weekends

As with alpha, activity onset varies based on day of week, with an approximately 1 h delay in onset times on the weekend compared to weekdays (6:52 ± 3 min versus 5:54 ± 2 min respectively; $F_{1,363} = 271.41$; $p < 0.01$). There is also a main effect of season, with approximately 1 h delayed onset times in the summer compared with the winter (7:01 ± 2 min versus 6:04 ± 2 min respectively; $F_{3,363} = 76.41$; $p < 0.01$; Figure 3). With regard to onset time, there is also an interaction between day of week and season ($F_{3,363} = 3.80$; $p = 0.01$). There is no difference in activity offset between weekdays and weekends (22:39 ± 2 min versus 22:34 ± 3 min, respectively; $F_{1,360} = 2.034$; $p = 0.155$), but there is seasonal variation in activity offset time such that offset time is latest in the summer and earliest in the winter (23:06 ± 3 min versus 22:19 ± 3 min, respectively; $F_{3,360} = 51.31$; $p < 0.01$). There is no interaction between day of week and season ($F_{3,360} = 0.64$; $p = 0.59$).

Analysis of activity under solar darkness

Shortening of day length during the winter months results in more time spent active in the dark under artificial lighting with the greatest amount of activity under solar darkness occurring in December, after which it begins to decline until July (7.42 ± 0.09 h versus 1.07 ± 0.18 h, respectively; $F_{12,393} = 224.02$; $p < 0.01$; Figure 4).

Phase disruption due to transition from standard to daylight saving time

Analysis of the Sunday one week prior to, the Sunday of, and the Monday after transition from Standard Time (ST) to Daylight Saving Time (DST) in the spring revealed no significant difference in onset time between the Sunday before and the Sunday of DST (6.07 ± 0.17 versus 5.94 ± 0.17 respectively; $F_{5,44} = 29.61$; $p = 0.54$), such that the full brunt of the spring circadian disruption is manifest on the Monday, rather than the Sunday, following the DST advance shift (5.94 ± 0.17 versus 4.86 ± 0.05 respectively; $F_{5,44} = 29.61$; $p < 0.01$; Figure 5). Analysis of variance reveals that the magnitude of this effect it twice as great as the normal Sunday/Monday advance as measured during the weekend prior to DST (1.04 ± 0.14 h versus 0.48 ± 0.16 h respectively;

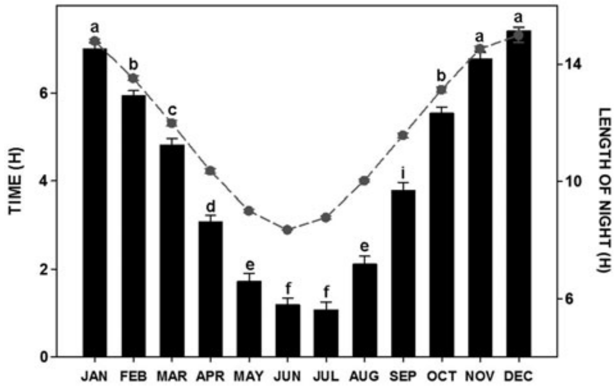

FIGURE 4. Bar graph illustrating average monthly variation in the duration of active phase (h) spent under darkness(left axis) and dots indicating the average night length for that month (right axis). Bars represent the average monthly activity period taking place under solar darkness ± S.E.M. Letters represent significant differences between means.

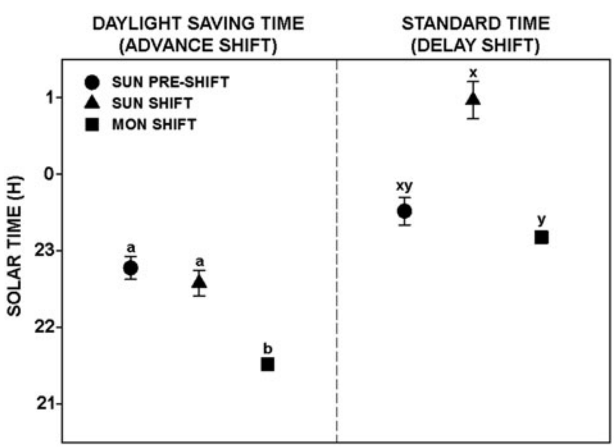

FIGURE 5. Scatter plot illustrating phase shift in onset times caused by transition from Standard to Daylight Saving Time. Points are plotted in solar time (ST) which divides the day up into hours based on the movement of the sun regardless of clock time, with sunrise as ST 0. Different letters indicate significant differences between either ST to DST (left) or DST to ST (right).

$F_{1,15} = 8.22$; $p = 0.01$). There is no significant phase shift between the Sunday and Monday associated with the delay induced by transition from DST to ST (7.32 ± 0.24 versus 6.52 ± 0.04 respectively; $F_{5,44} = 29.61$; $p = 0.16$).

DISCUSSION

The circadian regulation of endocrine, body temperature, and sleep/activity rhythms is critical for health and well-being (Kalsbeek et al., 1996; Khan-Hudson & Alessi, 2008; Mormont et al., 2000). While such knowledge is based primarily on research conducted at the individual level under controlled settings (Aschoff, 1965; Aschoff et al., 1967; Lewis et al., 1956; Lewis & Lobban, 1957; Mills et al., 1974; Orth et al., 1967; Rose et al., 1972), it is notable that very little is known about how these rhythms are expressed under normal life conditions within the general population. With the advent of large internet databases, it is now feasible to access downloadable data (ex. traffic patterns and electricity consumption) reflective of human circadian activity at the population level. In the present study, we utilized real-time residential electrical load (consumption) as an indicator of human household operative activity, and statistically analyzed it for circadian and circannual changes in onset and offset times, as well as alpha. This approach offers the advantages of being non-invasive, cost effective, and representative of large human populations. The salient features of our analysis are that: (1) alpha is longer during the spring than the summer and that significantly more activity occurs in the solar dark phase during the winter than during the summer; (2) there is a marked ''weekend effect'' where morning arousal occurs later than during the work week, and (3) a shift in activity onset time occurs on the Monday, rather than the Sunday of, the 1 h transition to Day Light Saving Time, but not during the transition back to Standard Time, owing to the ''weekend effect''. Such information has important implications for understanding the nature of human societal circadian patterns, and possibly, circadian disruptions contributing to disease and mortality.

Validation of selection criteria

The use of the sum of the daily minimum and 50% of the difference between the maximum morning peak or evening peak and minimum load each day was selected because these criteria reliably put onset and offset times during periods of power consumption that was rising from or returning to (respectively) baseline electrical consumption. Using this model, we calculated human alpha to be a yearly average of (16.4 h). Previously, the alpha of small human populations has been measured using wrist actimetry, in elderly participants (15.6 h; Evans & Rogers, 1994; wrist actimetry is reportedly not an accurate sleep/wake indicator compared with polysomnographic and EEG measurement; Pollack et al., 2001), polysomnographic analysis in healthy adults (15.8 h; Pollack et al., 2001), and EEG in healthy adults both on weekdays and on weekends (16.5 h and 15.5 h respectively; Carskadon & Dement, 2011). This is in line with the values generated by the present analysis.

Intra-week and seasonal variations in alpha

There is a pronounced, (~1 h) delay in activity onset observable on weekend days compared to week days (''weekend effect''), with a corresponding shortening of alpha. This is consistent with previous reports which indicate that maintenance of a socially entrained activity rhythm results in a ''social jetlag'' sleep debt that needs to be made up for on non-work days (Crowley & Carskadon, 2010; Roenneberg et al., 2003; Roepke & Duffy, 2010; Wittmann et al 2006; Yang et al., 2001). However, while previous work centered on small subpopulations such as adolescents (Crowley & Carskadon, 2010) or evening chronotypes (Roepke & Duffy, 2010), the present results indicate that the occurrence of sleep debt accrued through the week seems to be a general finding for the population as a whole.

In addition to the ''weekend effect'', there is also a marked seasonal variation in alpha caused by delayed onset times for weekend days at the study latitude. Surprisingly, alpha is longest during the spring months and shortest during the summer months under long solar days, indicating that day length is not the only modulator of human activity rhythms. One possible explanation is that this seasonal change is due to the altered power consumption because of heating/cooling requirements reflective of fluctuations in ambient temperature. This is not supported by correlational analysis, which indicates that alpha is poorly predicted by changes in temperature ($R^2 < 0.01$; $p = 0.54$; data not shown). Another explanation is that there is a circannual rhythm in human activity patterns, such as has been observed for plasma hormones (Nicolau et al., 1984; Reinburg et al., 1978) and male reproductive physiology and behavior (Abbaticchio et al., 1987; Tjoa et al., 1982; Reinburg et al., 1978). Further investigation will be required to elucidate the mechanism which drives this rhythmic pattern.

Also related to seasonality are significant changes in the proportion of the active phase spent under solar light and darkness. In the Northwestern United States, day length varies seasonally by 7 h, and the present analysis indicates that average weekly activity onset times are relatively stable throughout the year such that during the winter months, a larger portion of human activity takes place under artificial lighting during the dark phase of the solar day than during the summer. It has already been shown that circadian-related disorders such as seasonal affective disorder (SAD) are affected by day length changes caused by differences in latitude (Kegel et al., 2009; Rosen et al., 1990; Sourander et al., 1999). Future studies may be able to correlate solar dark phase activity with incidence of affective disorders regionally utilizing electrical consumption. This could provide key insights into the circadian adaptation of our physiological and behavioral rhythms as a function of season.

Phase disruption caused by shift to daylight saving time

The present results show an approximate 1 h advance from the Sunday of Daylight Saving Time to the proceeding Monday, a shift not seen in the transition from Standard Time to Daylight Saving Time, indicating a more abrupt transition during the advance than the delay. This phenomenon, theoretically exacerbating the stress of starting the work week, is consistent with studies which have shown that the incidence of mortality due to heart attack is significantly increased on the Monday following the shift to Daylight Saving Time. Conversely, this effect is reduced by nearly as much during the switch from Daylight Saving Time back to Standard Time (Janszky & Ljung, 2008; Janszky et al., 2012; Sandhu et al., 2014; Tonetti et al., 2013) and is also consistent with our finding that there is no significant shift from the Sunday before versus the Monday of this transition. This is due principally to the cancellation of the delay associated with the shift back to Standard Time by the regular weekly advance from Sunday to Monday (''weekend effect''). Future studies could focus on correlating reported cardiac incidence with power grid data from different regions to provide further evidence of a relationship between the daylight saving shift and increased cardiac mortality.

Caveats of power grid analyses

Power grid load is a potentially useful tool for analyzing circadian rhythmicity in large human populations, but there are a number of possible confounds that should be considered. Power consumption from industrial usage, as well as other non-residential sources such as hospitals and schools do not reflect operant human activity per se, and as such could skew analyses. The present data set is primarily from a region which is demographically residential (large cities in the sample region are not included in the BPA data stream), and is largely devoid of industrial influences. Another potential limitation comes from seasonal changes in ambient temperature in the area being sampled. While electrical heating during cold months is uncommon due to the prevalence of natural gas, heating as well as the use of air conditioning could potentially increase electrical load. As discussed above, for the present data, correlational analysis indicated that changes in alpha were not significantly correlated with changes in temperature. In addition, this method of analysis cannot take into account environmental factors that influence automated power consumption, such as street lighting, which consume power in a circadian-like pattern as well as displaying seasonal variation due to changes in day length. However, as the U.S. Energy Information Administration estimates that only about 14–17% of total power consumption is utilized for lighting (Annual Energy Outlook 2013), the impact of such non-human factors could be regarded as minimal. Additionally, it is not possible to use this analysis to isolate ''at risk'' subpopulations, such as shift workers. Hence, the potential value in the large-scale studies of human population activity levels merits further investigation.

CONCLUSIONS

The present study is the first to utilize electrical power grid load data as a measure of human activity rhythms. Using this analysis it is possible to discern seasonal and intra-week variations in activity duration and timing, as well as the shift in activity which accompanies Daylight Saving Time adjustment. This methodology is ideal for the study of human populations because it's freely available on the internet, its collection is non-invasive, it allows the study of discrete populations in different geographic regions permitting the analysis of large human populations (in this case ~43 million power users) in their ''natural'' settings.

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DECLARATION OF INTEREST

The authors report no conflicts of interest. This work was previously presented at the 2014 Society for Research on Biological Rhythms meeting (P17).

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