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MidnightSun: Software for Determining Light Exposure and Phase-Shifting Schedules During Global Travel

THOMAS A. HOUPT,*†[1] ZIAD BOULOS† AND MARTIN C. MOORE-EDE†

**E. W. Bourne Behavioral Research Laboratory, Department of Psychiatry, Cornell University Medical College, White Plains, NY 10605 USA and †Institute for Circadian Physiology, One Alewife Center, Cambridge, MA 02140 USA*

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HOUPT, T. A., Z. BOULOS AND M. C. MOORE-EDE. *MidnightSun: Software for determining light exposure and phase-shifting schedules during global travel.* PHYSIOL BEHAV **59**(3) 561–568, 1996.—The application of circadian principles has the potential to alleviate jet-lag in global travelers, but their application is hampered by the difficulty of determining light exposure along international flight routes. Computerized tools can solve this problem algorithmically. We have developed a program for Macintosh computers, called MidnightSun, which allows researchers to display ambient lighting conditions at any geographical location at any time of the year. The program contains a data base with the latitudes and longitudes of over 3000 airports. It calculates flight paths and durations, and prints a graphical itinerary indicating times of daylight during flights and layovers. Given a travel itinerary and a user-defined phase response curve (PRC) for light, it recommends light exposure times that may accelerate the reentrainment of circadian rhythms to new time zones and reduce the deleterious effects of jet-lag (depending on the efficacy of the PRC and the compliance of the traveler). Other potential applications include determining lighting protocols for photoperiodism experiments and providing data sets for mathematical circadian simulations under naturalistic lighting conditions.

Circadian rhythms Phase response curve Jet-lag Simulation Solar radiation Daylight

MODERN jet travel allows humans to overtake the sun in its daily course, but rapid translocation of people across multiple time zones has also allowed travelers to outrun the entrainment capacity of their biological clocks. Over 250 million international passenger flights were taken in 1990; a large number of those flights involved rapid crossing of time zones (24). Eastward and westward travel advances and delays, respectively, the natural solar photoperiod to which it is normally entrained. Because the translocation occurs more rapidly than their clock can resynchronize to the new day–night cycle, travelers experience jet-lag, a syndrome that includes sleep disturbances, daytime sleepiness and decreased alertness, gastrointestinal distress, and other psychosomatic symptoms (7,29,51). At best, the jet-lag syndrome constitutes an inconvenience; for flight crews and other persons in sensitive and demanding situations, however, jet-lag can pose a more serious threat.

Our increasing understanding of the neural basis of circadian rhythmicity and of the mechanisms of circadian entrainment by light suggests possible remedies for jet-lag. The mammalian circadian pacemaker, localized in the hypothalamic suprachiasmatic nucleus, receives monosynaptic input from the retina; in nocturnal rodents the clock has been shown to be highly sensitive to ambient light, as even brief pulses of low-intensity light can elicit large phase-shifts of their free-running rhythms (12,35). Characteristic phase response curves for light have been established for many different organisms, both nocturnal and diurnal; in all cases, light pulses administered early in the organism's subjective night phase delay the clock, whereas pulses administered in late subjective night advance the clock (26). In recent years, the human circadian clock has also been shifted with light, but at intensities and durations several orders of magnitude greater than those sufficient to phase shift nocturnal rodents

Copies of the compiled program and documentation are available to academic researchers upon request.

[1] Requests for reprints should be addressed to Dr. Thomas A. Houpt, E. W. Bourne Behavioral Research Laboratory, New York Hospital–Cornell Medical Center, 21 Bloomingdale Rd., White Plains, NY 10605 USA.

(5,9,10,14,21,34). Several nonphotic stimuli, including pharmacological agents [e.g., melatonin (1,30,42)] and locomotor activity [e.g., induced by benzodiazepines in rodents (49)] can also reset the clock.

Thus, it is now possible to contemplate ameliorating jet-lag using scheduled exposure to light or other phase-resetting agents. However, several variables of trans-meridian travel complicate the prescription. First, the individual's course between random origins and destinations must be tracked across the globe. Secondly, the daily photoperiod experienced by the individual along the route must be calculated, to characterize the abrupt phase shift of the entrainment signal. Finally, a light exposure schedule must be developed, indicating the times at which light will optimally shift the circadian clock towards synchrony with the new time-zone and, conversely, when light exposure would be detrimental, desynchronizing the clock even more.

Circadian researchers must coordinate these complex variables to routinely apply phase-shifting treatments for jet-lag. Computer simulation allows the rapid integration of the solar and geographical factors with the predicted biological (circadian) response. To this end, we have developed an Apple Macintosh computer program called MidnightSun—the name reflecting the disorienting appearance of the midday sun when the traveler's circadian phase is still mid-subjective night. MidnightSun allows the user to input a travel itinerary between international airports. It then calculates and displays natural light exposure along the route and indicates optimal times for light exposure that may tend to resynchronize the traveler's clock to the destination's local time.

SIMULATION FACTORS

The factors involved in simulating the effects of solar radiation on biological systems are outlined in Fig. 1. There are three broad categories that the ideal simulation should address. First, there are the astrophysical variables. The characteristics of the sun's electromagnetic spectrum outside the earth's atmosphere must be determined. The direct exposure of an earth-bound organism to sunlight is further determined by the geometrical relation of the earth to the sun during the course of its orbit, and by the organism's precise location on the globe. The astronomical equations describing the earth's rotation and orbit around the sun have been known for centuries (15,45); direct, extraterrestrial measurements of the sun's radiation by satellite and space probe are also readily available (20,39).

Secondly, the solar radiation is filtered by the organism's local environment, and altered by the reflectivity of surroundings. Variables such as cloud cover, humidity, aerosol content, turbidity, temperature, etc., affect the transmission characteristics of the atmosphere (31). The immediate habitat can also radically alter ambient illumination. For example, snow cover can increase illumination levels by 200% (41). Differences can also exist in both spectral distribution and intensity of light present in rural vs. urban areas, with filtering by tree cover and reflection by man-made buildings (13,32). Aquatic organisms, of course, perceive light that has been additionally filtered by the surrounding water (32).

Finally, the biological characteristics of the organism determine the pattern of light exposure, the transduction of the light input, and the organism's response. An animal's behavior, such as circadian rhythms of activity, foraging, or exploration, represents an adaptation to a temporal niche that can limit photic exposure to specific, self-selected times of day, night or twilight (48). Hibernation can also limit exposure to certain seasons, whereas migration might change an animal's geographic position and greatly expand the range of lighting regimes to which it is exposed (18).

The transduction of light input usually requires light transmission first through filtering tissue layers, such as the lens of the eye (23), cranial bone, skin, and feathers overlying the pineal gland of lower vertebrates (33), or even, in the case of the fetus,

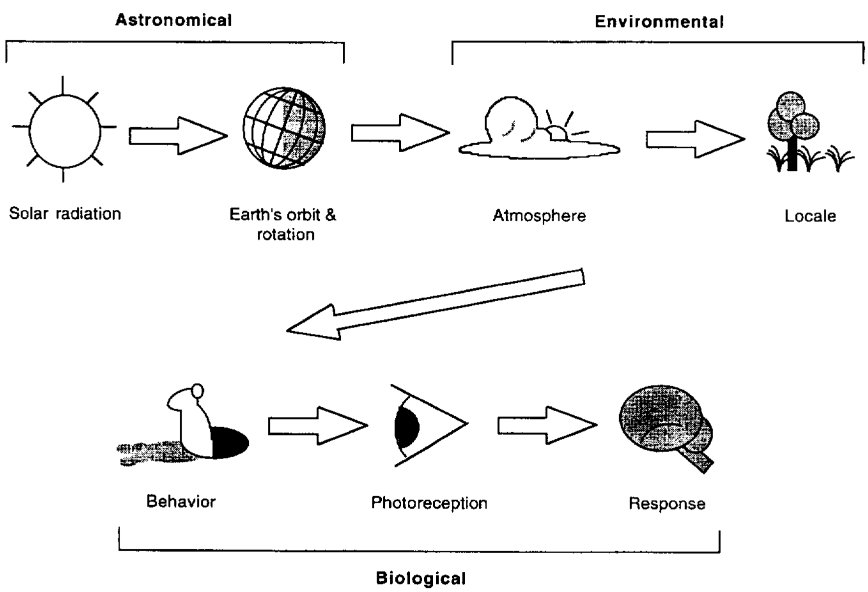

FIG. 1. The astronomical, environmental, and biological components of the ideal solar illumination and circadian simulation. Solar illumination is calculated from the extraterrestrial spectrum of the sun as seen at specific points and times on earth. The sun's intensity and spectral characteristics are modified by local environmental and atmospheric conditions. The biological response of an organism can then be modeled based on the animal's behavior, photic sensitivity, and circadian system. MidnightSun applies a subset of these components to predict and recommend light exposure during intercontinental jet travel.

the skin and uterus of the mother (50). The sensitivity of biological systems to light also depends on the response characteristics of its photoreceptors. The frequency and amplitude response of mammalian retinal photoreceptors, for example, differ between species, and can alternate between scotopic and photopic responses under low and high illumination levels, respectively (23). In the case of circadian rhythms, the greater sensitivity to blue-green light of retinal ganglion cells projecting to the SCN is responsible for the greater sensitivity of the circadian system to those light frequencies (46). The photoreceptive organs may themselves exhibit circadian rhythms of light sensitivity which further modulate the input to the central pacemaker (10,38).

Ultimately, having simulated the transmission and filtering of solar radiation from the sun to the output of photoreceptive mechanisms, a computer program must also be capable of modeling the biological response of the system. The mammalian circadian system's response to light exposure has been well characterized both empirically and mathematically in many species (26), and work has begun in humans (9,22,25,34).

MidnightSun does not attempt to model every one of the many variables described above. Rather, it provides some of the components necessary for more complex simulations, and can serve as a useful tool for circadian researchers interested in natural photoperiods, light PRCs, and jet-lag. MidnightSun can calculate the light exposure of any point on earth at any time and day of the year. The program can also predict the patterns of natural light exposure encountered by travelers along international flight routes. Finally, MidnightSun employs a simple PRC model of the circadian system to predict when exposure to high illumination levels would shift the endogenous pacemaker's phase in the appropriate direction for accelerating reentrainment to new local times.

PROGRAM DESCRIPTION

MidnightSun was written for the Apple Macintosh; the source files consist of over 500 kilobytes of C code. The majority of this code supports the user interface, which is highly interactive and graphical. The main window in MidnightSun is a rectangular projection map of the world. In addition to displaying the world at different scales, the world map window also indicates the geographical position of the mouse as it moves across the world, the nearest major airport, the current shape and position of the night's shadow, and the local times of major cities around the world displayed as a row of clocks.

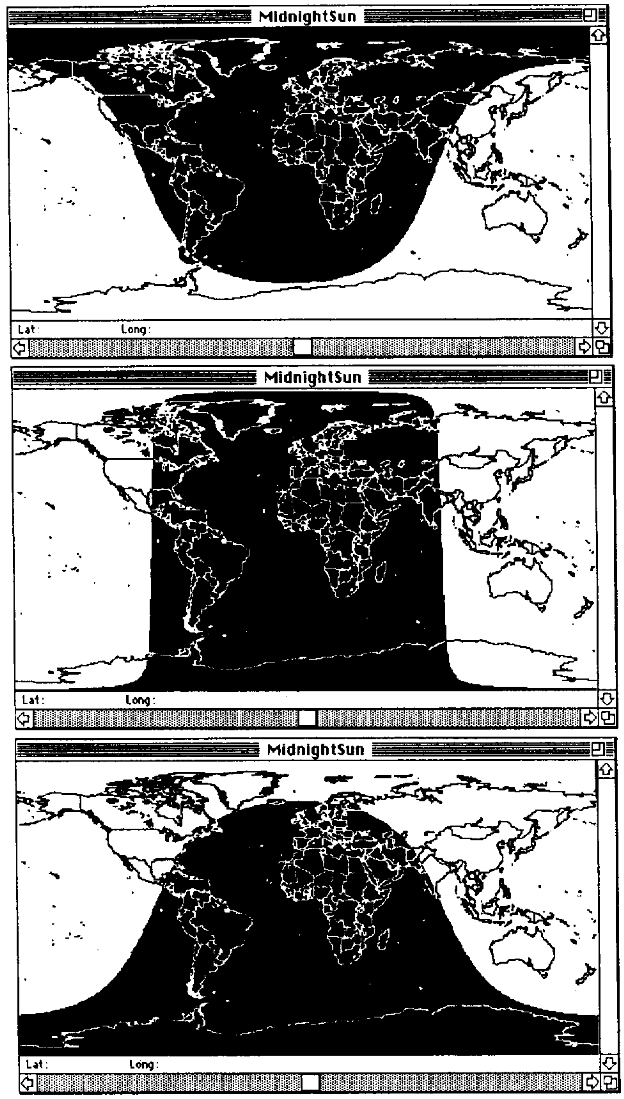

FIG. 2. The main window of MidnightSun is a rectangular projection map of the world, displaying the current shadow of the night, shown here at 7 pm E.S.T. at different times of year. Top: night at the winter solstice, with 24-h night at the north pole and 24-h light at the south pole. Middle: just after the spring equinox, when day and night are of equal length at every latitude. Bottom: night at the summer solstice, with midnight sun conditions now at the north pole.

Photoperiod and Illuminance

The shadow of night as it appears at the current local time (determined from the Macintosh's internal clock/calendar and the user-specified geographic location) can be overlaid on the world map; its position is updated every 4 min (approximately 1° of longitudinal rotation), so that it moves across the globe over the course of the day. The shadow's projection in two dimensions is a sinusoidal curve, whose shape varies over the seasons (Fig. 2). MidnightSun can also display a rotating spherical projection (as if the globe was viewed from space), to show the relative rocking of the shadow across the poles throughout the year.

In addition to displaying the shadow on the world map, the program can calculate solar variables at any given location. The times of sunrise, sunset, and the associated twilights, obtained from standard astronomical equations (15,45), are displayed graphically along axes showing local time of the distant location relative to local time (Fig. 3). Using National Bureau of Standards equations for architecture daylighting models (16), horizontal illuminance is calculated as a function of the sun's position above the horizon, at 5-min intervals across the day. These equations also allow some specification of environmental factors, such as whether the observer is in a rural or urban setting, the degree of cloud cover, and the humidity (13,16).

Both photoperiod characteristics and illuminance level can be calculated over a range of days and plotted in actogram format. The seasonal changes in photoperiod that occur at different latitudes can then be visualized (Fig. 4).

Although MidnightSun currently only determines the sun's visibility and illuminance, numerous solar variables (e.g., solar intensity, spectrum, below the horizon illuminance, filtering by vegetation or water, etc.) have been modeled by others, either by deriving equations from first principles of light-scattering and absorption by the atmosphere or by fitting parameters to empirical data. These models could easily be implemented as extensions to MidnightSun, taking advantage of the current program's ability to specify geographic, temporal, and environmental factors.

Travel Itinerary

Travel itineraries can be entered either textually (by typing in the times and endpoints of flights) or graphically with the mouse. In the latter case, the user clicks on the point of origin of the flight, and drags the mouse to its destination. Visual feedback is provided by the mouse cursor, which alters its appearance from the standard arrow cursor to an airplane icon. Upon releasing the mouse button, the specified travel stage is entered into the itinerary, and the great circle flight path is drawn on the world map (4). Alternatively, the flight itinerary can be entered explicitly into a spreadsheet-like window using the keyboard.

MidnightSun contains a data base of over 3000 airports (out of approximately 4000 airports that have been assigned codes by the Civil Aviation Organization), describing their names, geographic location, time zones, and three-letter airport codes (36). The airports are grouped in a hierarchical structure of continental regions, nations or islands, and national time zones. Destinations can be entered either by full name, by three-letter code, or by clicking the mouse near the airport on the world map. User input is rapidly matched to a specific database entry using Newton's method, or via a two-dimensional hash table in the case of mouse clicks. For completeness, the program also has a data base of over 600 airline names, which can be specified by standard two-letter codes (36).

Once the user has entered an itinerary, the program internally converts the local times of flight arrival and departure to standard universal time (and notifies the user of any contradictions in timing, e.g., arrivals at the destination before departures from the point of origin). The itinerary is divided into outbound and return legs, requiring at least 48 h of layover time between the two (flights separated by shorter intervals are considered to be different stages of the same leg). The program then iterates along the great-circle flight paths, calculating the ambient solar illumination as observed from the plane [i.e., day (sun above the horizon)], twilight, or night (when the sun is more than 6° below the horizon).

The resulting light schedules are plotted in actogram format within separate windows for each leg of an itinerary (Fig. 5). Time bars indicating origin and destination local times are drawn at the top and bottom of the schedule, respectively, and the times of departure and arrival are graphically indicated.

Light Exposure Schedule

The program overlays a suggested schedule of light exposure for the traveler on the schedule of natural ambient illumination. Using a simple PRC model the program indicates the two periods when the circadian pacemaker is sensitive to high levels of ambient light (i.e., the advance and delay portions of the PRC). Based on the change in local time between the passenger's origin and destination, MidnightSun indicates with pluses ("+") either the advance or the delay portion as advantageous for circadian reentrainment (depending on the direction of travel) and indicates with minus signs ("−") as undesirable the opposite portion of the PRC.

MidnightSun uses a generic light PRC similar to those described for many organisms (26), and assigns default values to the various parameters of that PRC. These values, however, can be modified graphically by the user, by clicking on and dragging on the beginning, peaks, and transition points of the advance and delay portions of the curve (Fig. 6). The magnitude of the phase shifts induced by light exposure is probably a function of the duration of light exposure and the intensity of the light. The intensity of the light cannot be specified explicitly, but the magnitude of the phase shifts induced by the light treatment can be specified by dragging on the peaks of the PRC. The default PRC assumes exposure to very bright light (e.g., greater than 2000 l0x) at the recommended times.

The default PRC is divided into a 6-h delay region, a 6-h advance region, and a 12-h unresponsive region or dead zone, all positioned relative to a standard circadian phase marker. The default phase marker is habitual wake-up time, which the user enters along with his or her flight schedule in the itinerary

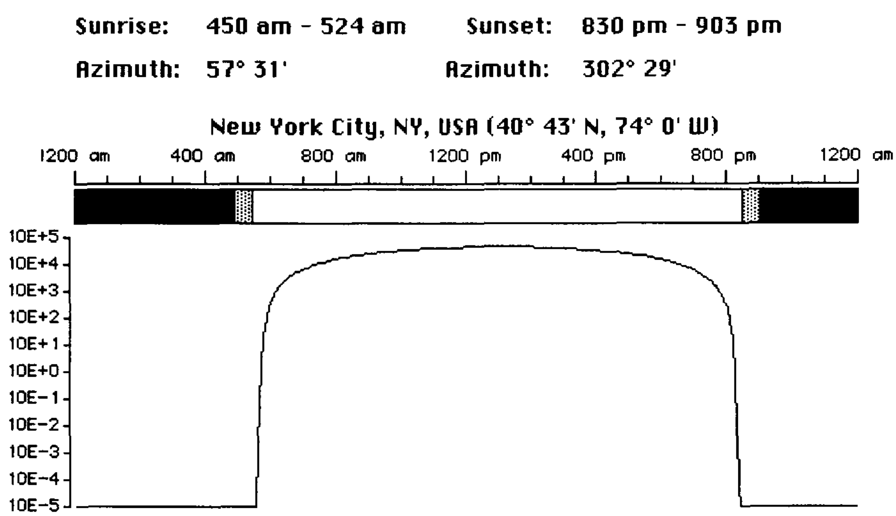

FIG. 3. The MidnightSun program can calculate the times of sunrise and sunset and illuminance for any day and any spot on earth. Shown here is the sun's times of rising and setting (with the start and ends of twilight, defined as the sun being less than 6° below the horizon) and its azimuths for New York City near the summer solstice. The day and night are represented graphically by a light bar (gray = twilight, white = daytime, black = night time). The above the horizon ambient illuminance is calculated at 1-min intervals from the sun's position on a log lux scale.

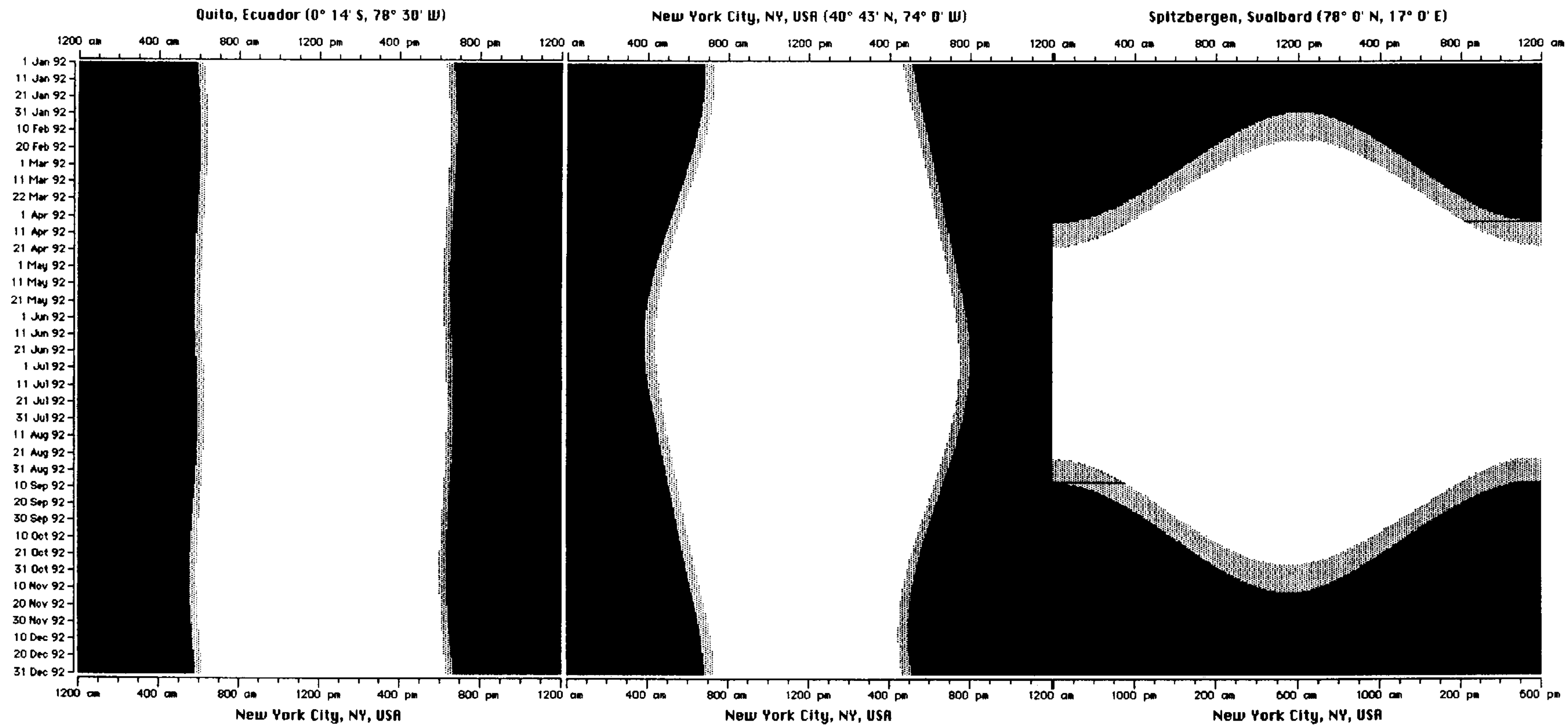

FIG. 4. The seasonal variation in photoperiod and times of sunrise and sunset are shown with light bars in actogram format. Left: annual photoperiod variation near the equator. Middle: annual photoperiods at New York City (40° N). Right: an extreme of photoperiodic variation within the Arctic Circle (Spitzbergen, 78° N).

window. In empirically derived PRCs for light in human subjects, the transition between the delay and advance regions coincides with the time of the daily minimum of the body temperature rhythm, which occurs about 2–3 h before habitual wake-up time (10,34). By default, the transition point is assumed to fall 3 h before normal wake-up time, but this value can be changed by dragging the transition point on the time axis of the graphical PRC. The durations of the advance, delay, and unresponsive regions can be altered in similar fashion. The program is flexible enough to allow users to specify circadian phase markers other than habitual wake-up time, for example, daily temperature minima or melatonin secretion onset.

If the shift in time zones is greater than 3 h, the program suggests two cycles of light exposure, starting on the day of the flight (the program was initially written to facilitate the scheduling of bright-light exposure for travelers equipped with portable, battery-operated light visors that could be used aboard the aircraft during the flight). For the second cycle, the PRC is assumed to have shifted by 3 h and the light exposure schedule is therefore offset by the same interval. This figure takes into consideration "normal" reentrainment rates, as well as the additional phase shift assumed to result from light exposure during the first cycle.

Actual reentrainment rates following transmeridian travel are just under 1 h/day after eastward flights and about 1.5 h/day after westward flights (2,29). These rates, however, are average values across the entire readjustment period; in general, reentrainment is fastest immediately after the shift, and slows down progressively thereafter (2,29).

Estimating the size of the phase shift induced by light exposure during the first cycle is equally problematic [see (3) for a recent review]. Only a few preliminary field studies of the effects of bright light on jet-lag have been published, all of which involved three or more cycles of light exposure (6,8,11,43). Human PRCs for single 3-h pulses of bright light show phase

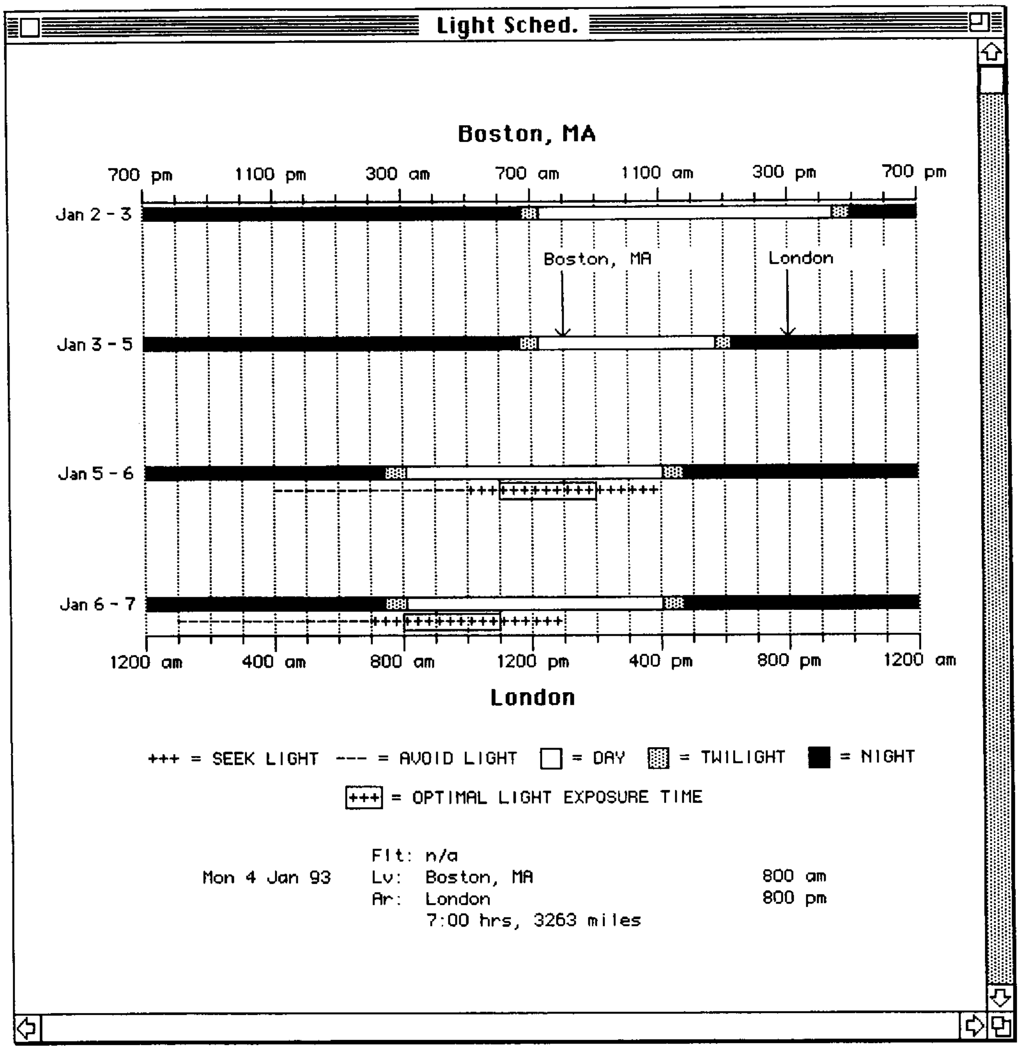

FIG. 5. After entry of a travel itinerary, MidnightSun generates a light schedule. Successive light bars in actogram format display the ambient light before, during, and after the flight. Shown here is a flight from Boston to London. Departure and arrival are marked with arrows. Note the shortened photoperiod on the day of the eastward flight, and the 5-h phase advance in the day–night cycle. +, optimal times for light exposure; −, times when light exposure would aggravate jet-lag.

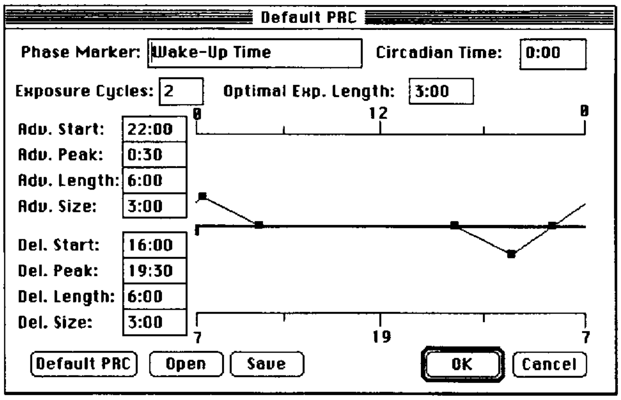

FIG. 6. MidnightSun's default PRC can be edited graphically by clicking and moving the vertices of its advance or delay portions. Other parameters, such as the circadian time of the marker used to determine the traveler's circadian phase and the number of exposures, can also be specified.

shifts in the order of ± 2 h, phase advances being somewhat larger and more consistently obtained than phase delays (22,34). Thus, a 3-h phase shift between the first and second light exposure cycles seems a reasonable, if somewhat arbitrary, assumption for both eastward and westward travel. The size of that phase shift, however, can be changed, and can be set independently for eastward and westward flights, by changing the maximum advances and/or delays on the graphical PRC.

The MidnightSun program recommends applying light exposure based on a strict interpretation of the PRC. Therefore, it often recommends light exposure in the middle of the traveler's subject night or at other inconvenient times, such as during flight. This raises the issues of the traveler's compliance to the suggested light exposure regimen and the practicality of providing very bright light at arbitrary times of treatment. These issues are of particular concern in the treatment of jet-lag and other circadian disorders when the effects of light exposure are critically dependent on the phase of treatment. For example, if a traveler missed one cycle of light exposure, a subsequent bright light exposure might have unpredictable or detrimental effects. The resolution of these real-world issues requires more research into the refinement of circadian treatment strategies.

APPLICATIONS

MidnightSun provides a framework and a foundation for the application of circadian principles to alleviate jet-lag. It combines a geographic data base with a model of solar light exposure, and allows the user to specify times, locations, and long-distance flights, while keeping track of time zones and daylight savings time. By providing a convenient user interface, the program relieves the investigator of tedious astronomical and time-zone calculations. The current version also supports a simple PRC model for suggesting times when exposure to bright light might accelerate the reentrainment of circadian rhythms to new time zones.

The simulation has two basic components: the first provides a model of light intensity and exposure based on geography, season, and flight itineraries, whereas the second applies a model of circadian phase shifting and entrainment by light. The light-modeling component can provide the input for laboratory studies of the circadian effects of naturalistic photoperiods. For example, Terman et al. have developed novel algorithms for simulating light intensity occurring during dawn and dusk twilights (47); these transitional times can make up the bulk of the light exposure of nocturnal fossorial species (48).

The program can also be used for simulating the extreme seasonal variations in photoperiod and light intensity found at high latitudes. Circadian rhythms have been studied under such conditions in several vertebrate species (19), including humans (17,27,28). Another possible application would be to provide seasonally varied light input for studies of seasonal affective disorder, which is linked to the reduction in daylight hours in winter (40). Finally, MidnightSun can replicate the changes in photoperiod encountered by migratory species in the course of their long-distance travels (18).

The model of circadian phase shifting and entrainment included in the program was developed primarily for predicting the responses of the human circadian system to bright-light exposure. The program can also generate reentrainment paradigms for phase-shifting agents other than light. Melatonin administration, for example, can also phase shift human circadian rhythms in a phase-dependent manner (30), and its effects on jet-lag have been tested in several studies (1,37).

Future versions might be enhanced with more sophisticated models of the circadian system, for purposes of both simulation and application. The repetitive light pulse paradigm implemented by MidnightSun assumes a classical phase response to light by the human clock. Multiple light exposures, however, may have phase-shifting effects that cannot be explained by a simple PRC model (44). Furthermore, the dual limit-cycle oscillator model of Kronauer et al. predicts that arbitrary phase shifting of the human circadian rhythm can be achieved by reducing the rhythms amplitude to near zero; this prediction has been recently verified empirically (25).

Two caveats in particular need to be stated about the utility of a program such as MidnightSun. First, the recommended light exposure schedule produced by the program is only as good as the PRC defined by the user. The human PRC to light is still being characterized, and future research may reveal more effective strategies than the simple model incorporated into MidnightSun. Second, the treatment of jet-lag and other circadian disorders involves complicated issues of practicality and compliance in administering bright light exposure at precise phases during a traveler's journey.

Although many improvements remain to be implemented, MidnightSun should be a valuable tool for the visualization, simulation, and application of circadian principles to the study and treatment of jet-lag.

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