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The Effects of the Mars Exploration Rovers (MER) Work Schedule Regime on Locomotor Activity Circadian Rhythms, Sleep and Fatigue

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December 2008

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Authors' Note

The research for the Mars Exploration Rovers (MER) mission incorporated into this report was conducted from December 18, 2003, to April 30, 2004. The writing of this NASA publication was completed in July 2006, at which time it was submitted for administrative review and approvals.

Therefore, referenced literature in this report includes only that literature published prior to July 2006.

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Contents

ABSTRACT

This study assessed human adaptation to a Mars sol by evaluating sleep metrics obtained by actigraphy and subjective responses in 22 participants, and circadian rhythmicity in locomotor activity in 9 participants assigned to Mars Exploration Rover (MER) operational work schedules (24.65 hour days) at the Jet Propulsion Laboratory in 2004. During MER operations, increased work shift durations and reduced sleep durations and time in bed were associated with the appearance of pronounced 12-hr (circasemidian) rhythms with reduced activity levels. Sleep duration, workload, and circadian rhythm stability have important implications for adaptability and maintenance of operational performance not only of MER operations personnel but also in space crews exposed to a Mars sol of 24.65 hours during future Mars missions.

INTRODUCTION

This study provided the opportunity to assess human adaptation to a Mars sol by evaluating sleep quality and circadian rhythmicity in locomotor activity data obtained by actigraphy from workers assigned to Mars Exploration Rover (MER) operational work schedules during MER operations at the Jet Propulsion Laboratory (JPL) at Pasadena, California in 2004. Humans normally operate on a 24-hour schedule and exhibit circadian rhythms in many behavioral and physiological factors including sleep/wake cycles, body temperature, activity, alertness, and neurobehavioral performance (Minors & Waterhouse, 1990; Colquhoun, 1971). Previous research has shown that sleep loss or a misalignment of circadian rhythms increases subjective and physiological sleepiness, negative affect, performance errors, adverse health, and accidents (Akerstedt, 1991; Bonnet, 2000). This was important in reference to the demands of the Mars Exploration Rover (MER) Surface Operations mission, which required personnel to perform mission critical tasks on schedules coinciding with a Mars day (24.65 hour), also referred to as a Mars sol. To adjust to a Mars sol, personnel had to start the work day 39 minutes (0.65 hour) later each day for three months (e.g., start work at 09:00 and the next day 09:39). No previous published studies were identified that explored the ability of personnel to shift work schedules 39 minutes daily for an extended period while being exposed to outside Earth-based exogenous cues, such as sunlight and social cues, which exhibit a 24.0 hour periodicity. Actigraphy involves the continuous acquisition of gross motor activity at short time intervals (e.g., 1-min samples) for several weeks, via an accelerometer mounted in a wrist worn watch-like device, and therefore provides the opportunity to evaluate circadian rhythmicity in locomotor activity in an operational environment without intrusive data acquisition procedures. Thus, an actigraphic ambulatory exploratory study was conducted during the first three months of MER operations to investigate the sleep patterns of personnel while delaying their work schedule 39-minutes each day. Results of sleep quality indices (e.g., the average time in bed) for this study were reported as well as case analyses of the circadian rhythm of activity to determine the effect of working a Mars sol on sleep patterns.

The MER operation schedules were coordinated with Mars daylight times since two rovers were reliant on sunlight for both electrical power and navigation. The two rovers were in operation in

Mars time zones approximately 12 hours apart and the first rover (“ Spirit” or MER-A) landed January 4th, 2004 at 4:35 UTC (January 23rd, 20:35 PST) and the second rover (“Opportunity” or MER-B) landed January 25th, 2004 at 5:05 UTC (January 24th, 21:05 PST). Missions were staffed to coincide with “Mars Time” for approximately 90 days for each rover to maximize scientific gain during the nominal mission. Detailed mission timelines were established for tactical operations of the rovers for receiving data, assessing the data, planning and developing a new set of commands for the next Sol (Bass, Wales, & Shalin, 2005; Parke, 2002).

The Fatigue Countermeasures Group at NASA, Ames Research Center (Oyung 2003) and other research groups (Ancoli-Israel, et al., 2003) have shown that locomotor activity data obtained by actigraphy were a useful means of documenting sleep disturbances associated with excessive workload and fatigue in environments without the need for intrusive or invasive sleep measures such as electroencephalography. Changes in circadian rhythm actigraph activity metrics (e.g., mean, amplitude, interdaily stability) have been associated with changes in neuropsychological functioning (Martin, et al., 2001), health status (Satlin, et al., 1995) and fatigue states (Mormon, et al., 2000) and may provide a biological basis for psychological distress (Mormon and Waterhouse 2002). Cancer patients with marked rest/activity circadian rhythms had better quality of life and significantly less fatigue (Mormon, et al., 2000). The relationship between fatigue and circadian rhythm desynchronization was also observed in cancer patients receiving chemotherapy, in which fatigue was associated with circadian rhythm acrophase phase delays and amplitude changes (Liu, et al., 2005). Therefore, the reliable statistical evaluation of changes in circadian rhythmicity in locomotor activity provides the opportunity to document physiological changes which may be predictive of subsequent sleep disturbance and impaired performance in operational work environments. One of the primary manifestations of fatigue in field operations is circadian rhythm disruption resulting from transmeridian flight or shift work schedules. Preliminary results of this MER study obtained on one participant during the MER 24.65 hour work schedule showed decreased circadian rhythm stability, the appearance of additional rhythms, and pronounced changes in the circadian rhythm waveform during the MER work shift phase (DeRoshia, et al., 2005). These changes were associated with a significant decrease in total bedtime in this participant (Colletti, et al., 2004).

Actigraphy data have been used to assess circadian rhythmicity in disease states (Liu, et al., 2005; Mormon, et al., 2000; Mormon and Waterhouse, 2002; Satlin, et al., 1995; Van Someren, et al., 1996), aeronautical operations (DeRoshia, et al., 2005; French, et al., 1994), age, gender, and ethnicity differences (Jean-Louis, et al., 2000a, 2000b) and even spaceflight (Monk, et al., 1999; Dijk, et al., 2001). While several investigators have evaluated changes in circadian locomotor activity rhythms as an indicator of changes in health status (Satlin, et al., 1995; Mormon and Waterhouse 2002), some reports have criticized the suitability of actigraphy data for reliable estimates of circadian rhythm metrics due to large transient changes in voluntary activity (outliers or masking effects), the presence of square wave circadian wave forms, which were not appropriate for harmonic or spectral analysis, and poor goodness of fit of activity time series data by harmonic analysis (Van Someren, et al., 1996; Bos, et al., 2002). Research was previously conducted to develop and test mathematical techniques to establish that statistically reliable estimates of circadian rhythm metrics can be obtained to document circadian rhythm changes associated with fatigue states and performance decrements in operational environments, and these methods have been applied to quantify changes in circadian rhythms associated with fatigue states in shift work and operational transmeridian flight environments (DeRoshia, et al., 2004, 2005) and also to evaluate adaptation to hyper gravity environments (Holley, et al., 2003). These methods can be valuable for assessing changes in circadian rhythms in operational environments, where it is not feasible to use body temperature probes or to take regular blood samples to assess circadian rhythmicity. The failure of other investigators to perform reliable circadian rhythm analysis on actigraphy data probably reflects differences reported in sampling rates (10 sec to 15 min), the use of raw data with large masking effects and high sample-to-sample variability, and inappropriate use of mathematical procedures for circadian rhythm analysis (DeRoshia, et al., 2005).

These techniques outlined by DeRoshia, et al. (2005) were incorporated into the circadian rhythm analysis methods used in this study. The initial purpose of this report was to evaluate sleep quality changes derived from actigraphy data while working different schedule types including two weeks before the rovers landed (baseline), while working a Mars sol (MER rotation) and two weeks after rotating (MER reduced-rotation, Colletti 2006). Data collection days during the study, which were not assigned to baseline, MER rotation, or MER reduced-rotation, i.e., days in which subjects were on nominal work schedules, were designated as transitional days. The rovers lasted over three months and therefore, a modified rotation with reduced hours between 6:00 and 22:00 was worked instead of the continuous rotation. The primary purpose of this report was to evaluate changes in circadian rhythmicity associated with rotating MER schedules and the interrelationship between circadian rhythm and sleep quality changes. Methodology and results for the actigraphic evaluation of sleep quality metrics and also subjective assessment of sleep quality were previously reported as part of a Master's Thesis project (Colletti 2006).

METHODS

Participants

Thirty of the 250 MER mission personnel, seven females and 23 males, age 21 – 59 (M= 38.2, SD=11.0) volunteered for this study, which was approved by the NASA Ames Research Institutional Review Board. The participant demographic information is presented in Appendix G. The participants were almost equally divided on locality to JPL: sixteen lived local to JPL and thirteen reported their residences in Mountain, Central, or Eastern Time zones, and one international participant (GMT-3) volunteered as well. Recruitment occurred with assistance from the MER Surface Operations managers. Participation was not limited by age, gender or race. No monetary compensation was given to participants; however, a personal analysis of their sleep history was made available to them upon request. The volunteer subject group consisted of engineers, who performed rover operations, scientists, who controlled mission operations, and managers. Baseline locomotor activity data were collected approximately two weeks before the rover landings in most subjects, starting on or about December 18, 2003 and data collection ended for all participants by April 30th, 2004.

Materials

The Actiwatch recorder (AW-64; Mini-Mitter, Inc., Bend, OR; Figure 1) is a small waterproof, wrist worn device (17 grams) used to measure gross motor activity for estimating sleep. The Actiwatch was powered by a 3V, 150 mAmp-hr lithium manganese battery that has a lifetime of 180 days. Each Actiwatch contains an accelerometer capable of sensing motion with a minimal resultant force of 0.01g. Measurements were collected at 32 Hz and amplified, filtered and passed into an analog to digital converter. The peak value at each second was summed over the minute to create an activity score that was logged onto the non-volatile memory. The AW-64 also has an event-marker button on the face for participants to record events such as the bedtime, wake time and periods in which the Actiwatch was removed.

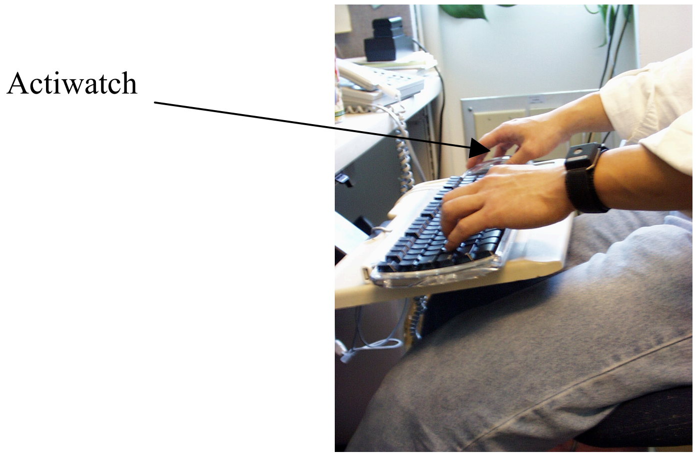


Figure 1. Participants wore the Actiwatch on the non-dominant wrist for approximately four months.

Data were downloaded to a computer using a special reader and then Actiware-Sleep scoring software (version 3.3; Mini-Mitter, Inc., Bend, OR) was used to calculate the sleep measurement, defined as time in bed, bedtime and wake-up time**.** The software requires a sleep analysis window to be set for each sleep episode, which was defined using the event markers pressed at bedtime and wake time. The technical problems in the reliability of sleep quality assessment by actigraphy are described in Appendix E . We decided to use the sleep efficiency metric since its reliability was supported by two publications (Lichstein, et al., 2006; Tworoger, et al., 2005). We selected time in bed as the primary dependent measure of sleep for group analyses and sleep efficiency, percentage of actual wake time, bed times and wake-up times were used to further examine sleep disturbances observed in circadian rhythm analyses of individuals. Time in bed per 24-hour period between the hours of 00:00 to 23:59 was calculated from the time in bed measure to determine whether personnel obtained an equivalent amount of sleep per 24-hours during the 24-hour and 24.65-hour work schedules. This provided a common 24-hour measurement period for the different schedules.

The paper-and-pencil Sleep Log was a daily log with inputs for bed times and awakenings. These sleep times were used to validate the Actiwatch event markers or mark the sleep times if event markers were unavailable. Additionally, participants reported the onset and end times for work schedules, naps, and subjective ratings of alertness and fatigue ("How rested do you feel upon awakening?" and ("How sleepy do you feel upon attempting to sleep?") in their daily logs. During the second half of the study an additional rating scale was added ("Since your wakeup time listed above, how sleepy were you on average during your waking hours?"). All rating scales ranged from 0 ("Not at all") to 9 ("Extremely"). In addition, the logs included a line where the subjects could check the operational work status ("Day off, or "MER"). Participants also marked extended periods of time in which the Actiwatch was not worn and recorded anomalies such as traveling to different time zones. These items provided additional information to help interpret the activity data. Instructions for use were included with the Daily Sleep Log. This study was conducted secondary to the primary personnel objective, which was to operate the Mars Exploration Rovers. Therefore, this log was completed by the personnel only if time permitted.

Two paper-and-pencil surveys were administered throughout the protocol: the Background, and Post-study. The Background Questionnaire was a 30-item survey with questions about participants' age, gender, family status, sleep profile and commute profile. The Morningness/ Eveningness (M/E) Questionnaire (Horne & Ostberg, 1976) has been used to determine whether participants normally feel most alert in the morning or the evening. This questionnaire was important to incorporate into this study since it has been shown that morningness-eveningness was correlated with circadian period, wake times (Duffy, et al., 2001), sleep satisfaction, sleep quality (Kato, et al., 2006), and time in bed (Taillard, et al., 1999). The M/E questionnaire and the background questionnaire (Appendix C) were administered to all subjects at the beginning of the study. A 28-item paper and pencil Post-study questionnaire (Appendix D) was administered at the end of the study to determine the subjective impact of working a Mars sol on personnel. This questionnaire incorporated a mood test to assess levels of fatigue, irritableness, concentration, energy, and sleepiness. Fatigue was defined in this report as subjective loss of desire or ability to continue performing and sleepiness was defined as desire to sleep (Van Dongen and Dinges 2005). A composite fatigue scale was created by assigning numerical weights to the responses, ranging from “strongly increased (-2)”, “moderately increased (-1) ”, “neither increased or decreased” (0), “moderately decreased” (1), and “strongly decreased” (2) for the fatigue, irritableness, and sleepiness scales, and “strongly increased (2)”, “moderately increased (1) ”, “neither increased or decreased” (0), “moderately decreased” (-1), and “strongly decreased” (-2), for the concentration and energy scales. The values across the five scales were summed for each participant to create the composite fatigue scale.

Procedures for Actiwatch Data Acquisition

Upon signing the Consent Form, participants were sent an Actiwatch, Background questionnaire, M/E questionnaire and Daily Sleep Log two weeks before the MER landing on January 4th, 2004. Materials were mailed directly to the participants with a self-addressed envelope for immediate return of the questionnaire and materials at the end of the study.

Actiwatches are usually worn on the non-dominant wrist; however, participants were allowed to place the Actiwatch on the dominant wrist for the duration of the study, if discomfort occurred, to reduce participant non-compliance. A review of the literature on actigraph placement found inconclusive findings with more research required (Ancoli-Israel et al., 2003).

The Actiwatch was worn on the wrist at all times including sleep and wake except during bathing or high-impact activities to avoid damaging the watch. Upon attempting to sleep or upon awakening, the participant pushed an event marker on the top of the watch. They also input the sleep/wake time on the daily sleep log. At regular intervals, the researcher would travel to JPL to exchange equipment with participants due to the limited memory capacity of the Actiwatch. It would have been preferable if participants wore the same Actiwatch throughout the protocol; however, experience during an operational readiness test found the high workload and unusual schedules of the participants interfered with getting the same Actiwatch back to each participant after processing without missing one or several sleep cycles. We decided that it was more important to switch Actiwatches to maintain continuous data collection. Therefore, the participants immediately received a replacement Actiwatch, when turning in the previous one for downloading, battery change, memory clearing and re-coding. At the end of the protocol, the Post-study questionnaire was distributed and the materials were picked up or returned via pre-paid delivery service to NASA Ames Research Center. Daylight savings occurred on Sunday, April 4, 2004, at 0200; however, the Actiwatch remained on standard time throughout the protocol.

Circadian Rhythm Data Analysis

Mathematical and statistical methods for analysis of the Actiwatch locomotor activity data were based primarily upon previous verification of these methods for use on locomotor activity data (DeRoshia, et al., 2004, 2005; Holley, et al., 2003). First, the 1-minute raw data were filtered to eliminate or reduce the statistical effects of outliers and transient activity anomalies by clipping activity values > 95% of the sorted activity values >0 (i.e., setting these values to the clipped value).

Robust locally weighted regression (RLWR) was next used to filter and smooth the locomotor activity data. RLWR provides a locally weighted non-linear curve fit (Cleveland 1979) and was therefore an ideal procedure for smoothing spiky data with large transients such as locomotor activity (Holley, et al., 2003). The computer program utilized was derived from the "lowess" transform provided in SigmaPlot software (2001, SPSS, Inc.). The filter was tested by evaluating different filter lengths ranging from 30–180 sample points. The optimum filter used a number of terms equivalent to one hour of data (60 data points, DeRoshia et al., 2005). The filtered data were then converted to half-hourly means for most circadian rhythm analyses since the data sets collected in this study were extremely long (maximum of 125 days, 180,000 consecutive 1-minute samples). Circadian rhythm metrics were extracted by harmonic analysis using the complex demodulates analysis method (Redmond, et al., 1982; Sing, et al., 1980). The metrics obtained were acrophase (circadian rhythm peak time derived from harmonic least squares fit), amplitude (circadian rhythm peak-to-trough range), mesor (mean estimated statistic of the mean, the circadian rhythm means estimated from harmonic least squares analysis), goodness of fit (correlation between activity data and fitted harmonic), and percent rhythm (ratio of residual harmonic variance to total data variance). The latter two metrics provide a measure of circadian rhythm stability, as well as the goodness of fit by harmonic analysis. In this study, relative amplitude (ratio of the amplitude to the mesor; Satlin, et al., 1995; Van Someren, et al., 1999) was used in place of the amplitude or mesor metrics since Actiwatch sensors were found to differ significantly in accelerometer sensitivity and the Actiwatch sensors are sensitive to changed positions on the wrist. In this study, Actiwatches were exchanged up to five times due to limited memory capacity of the Actiwatch and since the position of the watch on the wrist may change slightly after changing watches or as a consequence of removing the watch temporarily for hygiene. The relative amplitude metric provides a reliable estimate of rhythm strength independent of changes in amplitude or mesor subsequent to removing or replacing watches. Circadian rhythm statistical significance was established by Cosinor analysis (Nelson, et al., 1979), which provides a statistical significance test and 95% confidence limits for acrophase and amplitude. Circadian rhythm periodicity was evaluated using a non-parametric waveform-based method (profilogram, Citta 1982) and also by power spectral analysis utilizing a modified (Powerspec) transform provided in SigmaPlot 2001 software. Since classical power spectral analysis can result in periodicity artifacts at harmonics of the main circadian rhythm frequency as a consequence of non-stationary, asymmetric, or non-sinusoidal circadian waveforms, the profilogram was used primarily to verify the biological reliability of spectral peaks derived from power spectral analysis. Spectral peaks in the profilogram represent the ratio of the variance of the mean educed cycle to the total data variance and spectral peaks in the power spectrum represent relative spectral power amplitude at a given frequency. Moving spectral analysis (pergressive, or moving periodogram analysis, (Kramm 1973) was used to reveal short-term changes in periodicity and non-stationary transient changes in rhythmicity during MER and non-MER regimens. This was accomplished by employing power spectral analysis stepwise through the data, usually by evaluating periodicity in consecutive 4-day data blocks. Educed circadian cycles were computed by first estimating the circadian rhythm period length in a given data segment, using power spectral methods, averaging data across the total number of cycles, given the input period length, then reducing the educed cycle data from 1-min to 30-min means. Educed circadian cycle data were used to evaluate changes in circadian rhythm waveforms during the MER regimes and also to calculate interdaily stability. Interdaily stability (the ratio of circadian cycle variance at the peak estimated circadian period length to total variance; Satlin, et al., 1995; Van Someren, et al., 1999; Teicher, et al., 1997) was computed as a measure of rhythm stability. The Cosinor (Martin, et al., 2001), wave form based periodograms (Pollak, et al., 2001) and spectral analysis have been used for circadian rhythm analysis of actigraphy by other investigators.

The rotating MER schedule resulted in the timing of operational MER schedules during the subjective night in several subjects. Therefore, we deemed it important to compare sleep quality and circadian rhythmicity in the same participant during day and night shifts wherever possible. Activity circadian rhythm metrics and waveforms were selected from day shift and night shift times defined by the activity circadian rhythm acrophase. Day shifts included data where the acrophase occurred between 11:40 and 19:40 and night shifts included data where the acrophase occurred between 23:40 and 07:40. These time ranges were selected to incorporate at least five days of activity data from as many subjects as possible.

Baseline data and MER regimes were established by inspecting participant daily work activity logs and post-study questionnaires, which document MER operations duty days and start and end dates for MER operations regimes, and also by inspecting plots of Actiwatch actigraph plots and recorded wake-up times to determine baseline and MER regime start and end dates. This was necessary since the participants did not maintain complete records of their workload schedules and duty assignments. The baseline data segments consisted of data recorded before the onset of MER operational duties in most participants. In other participants, baseline segments were defined as the start of a sequence of days in which activity onsets were relatively constant. The MER rotating schedule onsets were defined as the start of a sequence of days in which the participant was participating in MER operations.

RESULTS

MER Operations Workloads

The MER mission operational workload demands defined the workload schedules of the MER workforce and the MER operational activities contributed to the locomotor activity levels recorded by actigraphy. The MER workload schedules include activities performed during the Mars sol and activities performed between sunset and sunrise on Mars. The activities during the Mars sol included Mars rover sequence plan reviews, real time rover monitoring, tactical science assessment, and observation planning. The post-sol activities included end-of-sol science and engineering assessment meetings, rover activity plan integration and development, and activity sequence development and approval (Bass, et al. 2005). The MER workloads were also categorized as tactical processes, which involved planning and directing rover operations, and strategic operations, which involved long term mission activities, resource allocations, coordination of the two rover missions, satellite communications, determination of rover resource situations, and public outreach activities. The tactical workload was scheduled on Mars sol time, while the strategic work was done on earth time (Bass, et al., 2005). The tactical work necessitated a scheduled 10-hour downlink shift staff, who analyzed received data and made recommendations for rover activity execution, and two scheduled 10-hour uplink shift staffs, who converted the recommendations into spacecraft commands. These shifts initially took 19 hours to complete; however, by the beginning of the reduced-rotation operations, the process was reduced to an average of 8 hours by improvements in automation, increased staff training, and expertise development (Bass, et al., 2005). The success of the MER mission resulted in the extension of the mission past the scheduled three-month period for about another 1–4 weeks for most personnel. During this latter period, the rotating MER schedule was changed to a “reduced MER rotation” schedule, in which personnel were limited to work shifts between 07:00 and 21:00 hours. The rover Spirit went on the new schedule on 3/29/04, while the rover Opportunity transitioned on 4/6/04. For the duration of this study, personnel were either working on a rotating MER schedule based upon a Mars sol (24.65 hour day), or they were working on their normal job assignments during the approximately two-week data collection period (baseline period) preceding the rover landings on Mars, working on the reduced MER rotation schedule, or they were on days off. Since the baseline period, MER reduced rotation schedule and days off were based upon 24.0 hour days, these days will be referred to as “earth time”. During the MER mission, five of the 30 study participants were required to switch work shifts between the MER-A and MER-B missions, which necessitated a 12-hour shift in their work/rest schedules. The changes in rover assignments and the transition to the reduced MER rotation schedule may have resulted from personnel shortages and the lack of sufficient funding to cover the mission extension. The details of participant baseline data recording, MER operations schedules and experimental notes are provided in Appendix G.

Adaptation to MER Mars Sol Schedules: Subjective Responses

Twenty-seven participants completed the Post-study questionnaire which documented changes in moods and difficulty during Mars sol MER operations. Five of these participants were excluded from the evaluation of sleep and fatigue-related responses for the reasons specified in the *Sleep Quality* results section, which left 22 subjects for the subjective sleep and fatigue evaluation. Eleven subjects (50%) found it difficult working a Mars sol, six (27%) were neutral and five (23%) found it easy (Figure 2).

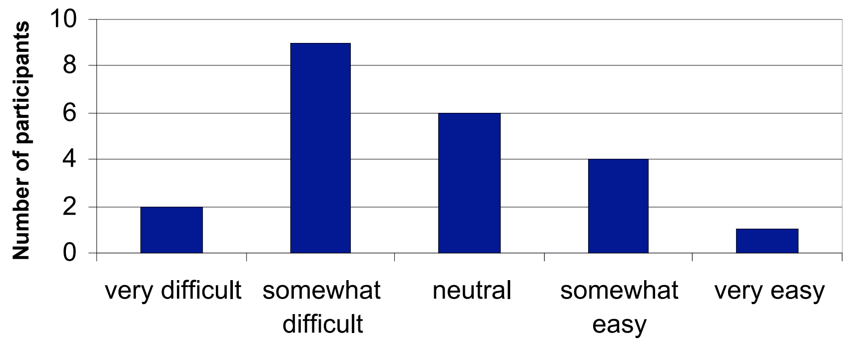


Figure 2. Frequency of responses to the post-study question "How difficult was it working a Mars Sol?".

Open-ended questions about what participants found most challenging about working a Mars sol and general comments identified:

- Major changes in work shift times due to switching between MER-A and MER-B rovers (5/22, 23%)
- Major changes in rest/activity schedules due to switching between a Mars sol and earth time (6/22, 27%)
- Working the graveyard shift during the MER rotation (4/22, 18%)
- Social/daily living factors in completing chores, shopping and socializing (or social isolation) (8/22, 36%)
- Sleeping during the day (3/22, 14%)
- Awakening by children (5/22, 23%)
- Workload fatigue: working long hours for many consecutive days and additional tasks outside of MER operations (2/22, 9%)

There were many anecdotal comments that did not fall into the above categories but provide further insight into experiences of participants while working a Mars Sol. One participant commented that their "schedule was quite easy because I stayed on LST-B daytime. I served as MER-B SOWG chair or MER-A SUR (which are about the same time-of-day in LST-B time)." Thus, this participant remained on a consistent Earth schedule by working multiple job responsibilities and therefore found the scheduling easy. One participant indicated that the inconsistency of work and off day schedules was a problem in adaptation. However, another participant indicated that multiple days off provided the opportunity to readjust sleep/wake timing for the upcoming MER regime. The changes in work shift times between MER-A and MER-B operations was considered a major problem by all four individuals required to perform these shifts and one participant recommended that personnel should be assigned to a single MER mission. Mission excitement (adrenaline) promoted adaptation in one participant. Other comments of interest included the deleterious effects of meetings scheduled at the start or end of MER shifts, and the inadequate lighting during night shifts. Two participants indicated that they were able to adapt to the MER operations regimes after the initial 2–4 weeks of working a Mars Sol, after which their mood and sleep times stabilized.

Mood responses as a consequence of MER operations, which were extracted from the post-study questionnaire, showed a negative impact of working a Mars Sol in most participants (Figure 3). In particular, 18 participants (82%) indicated that fatigue increased while working MER operations. In addition, sleepiness (n=14, 64%) increased, while concentration (n=12, 55%) and energy (n=13, 59%) decreased. The composite fatigue score was negative in 18 participants (82%). However, responses were variable since two participants exhibited positive composite mood scores, in response to MER operations, while four participants exhibited highly negative composite mood scores (Figure 4, -6 to -8, indicative of an average of moderately to strongly negative mood responses across the five mood scales). The best adapters to the MER regime, suggested by the combined fatigue scores, were participants M310 (+3) and M323 (+1). These participants reported MER sleep durations of 8 and 9 hours, respectively. The worst adapters were participants M0306 (-8), M0325 (-7), M0330 (-6), and M0319 (-6). These participants reported MER sleep durations of 5, 8, 6, and 6 hours, respectively. Participant M0306 reported problems with frequent awakenings and the necessity of attending several meetings immediately before and after MER shifts, which reduced the time available for sleep. Participant M0330 had a morningness-eveningness score of 66 (moderate morning type) and indicated that he had difficulty adjusting to the longer Mars sol schedule since he was a morning person. This participant also reported difficulties in switching from MER-A to MER-B work shifts. Participant M0319 reported difficulty in sleeping in daytime during the MER rotation.

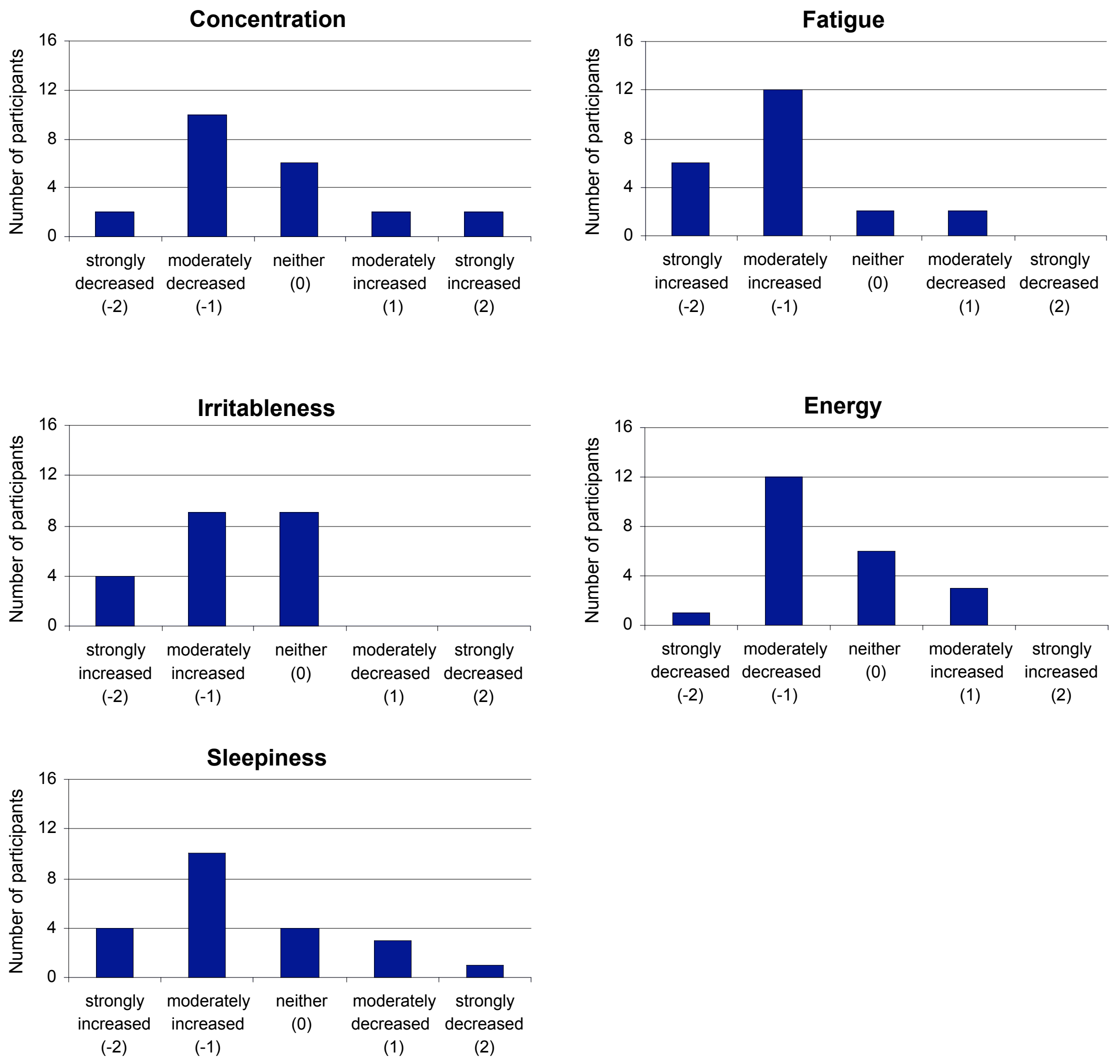


Figure 3. Changes in fatigue variables obtained from the post-study questionnaire of participants while working MER operations.

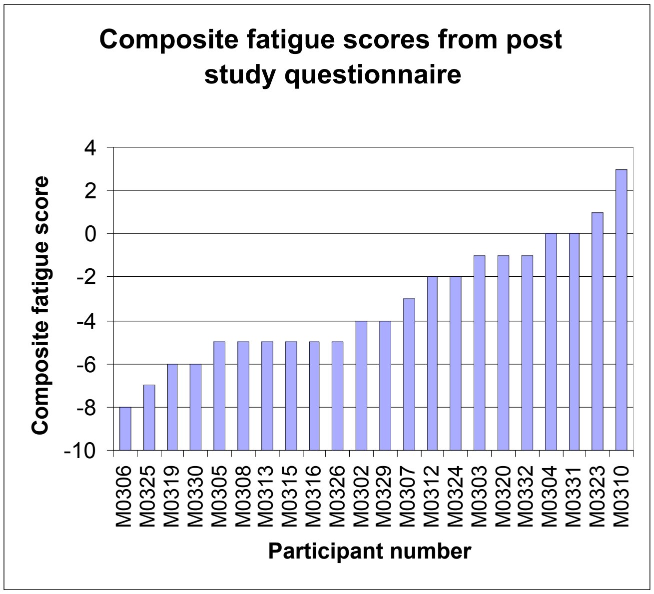


Figure 4. Changes in participant composite fatigue scores obtained from the post-study questionnaire sorted from maximum fatigue responses (left) to minimal fatigue levels (right). The effects of the MER operations regime on fatigue were highly variable between subjects. Four subjects showed no change or a reduction in composite fatigue (M0304, M0331, M0323, M0310) and four subjects showed a pronounced increase in composite fatigue (scores of -6 to -8, M0330, M0319, M0325, M0306).

While the subjective questionnaires and daily log did not focus on the stressful aspects of MER operations workload, participant responses indicative of reactions to stressful conditions were reported, aside from the workload stresses associated with the MER operations workload. Most (*n*=13, 59%) participants indicated that irritability increased during the MER regime. Three participants reported that social isolation during the MER regime, particularly during night rotation shifts, was a major challenge since they were isolated from social contacts with friends and family. Another source of stress expressed by several participants was the difficulty in completing household chores during MER operations. The challenge of being awakened and attending to children reported by five participants may have been another source of stress during MER operations. One participant indicated that social camaraderie, which helped to alleviate stress during a previous mission operation (1997 Mars Pathfinder), was absent during the MER mission.

Several strategies were employed by the participants to counteract sleep problems and fatigue during MER operations. The most common strategy was the use of caffeinated beverages (n = 15, 68%). Other strategies included naps (n = 11, 50%), exercise or walking (n = 7, 32%), days off or vacations (n = 5, 23%), ensuring 8+ hours of sleep (n = 4, 18%), and the use of eye shades or window shades (n = 3, 14%). One participant took melatonin to promote sleep. Another participant indicated that reducing work responsibilities as much as possible was helpful. Although seven participants indicated that exercise was an important adaptation strategy, one participant indicated that a reduction in exercise activity was useful to reduce fatigue.
During MER operations, personnel had days off ranging from 1–7 consecutive days. The days off schedules were determined by MER task subgroups within the MER operations team. The

operations teams implemented these schedules differently. One team chose to work four days on MER operations followed by three days off, while another team worked seven days on with seven days off (Bass, et al., 2005). Two participants in our study elected to stay on Mars time throughout MER operations, while the other participants transitioned to earth times on their days off. The number of consecutive MER operations days ranged from 1–31 (mean = 6.8), while the number of consecutive days off ranged from 1–11 (mean = 3.0). There were eight cases in which participants worked 17 or more consecutive days, which represented 9% of the total cases. The ratio of consecutive MER operations days to days off ranged from 3/3 to 17/5. Work time duration data records were not completed for all work days by all participants. However, at least five days of data were available from 17 participants to compare work shift durations between earth time days and MER operations days. The work time duration data indicated that workload duration significantly increased from earth time (mean = 8.8 hours, range = 6.4–12.3 hours) to the MER regimes (mean = 10.4 hours, range = 7.7–12.2 hours, paired t-test, t(*df* = 17) = -4.9, P = 0.001). The subjective sleep duration data indicated a reduction in sleep time from earth time (mean = 8.2 hours, range = 6–11 hours) to the MER regimes (mean = 6.9 hours, t(*df* = 21), t = 6.2, P = .000004). The distribution of work time durations is shown below (Figure 5). Individual work time durations ranged from 0.5–20.5 hours (earth time) to 1.3–23 hours during the MER regimes. During the MER regimes, 58% of shift durations exceeded 10 hours, and 26% of workload durations exceeded 12 hours.

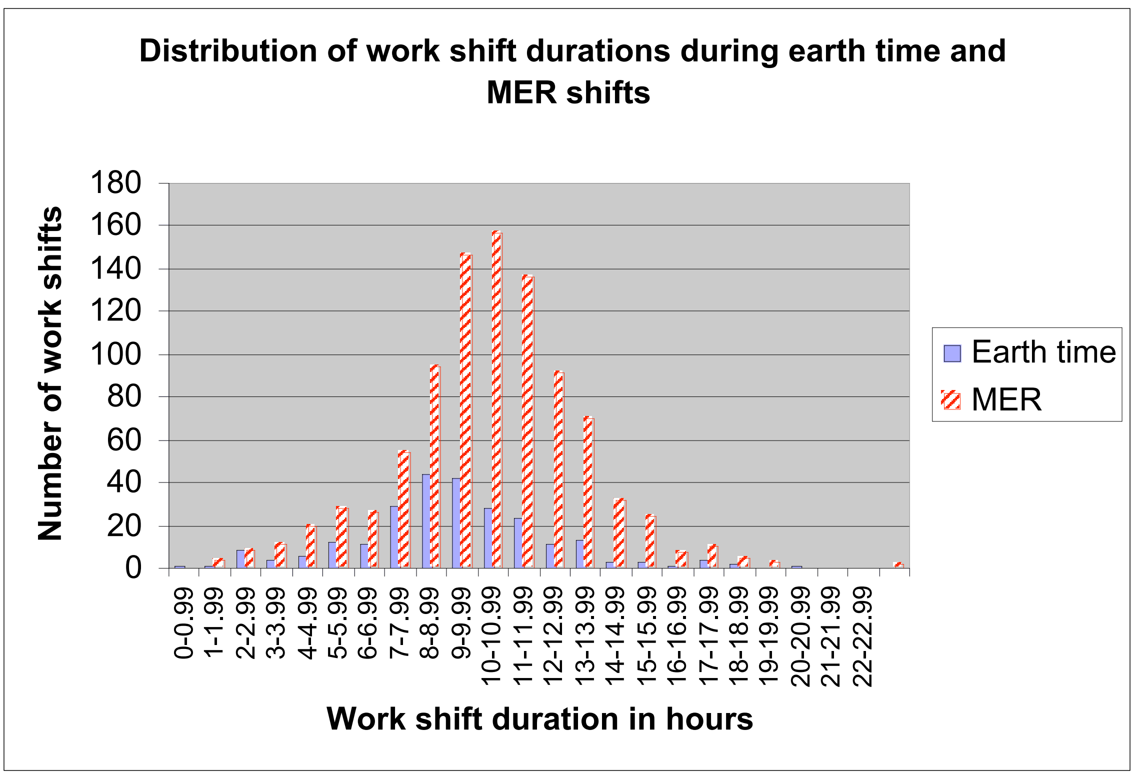


Figure 5. Comparison of work shift durations between earth time and MER operations shifts.

Sleep Quality

Six participants were removed from the study due to missing sleep log data (n = 2), inconsistent sleep log entries compared to actigraphy (n = 1), medical issues (n = 1), international location (n = 1), or family emergencies (n = 1). Actiwatch software cannot accurately predict active sleep from restful wake without specifying bedtimes. Therefore, sleep quality analyses were computed using the remaining twenty-four participants out of the original thirty. Five participants that visually appeared to maintain a sleep/wake schedule that coincided with a Mars sol were selected for circadian rhythm analyses to examine the effect of working a Mars sol on activity circadian rhythms. Two participants were selected who shifted back and forth from Mars sol time to earth time on days off. Two additional participants were selected since they maintained a rotating MER sleep/wake schedule throughout the MER mission, which included maintenance of the schedule during days off. Four participants were required to undergo the transition from a MER-A schedule to a MER-B schedule, which required a 12-hr shift in rest-activity patterns since the MER rovers were located on opposite sides of the planet. Two of these participants were selected for evaluation of the effects of the MER-A to MER-B schedule shift.

The Actiwatch was worn on average 109.2 days (range 49 –136 days). The average number of days per work schedule was 13.9 days (range 3 –42 days) during baseline, 77.3 days (range 37–100 days) during MER-rotation and 20.1 days (range 9 –33 days) during the MER modified-rotation schedule. The start dates for baseline, MER-rotation and MER reduced-rotation schedules were determined by the post-study questions requesting the start and end dates for working a Mars sol.

Average Time in Bed per 24-Hour

Time in bed was analyzed using SAS (ver. 8.02) and SPSS (ver. 11.5) to determine changes in 24-hour time in bed. Repeated-measures analyses of variance (ANOVA) were run using SAS PROC MIXED to allow for missing values within a subject. Analyses investigated time in bed for two within-subject factors: 1) work schedule (baseline, MER rotation, MER reduced-rotation); and 2) working or not working during a MER rotation. The MER reduced-rotation was scheduled to be the recovery period; however, the rovers continued to operate after three months and the MER schedule was reduced to rotate between 06:00 and 22:00. Sleep periods or days in which the participants were sick, had no event markers and no sleep log entries, or varied greatly from sleep log entries were removed from the data set. Additionally, New Year’s Eve (12/31/03) and Daylight Savings day (04/04/04) were removed if the sleep period varied more than two hours from the preceding and following two days. Two Actiwatch recordings for participants M0304 and M0313 were missing due to hardware problems and sleep log entries were used instead.

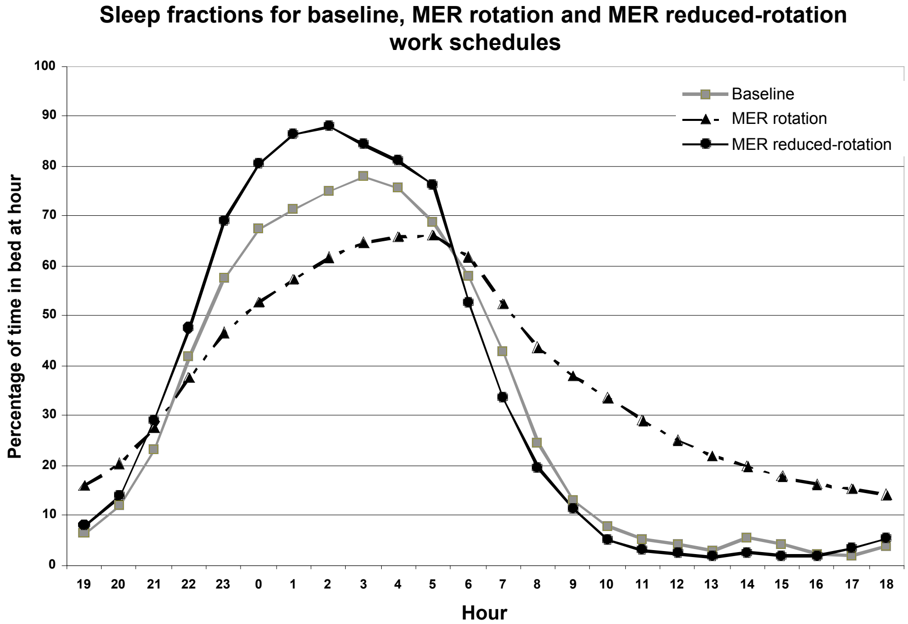


Figure 6. Percentage of sleep episodes (also referred to as sleep fractions) in which participants were in bed at the time of day specified along the x-axis. Notice the increase in sleep occurring during normal wake times between 09:00 and 20:00 while participants worked Mars sols (MER-rotation).

To determine how the timing of sleep changed during the different work schedules, sleep fractions or percentage of sleep periods in which participants were in bed at each hour of the day were plotted for the different work schedules in Figure 6 (Lewis and Masterton 1957; Naitoh, et al., 1991). Sleep from midnight to 04:00 was below 80% during the baseline period, which suggests that other factors were affecting the sleep schedules of personnel and this period did not represent a true "baseline". Sleep during the MER reduced-rotation was above 80% from midnight to 04:00 (range 80 –88%) suggesting personnel slept more consistently during the night for this work schedule.

While personnel worked the MER-rotation, shifting 39 minutes daily, time in bed decreased from baseline during the night hours from midnight to 04:00 from 52% to 66%. Time in bed increased during the day and early evening with a larger percentage of sleep episodes occurring in the late morning (43% at 08:00) and decreasing across the day until only 14% of the sleep episodes occurred at 18:00. The highest percentage of sleep was still obtained during normal sleep times from 00:00 to 07:00 and the smallest percentage of sleep episodes occurring during the early evening 16:00–19:00. The peak time of day in which most sleep episodes occurred was 03:00 for baseline, 05:00 for the MER-rotation and 02:00 for the MER reduced-rotation.

To determine whether the time in bed obtained by the MER operations personnel differed among the different schedules (baseline, MER-rotation and MER reduced-rotation) operations, a repeated-measures ANOVA was run. Since two participants were missing baseline data due to late recruitment and one participant stopped wearing the Actiwatch after 49 days before working a MER-rotation schedule, their data were included by using mixed-model ANOVA.

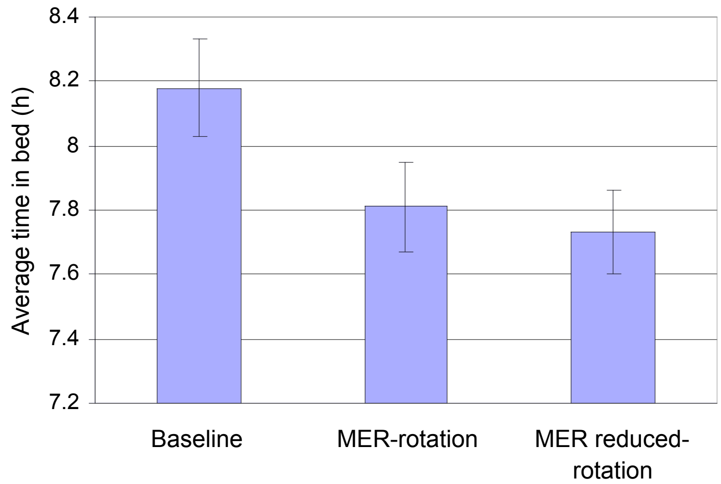


Figure 7. Average time in bed for participants across baseline, MER-rotation and MER reduced-rotation work schedules showed a significant difference between schedules. Error bars represent standard error of the mean.

Average hours of time in bed for participants across baseline (M = 8.18, SD = 0.70), MER-rotation (M = 7.81, SD = 0.67) and MER reduced-rotation (M = 7.73, SD = 0.61) work schedules showed a significant difference in work schedule ($F(2, 43) = 7.92$, $p < .01$) with baseline time in bed significantly higher than the MER-rotation ($t(43) = 3.29$, $p < .01$) and MER reduced-rotation schedules ($t(43) = 3.63$, $p < .001$; Figure 7). Time in bed for the MER-rotation and reduced-rotation schedules were not significantly different ($t(43) = 0.41$, n.s.). Results suggest that participants obtained more sleep before the landing of the rovers and 24-hour time in bed while working a MER-rotation and reduced-rotation was about the same.

By averaging sleep across each participant, resolution was lost in the data analysis. For example, the minimum time in bed for each participant across all sleep episodes for a MER-rotation schedule ranged from 0 to 5 hours and the maximum ranged from 10.7 to 18 hours; yet the average minimum time in bed averaged across each participant was 6.4 hours and maximum was 9.0. Therefore, the variability of each participant's time in bed was also analyzed.

To examine the variability of sleep, the standard deviation of time in bed was used. A significant main effect was found for the standard deviation of average time in bed for participants across baseline, MER-rotation and MER reduced-rotation work schedules ($F(2, 43) = 8.54$, $p < .001$; Figure 8). The variability of time in bed during the MER-rotation schedule was significantly higher than baseline ($t(43) = -3.60$, $p < .001$) and MER reduced-rotation ($t(43) = 3.52$, $p = .001$) schedules. The variability of time in bed was not significantly different between baseline and the MER reduced-rotation schedules ($t(43) = -0.12$, n.s.). These results suggest that a work schedule that rotates 39 minutes daily causes increased variability in the length of sleep episodes, which could result in circadian disruption affecting alertness and performance.

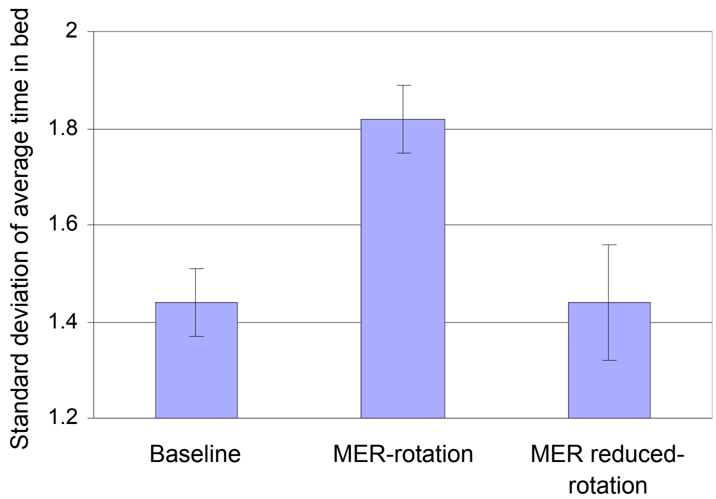


Figure 8. The variability of time in bed for the MER-rotation schedule was significantly different than baseline and MER reduced-rotation suggesting sleep durations were more variable while working a Mars Sol. Error bars represent standard error of the mean.

To determine whether the average sleep duration (time in bed per 24 hours) of personnel working a Mars sol (MER-rotation schedule) differs between non-working days and working days, a repeated-measures ANOVA was run. A day was scored as a work day if the participant worked more than two hours within the 24 hour period. Only twenty-one participants were included in this analysis due to removal of three participants with missing work schedules from the sleep log.

Time in bed while working (M = 7.59, SD = 0.62) was significantly different from time in bed while not working (M = 8.63, SD = 0. 71; $F(1, 20) = 78.9$, $p < .001$; Figure 9). These results suggest that personnel slept more on days off, therefore potentially compensating for sleep lost while working. Sleeping longer on non-work days was common for all permanent workers; although, night shift workers tend to sleep less during workdays and sleep more on non-work days compared to day workers (Tepas and Carvalhais 1990).

The standard deviation of time in bed across participants was also analyzed to determine whether the variability in sleep duration was different for days working and not working. The repeated-measures ANOVA on the standard deviation of time in bed while working (M = 1.65, SD = -.37) and not working (M = 1.75, SD = 0.57) found no significant main effect ($F(1, 20) = 0.55$, n.s.).

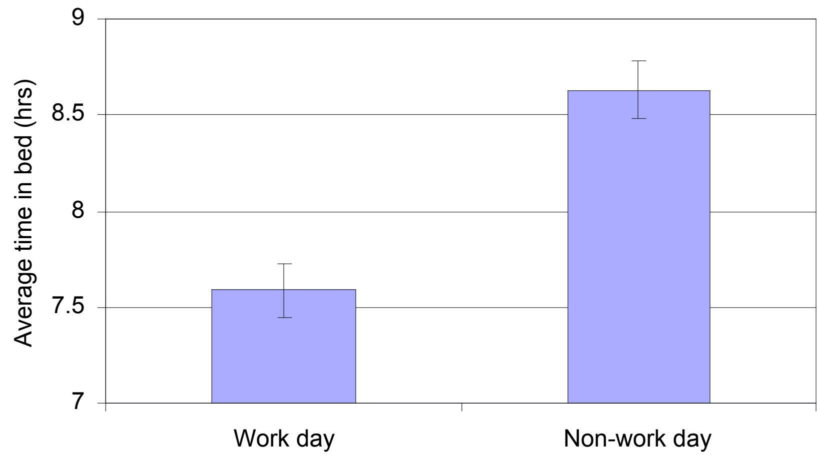


Figure 9. Comparison of average time in bed during work days and non-work days. During the MER-rotation, average 24-hour time in bed while working was significantly less than while not working. These results suggest that personnel slept more on days off potentially compensating for sleep lost while working a schedule that coincided with the Mars Sol. Error bars represent standard error of the mean.

Naps

A total of 325 nap periods were identified in 24 participants, which is an average of about one nap per participant per eight days. Naps tended to occur in clusters during consecutive days in most participants (Figure 10) and were often associated with large reductions in time in bed (Figure 19e).

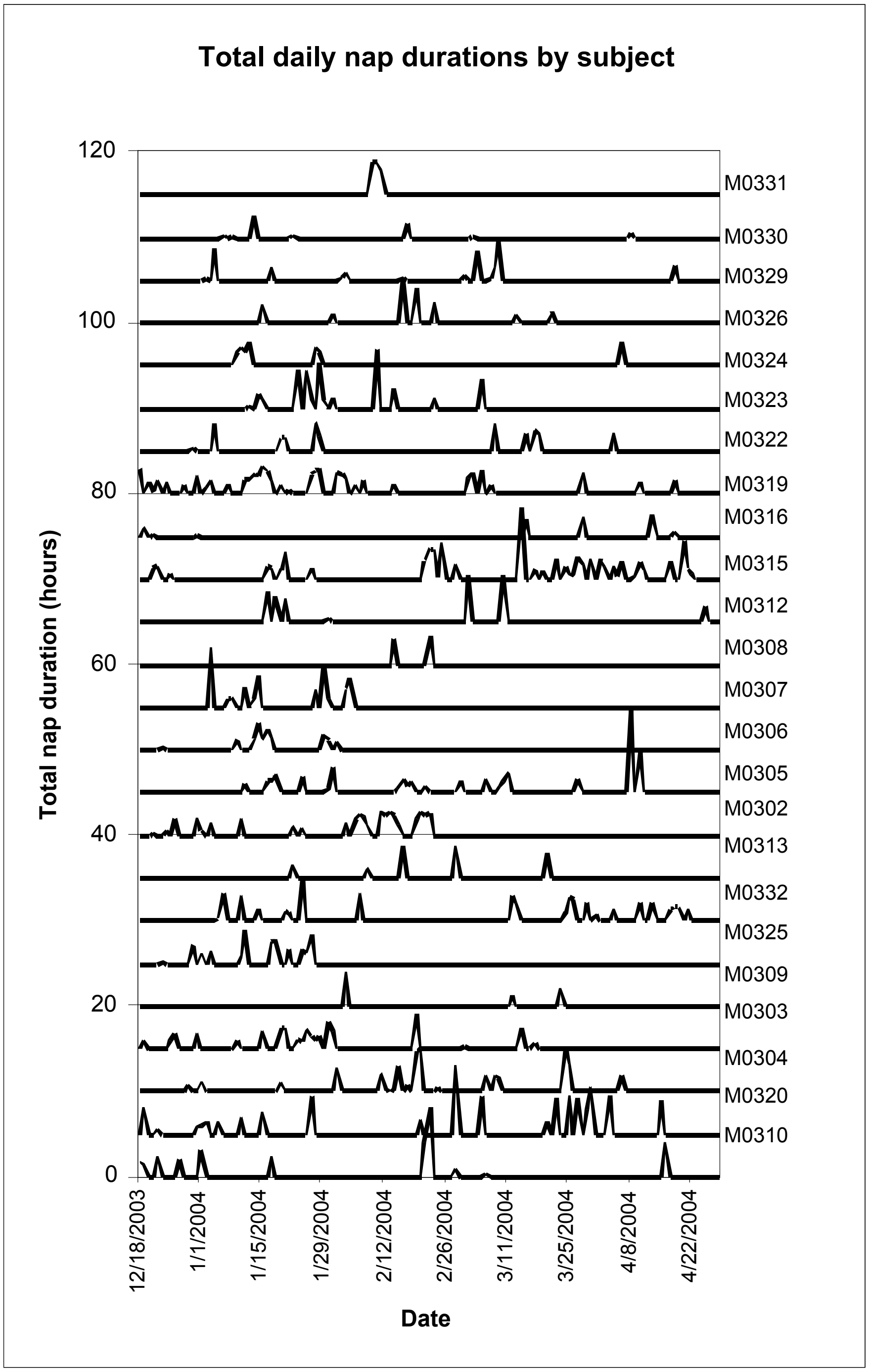


Figure 10. Total daily nap durations are shown for 24 participants. The ordinate scale ranges from 0-5 hours total nap duration for each participant. The naps tended to occur in clusters for most participants.

Circadian Rhythm Analysis

A comparison of mean circadian rhythm metrics between a laboratory baseline group (data collected from participants in research studies by the Fatigue Countermeasures Group [FCG], Human Factors Division, NASA Ames Research Center, California), the MER study baseline and MER regimes are shown in Table 1 and the individual circadian rhythm metrics are shown in Appendix B.

TABLE 1. SUMMARY OF CIRCADIAN RHYTHM METRICS (MEANS AND VARIABILITY) BETWEEN THE LABORATORY BASELINE (FCG DATA), MER BASELINE, AND MER REGIME

ID	N[1]	Per-iod	Ampli-tude	%Rhy-thm	Acrophase Degrees	Mesor	Relative Ampli-tude	Good-ness of fit	Inter-daily Stability	Rhythm Sig Prob	95% CL
Comparison of circadian rhythm means between laboratory data and MER study data											
Lab FCG data[2]	7	24.04	202.31	47.36	208.11	237.27	0.836	0.68	0.51	3.10E-04	30.56
MER baseline	9	24.08	115.91	53.35	223.30	187.12	0.673	0.75	0.49	5.44E-04	74.56
MER regime	9	24.84	166.66	39.27	284.07	151.50	1.101	0.71	0.50	8.38E-05	33.45
Comparison of circadian rhythm between MER baseline, MER regime and transitional days											
Baseline	9	24.08	115.91	53.35	223.30	187.12	0.67	0.75			
Transition days	5	24.41	113.55	38.45	285.39	133.60	0.84	0.66			
MER regime	9	24.84	166.66	39.27	284.07	151.50	1.10	0.71			
Comparison of circadian rhythm variability (standard deviation) between MER baseline, MER regime and transitional days											
Baseline	9		34.96	16.10	66.70	44.15	0.20	0.10			
Transition days	6		47.06	17.20	61.59	39.04	0.36	0.11			
MER regime	9		35.40	13.62	25.70	28.85	0.24	0.09			
MER study circadian rhythm statistics: Subjects with strong Circasemidian rhythms											
Baseline		24.06	125.30	49.84	231.24	199.34	0.72	0.72	0.43	4.95E-04	69.19
MER regime		24.98	171.91	29.67	298.01	148.52	1.15	0.65	0.51	9.69E-06	38.64
MER study circadian rhythm statistics: Day vs. night MER rotation shifts											
Day			100.46	47.24	246.28	16.42	0.68	0.72			
Night			111.95	31.63	207.99	13.87	1.02	0.64			

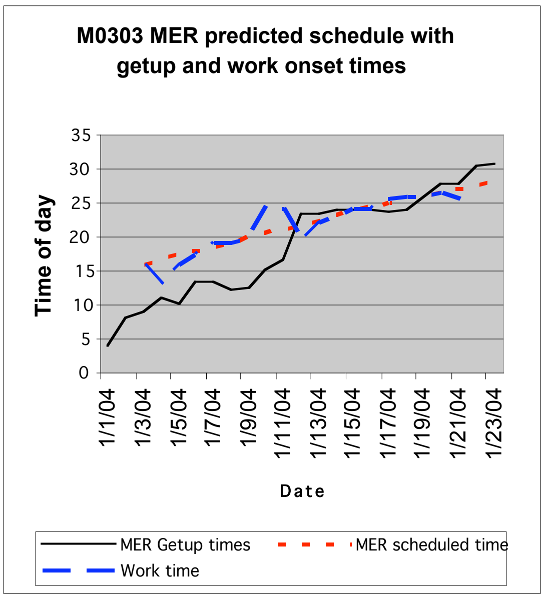
[1] Number of participants in analysis, [2]Fatigue Countermeasures Group subjects

Circadian rhythm analyses were performed on nine participants for this report. Estimates of circadian rhythm amplitude, mesor, and relative amplitude were lower in the MER study participants during earth time (baseline, 115.9, 187.1, and 0.67, respectively) than in our Fatigue Countermeasures Group laboratory participants (202.3, 237.3, and 0.84, respectively), indicating that locomotor activity and circadian activity oscillations were lower in the MER participants. However, comparison of the circadian rhythm metrics of period length, acrophase in degrees, relative amplitude and interdaily stability revealed no statistically significant differences between the MER baseline and the laboratory participants ($t_{14}<1.8$, ns). The mean circadian period length increased from 24.08 hours (earth time) to 24.84 (MER, paired-t test, $t8 = 8.4$, P<0.001, P<0.002 with Bonferroni correction). Circadian acrophase (223^o) and relative amplitude (0.673) both increased during the MER regimes, (284^o and 1.101, respectively, $t_8 = 3.5, 3.8$, P<0.01, P<0.05 with Bonferroni correction). No statistically significant changes between earth time and MER regimes occurred in amplitude or interdaily stability. The Morningness-Evening questionnaire (Horne and Ostberg, 1976) showed a subject response range from 29 (Definitely Evening chronotype) to 72

(Definitely morning) among the 24 participants evaluated. In the nine participants in which circadian rhythmicity was evaluated, the participant scores ranged from 65 (moderate morning) to 32 (moderate evening) A negative correlation with activity circadian rhythm acrophase values during the baseline regime was obtained for these participants ($r = -0.2$, $df = 8$, n.s.). Although this value was not statistically significant, the acrophase showed an increase with lower morningness-eveningness scores (i.e., higher trend toward an eveningness chronotype), as was found in previous studies (Horne and Ostberg, 1976; Duffy, et al., 2001).

Activity circadian rhythm goodness of fit estimates averaged 0.75 for the study baseline regimes. This value was well above goodness of fit estimates reported in a previous study using 5-min sampling (0.49, Satlin, et al.,1995) and was comparable to the highest estimates reported (0.8-0.95, Teicher, et al., 1997). Therefore, the methodology employed in processing the raw activity data (clipping, robust locally weighted regression, followed by conversion from 1-min to 30-min samples) was fully adequate to provide extraction of reliable activity circadian rhythm wave forms which could be reliably processed by single harmonic analysis. Since the MER participants only slept 80% of the time during the 00:00–04:00 interval during baseline, it was possible that the reduced activity was associated with higher fatigue levels in this group. Activity circadian rhythm amplitude and mesor were also lower in the MER participants during the MER regime than during baseline, which may also reflect increased fatigue levels during the MER regime, relative to the baseline regime. However, relative amplitude was higher during the MER regime, indicating that robust circadian oscillations were maintained during the MER regime. It was interesting that activity circadian rhythm amplitude goodness of fit and mesor were actually lower during the transitional days (intervals between baseline and MER regimes) than during baseline or MER regimes. In addition, the variability (mean standard deviation) of all the circadian rhythm metrics was higher during transitional days. This indicates that the degree of circadian rhythm disruption was higher during transitional days, which may reflect the effects of time zone travel back and forth between MER operations, or transitions between MER schedules and normal duty or weekend schedules. No statistically significant differences in circadian metric variability were detected between earth time and MER regimes, $t_8 < 1.7$, ns).

Table 2 (Appendix B) indicates that intra-individual variability between subjects was relatively high, particularly during MER regimes. The differences in circadian periodicity were of particular interest. While the baseline circadian period lengths clustered around 24.0 (mean = 24.08 hours), seven of nine period lengths during the MER regime exceeded the expected MER workload schedule of 24.65 hours with a mean period length (24.84 hours) that exceeded the MER schedule by 0.2 hours per day. We then attempted to elucidate this phenomenon by comparing participants with available wake-up and work onset and end times with the expected MER 24.65 hour schedule. Figure 11 shows two participants (M0303 and M0310) who had a relatively long circadian period (25.3 hours and 24.98 hours, respectively) during the MER regime but nonetheless maintained wake-up and work times according to the expected MER schedule. This indicates that this participant may have had a free-running activity circadian rhythm which was not entrained to the 24.65 hour MER schedule despite the maintenance of wake-up and work times which did follow the MER schedule. Another participant (M0310) also had a long circadian period (24.98 hours), in which the MER work schedule was maintained but the wake-up times delayed progressively, relative to the MER schedule, until the wake-up times occurred immediately prior to the work onset times. This participant may also have had a circadian rhythm which may have been free-running or entrained by the longer period wake-up time schedule. Of six participants whose wake-up and work times were evaluated with respect to the MER schedule, three participants wake-up times were synchronized with the MER schedule, two participants wake-up times diverged from the MER schedule, and one participant (M0313) had wake-up times which were synchronized with the MER schedule during one MER regime but diverged from the schedule during a second MER regime. Therefore, individual synchronization of wake-up times with the MER regime was variable and in most cases the activity circadian rhythm did not appear to be directly entrained to the 24.65 hour MER schedule. Thus, the circadian rhythm in these participants was not entrained to a schedule that shifted consistently 39-minutes daily. More likely, their rhythm was modulated by the MER schedule by relative coordination, in which the circadian rhythm periodicity was modulated, but not directly synchronized by the MER schedule.



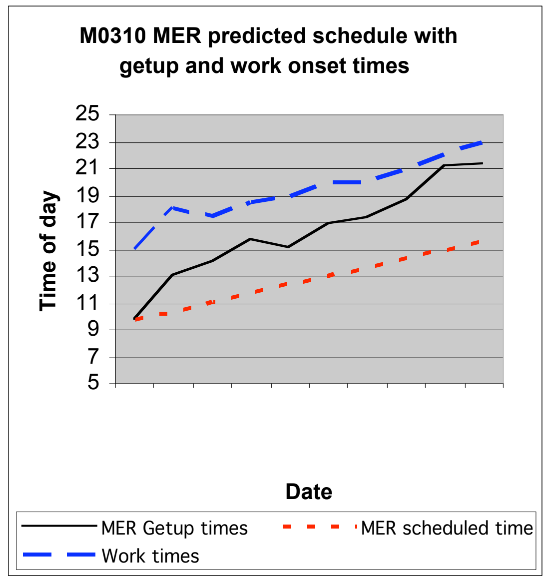


Figure 11. Comparison of wake-up and work onset and end times with expected MER 24.65 hour day schedule. The work onset schedule was synchronized to the MER schedule in M0303 but the wake-up times occurred several hours before the work onset times until 1/12/04, at which date, the work onset times became synchronized with the work onset and MER schedules. The wake-up times in M0310 progressively delayed relative to the MER schedule and the work onset times during this MER operations time period.

Two participants (M0332, 75 days; M0325, 72 days) stayed on a MER schedule during the transitional days between MER regimes. However, their wake-up times and activity circadian rhythm acrophases did not remain constant during this schedule but exhibited transient, non-stationary changes in wake-up times and circadian rhythm acrophases during this phase (Figures 12a–d). These changes coincide with increased napping while transitioning to a Mars Sol. Since non-stationary changes were evident in these and other MER regimes, we decided to use shorter MER data segments, in which non-stationary changes in circadian phase, amplitude, and amplitude were minimal, to perform direct comparisons between baseline and MER regime circadian rhythm data. Both of these participants lived local to JPL and therefore no traveling occurred between different time zones.

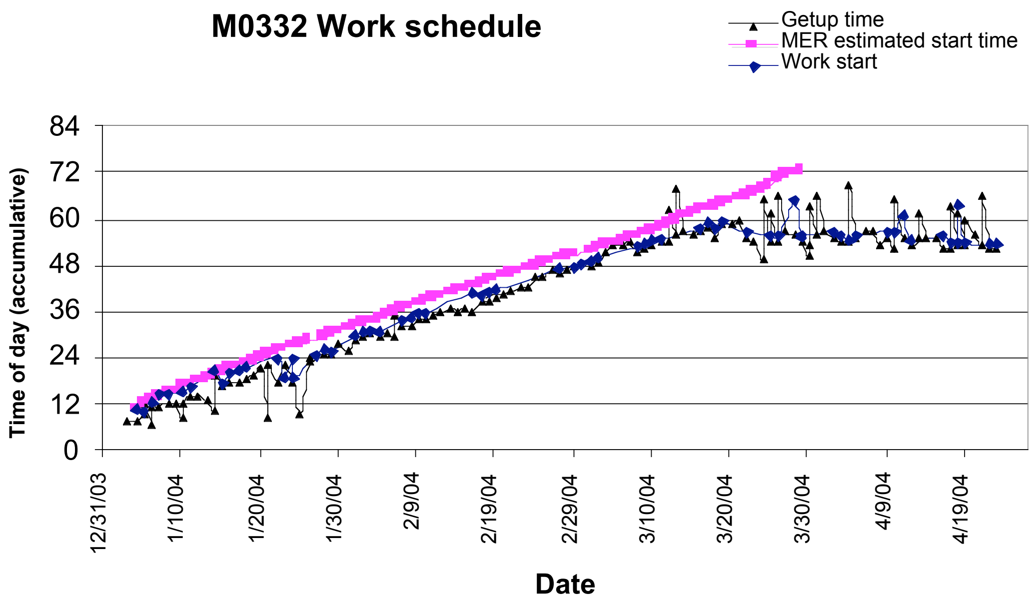


Figure 12a. Comparison of wake-up times with work start times and estimated MER start times in participant M0332, who stayed on a MER schedule for 72 days. Time of day was accumulated to incorporate transitions at midnight (i.e., 00:00 = 24 hours, 01:00 = 25 hours). Spikes in the plots represent multiple sleep periods (napping) or a large shift in sleep times, which was indicative of difficulties in adjusting to the Mars sol. This appears to occur in transitioning to and from a Mars Sol. Transitioning back to an Earth day required a phase advance.

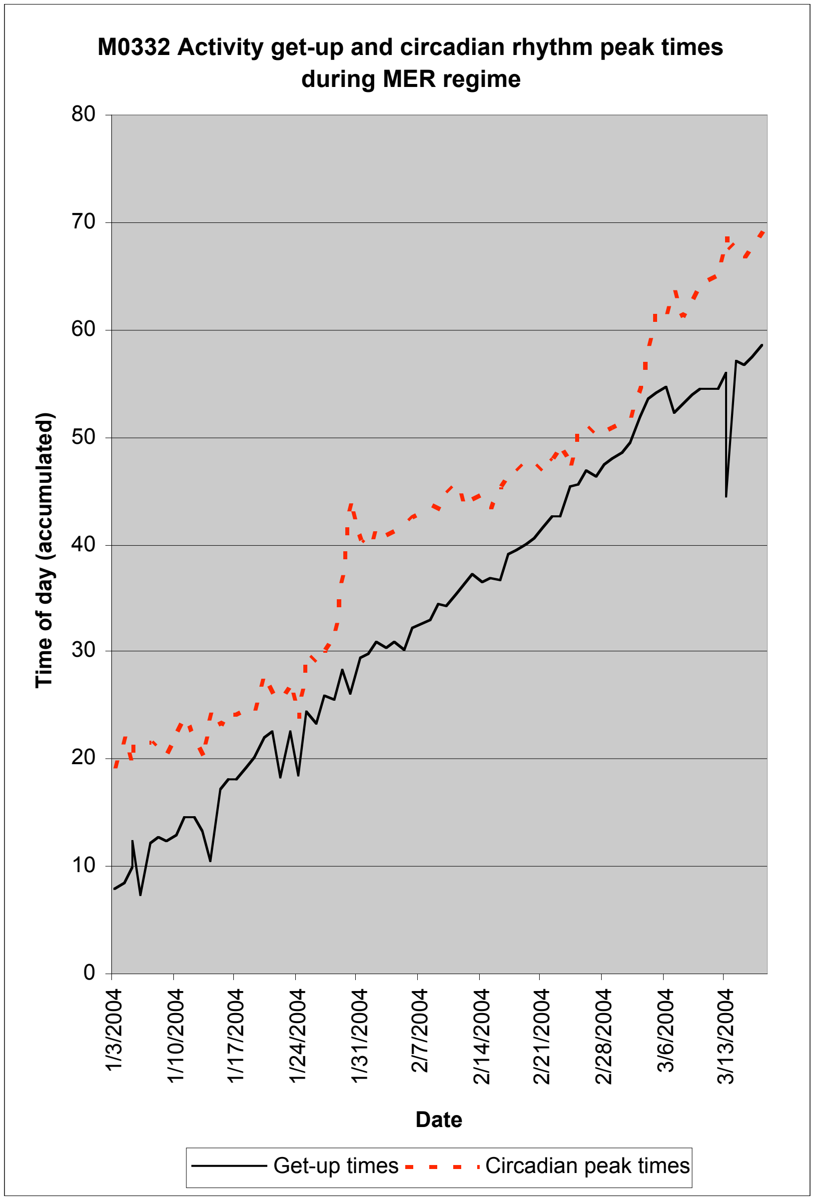


Figure 12b. Comparison of wake-up times with activity circadian rhythm acrophase converted to time of day in the same participant plotted in Figure 12a. A large non-stationary phase shift in the activity circadian rhythm was evident on 1/20/04 which coincides with the shifts in wake-up times in Figure 12a, after which the circadian rhythm peak time slowly converges with the wake-up times.

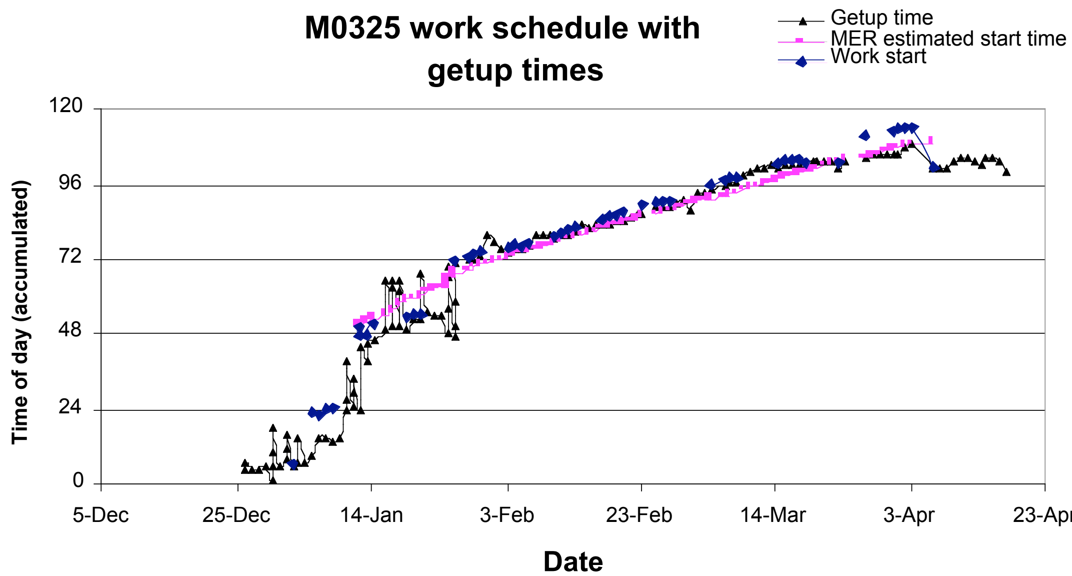


Figure 12c. Comparison of wake-up times with work start times and estimated MER start time in participant M0325. Increased napping occurred during the transition to a Mars sol; however, increased napping did not occur upon transitioning back to an Earth day despite the presence of a phase advance in the activity circadian rhythm.

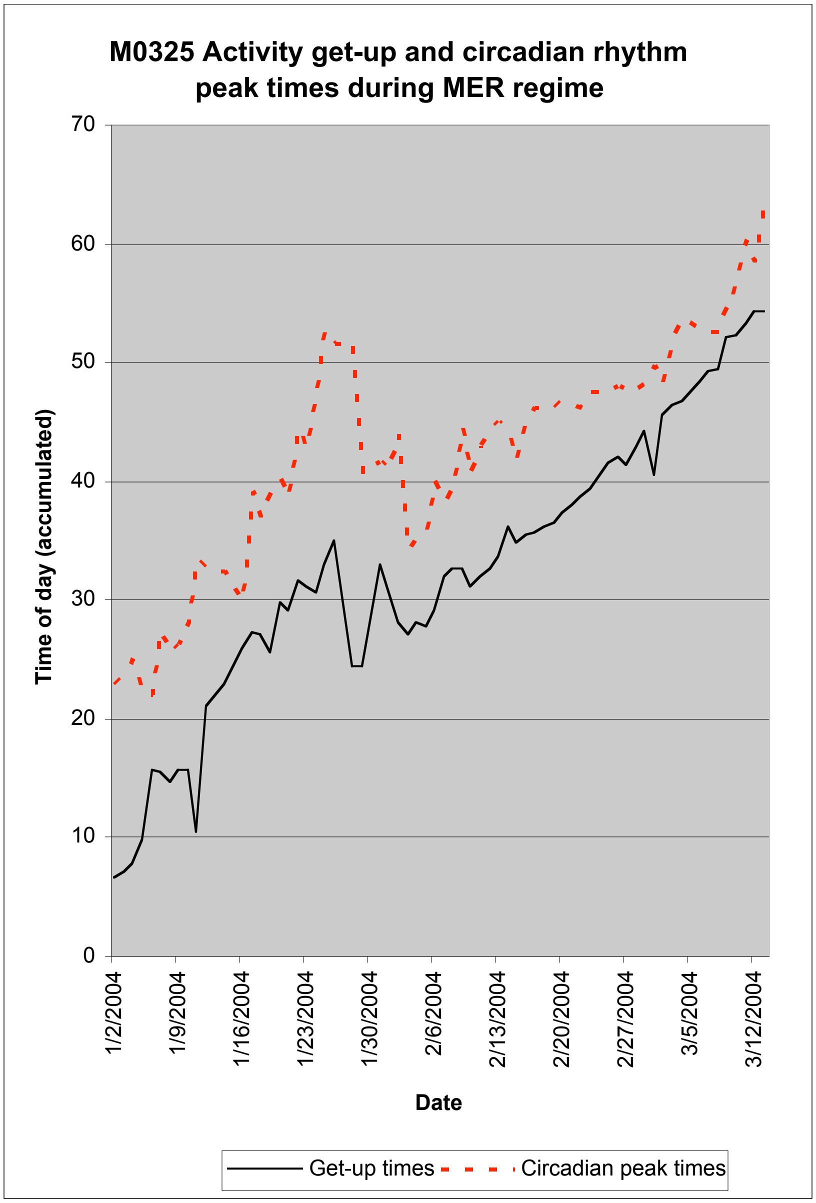


Figure 12d. Comparison of wake-up times with activity circadian rhythm acrophase in the same participant shown in Figure 12c. A large non-stationary delay in wake-up times was evident starting on 1/12/04, followed by a phase advance on 1/28/04. A subsequent phase shift in the activity circadian rhythm was evident on 1/23/04, after which the circadian rhythm peak time slowly converges to its original phase position with the wake-up times.

Changes in activity circadian rhythm periodicity during the MER regime were further evaluated by moving periodogram analysis (Figures 13a–i). This analysis indicated the appearance of non-stationary changes in circadian rhythm period length and amplitude throughout the MER regimes, including the progressive lengthening or shortening of circadian periodicity, the occasional appearance of arrhythmic or bimodal circadian periodicities during four-day segments, and the appearance of increased power in the 12-hour, or circasemidian rhythm periodicity.

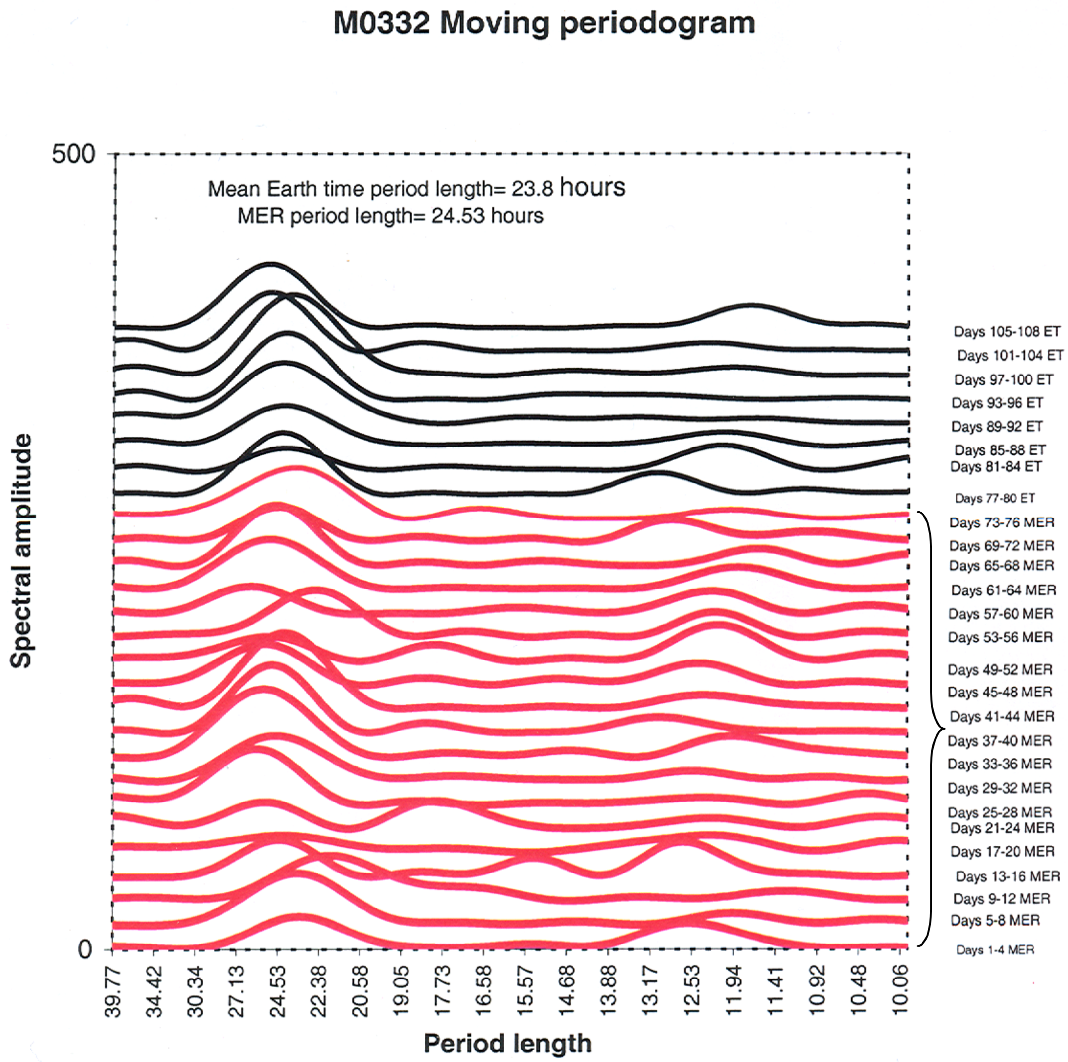


Figure 13a. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The graph starts with MER regime days 1–4 at the bottom and ends with baseline days 105–108 at the top. During the MER regime, the circadian rhythm progressively lengthens and shortens, with increasing power evidenced in the 12-hr (circasemidian) rhythm component.

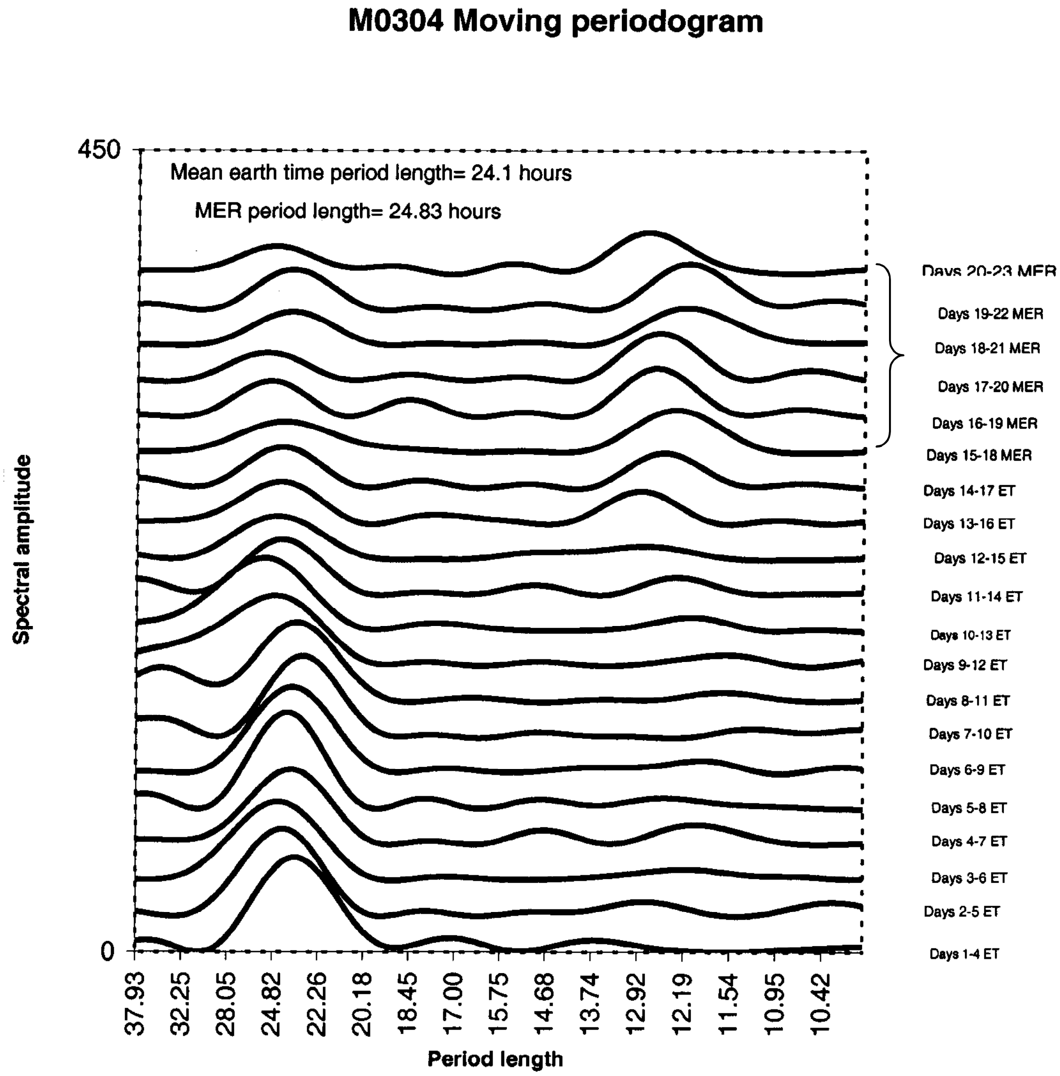


Figure 13b. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The graph starts with baseline data (days 1–4), and continues with the MER regime starting at days 15–23. Circadian rhythm stability was maintained during the MER regime, but spectral power in the 12-hr (circasemidian) rhythmic component increased while the circadian component decreased.

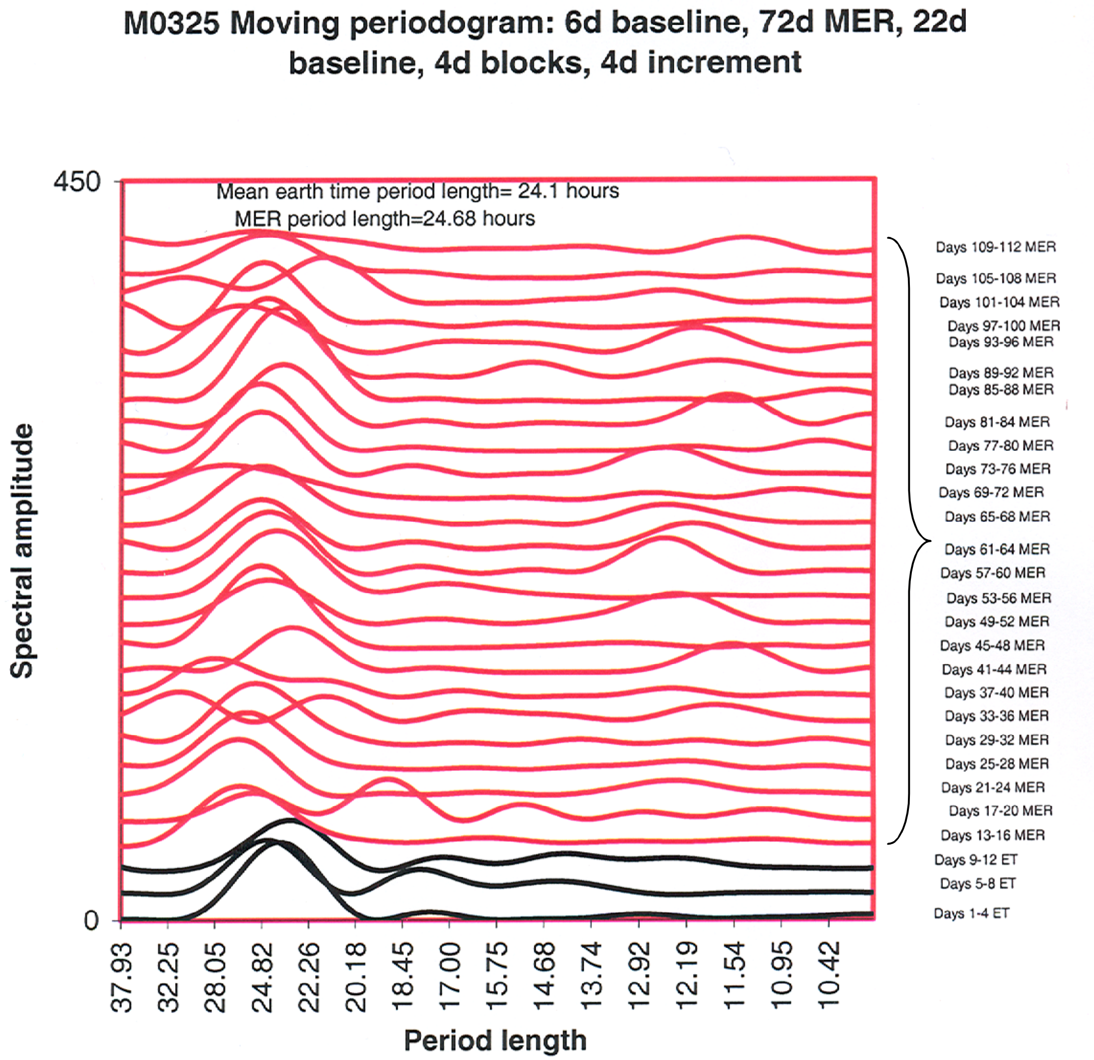


Figure 13c. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The graph starts with baseline regime (days 1–4) at the bottom. The MER regime starts on days 13–16. The circadian periodicity progressively lengthened and shortened, with segments showing circadian instability, with decreased spectral power and the appearance of bimodal periodicity components, especially during the day 33–36 block, which was associated with circadian acrophase instability. There was also increased spectral power in the 12-hr (circasemidan) rhythmic component during the latter half of the MER regime.

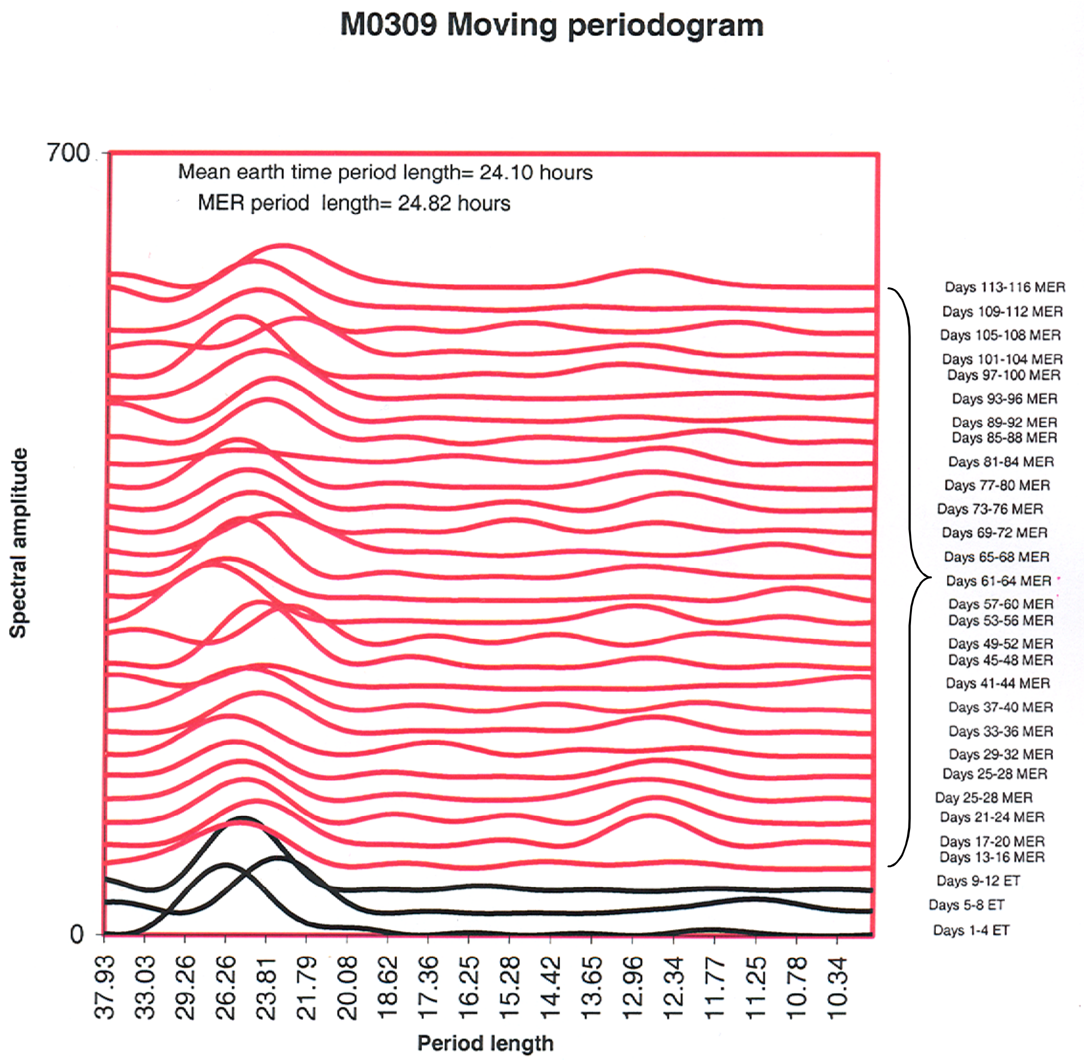


Figure 13d. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The graph starts with the baseline regime (days 1–4) at the bottom. The MER regime starts on days 13–16. Circadian periodicity was relatively stable, with progressive lengthening and shortening of the circadian rhythm periodicity.

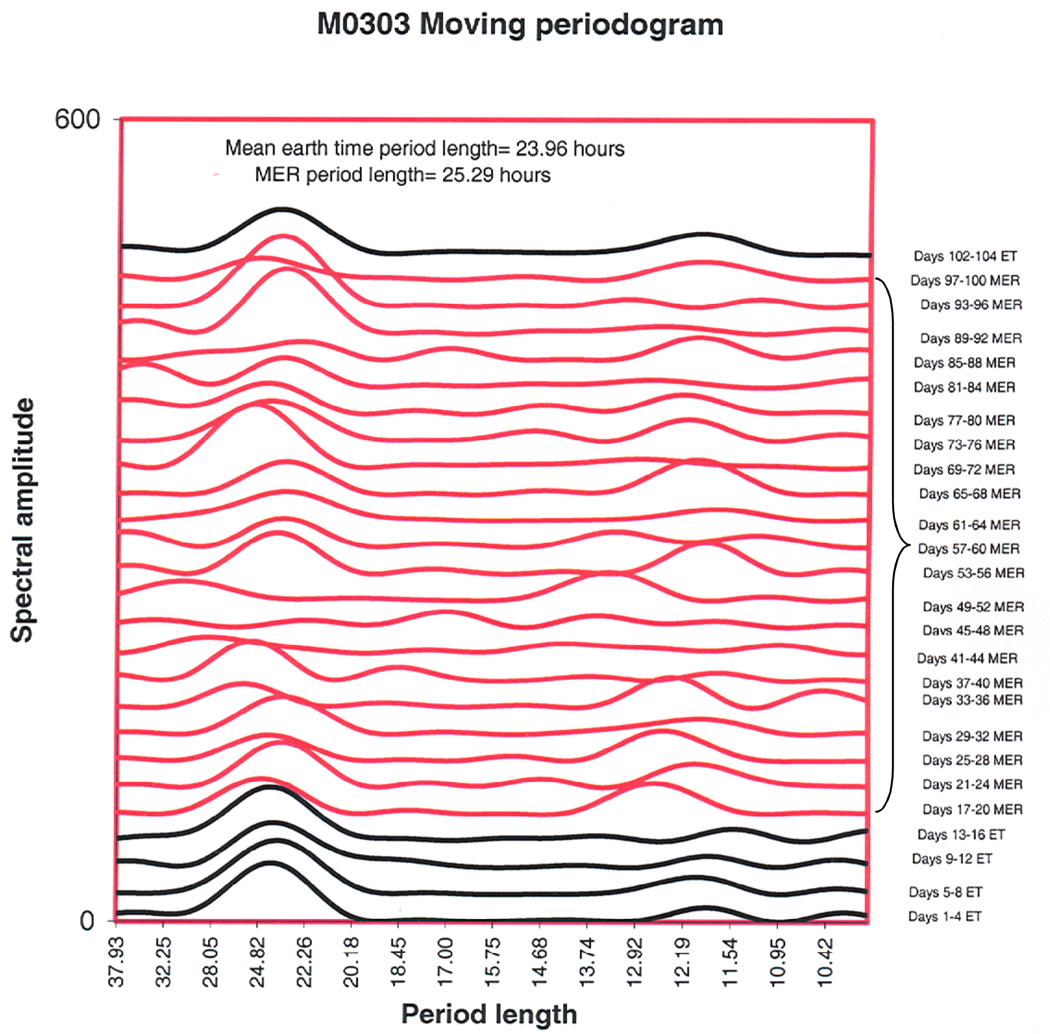


Figure 13e. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The circadian periodicity progressively lengthened and shortened, with higher spectral power in the 12-hr (circasemidian) periodicity, relative to baseline.

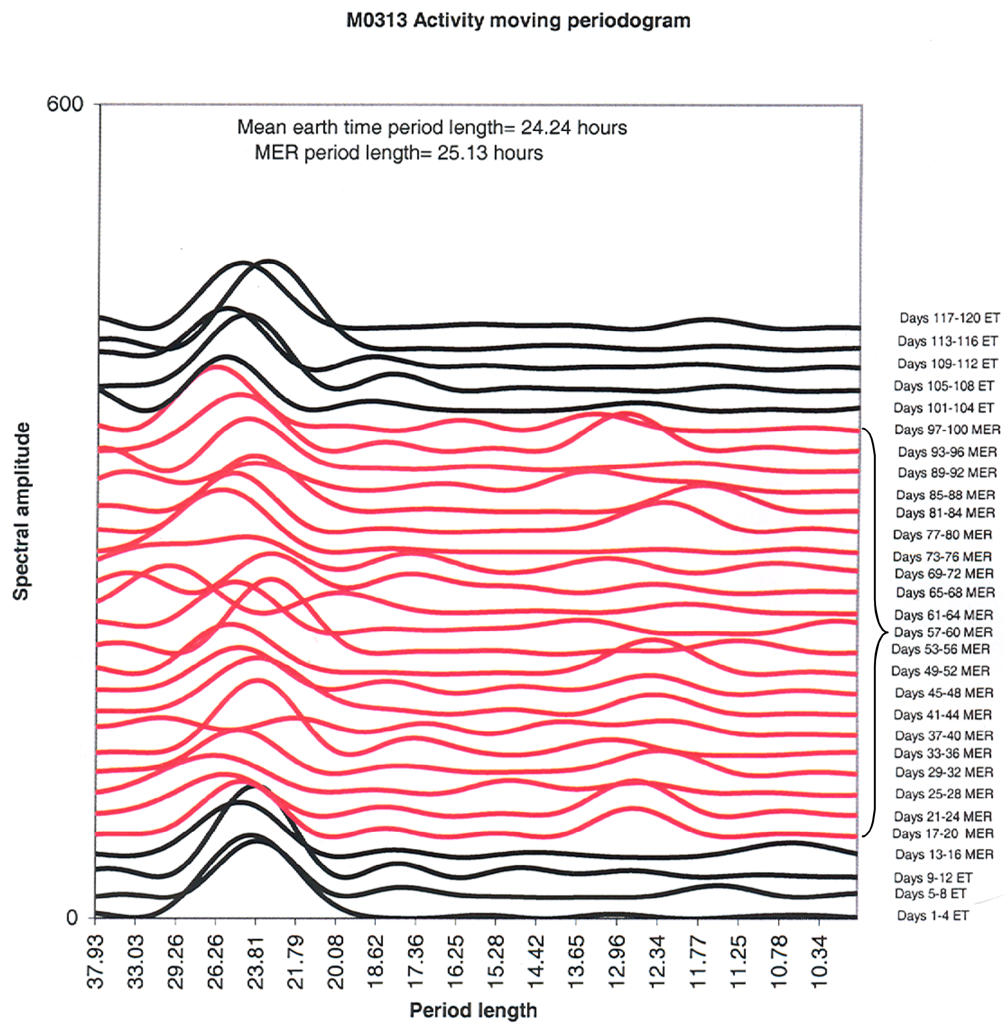


Figure 13f. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The circadian periodicity progressively lengthened and shortened, with higher spectral power in the 12-hr (circasemidian) periodicity, relative to baseline. After the participant switched from a MER-A to a MER-B schedule (days 33–36) and from a MER-B to a MER-A schedule (day 59), the subsequent blocks of days (days 37–40 and 61–64) show the appearance of a bimodal circadian rhythm peak with reduced spectral amplitude.

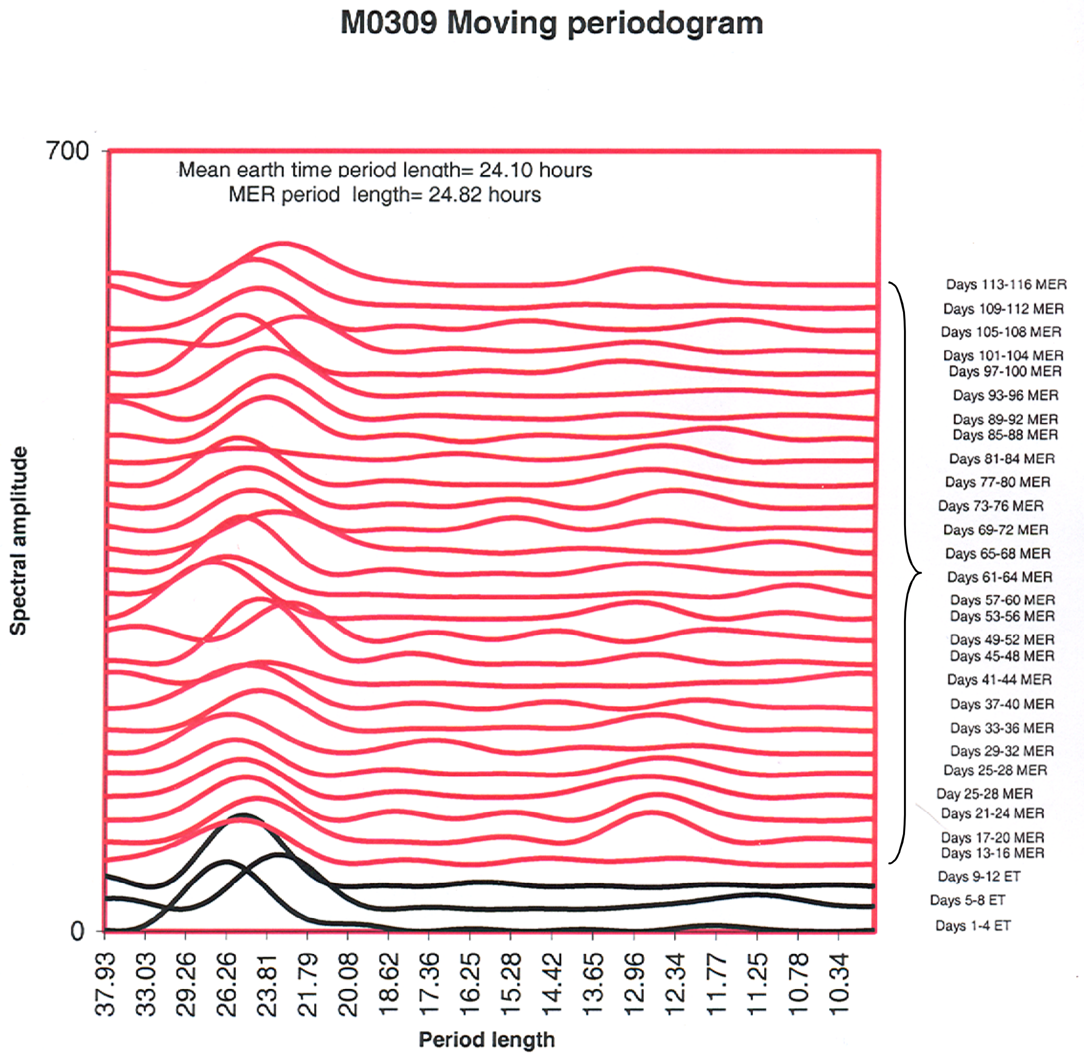


Figure 13g. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The circadian rhythm period progressively shortened during days 17–32. The circadian rhythm became unstable on days 41–52, and then lengthened thereafter. Circadian arrhythmia is evident during days 81–84 and days 105–108.

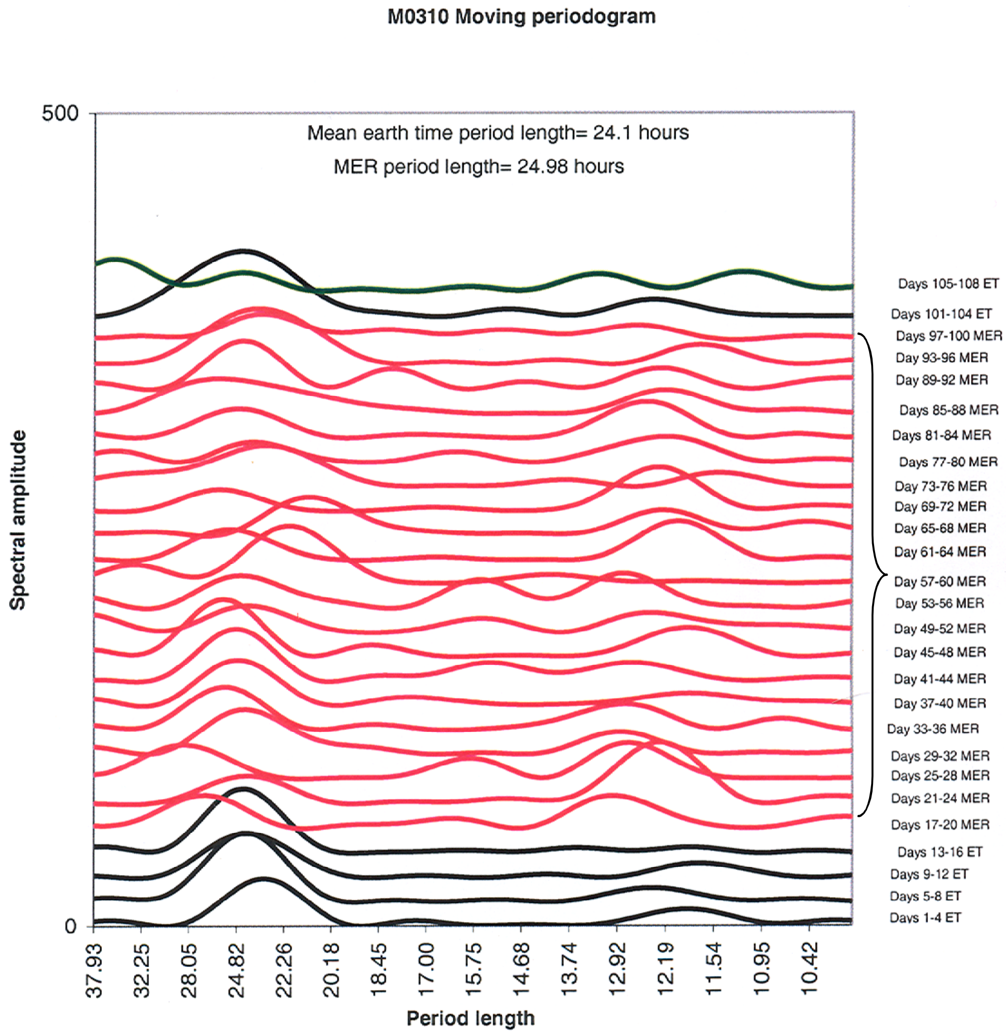


Figure 13h. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. Relatively large changes in circadian period length indicate that the circadian rhythm was unstable at the onset of the MER regime (days 17–28) and also during days 57–72, during which large changes in circadian rhythm acrophase were also observed. During the MER regime, spectral power increased in the 12-hr (circasemidian) periodicity, relative to baseline. The circasemidian rhythm had higher spectral power than the circadian rhythm during days 69–72 and 81–84.

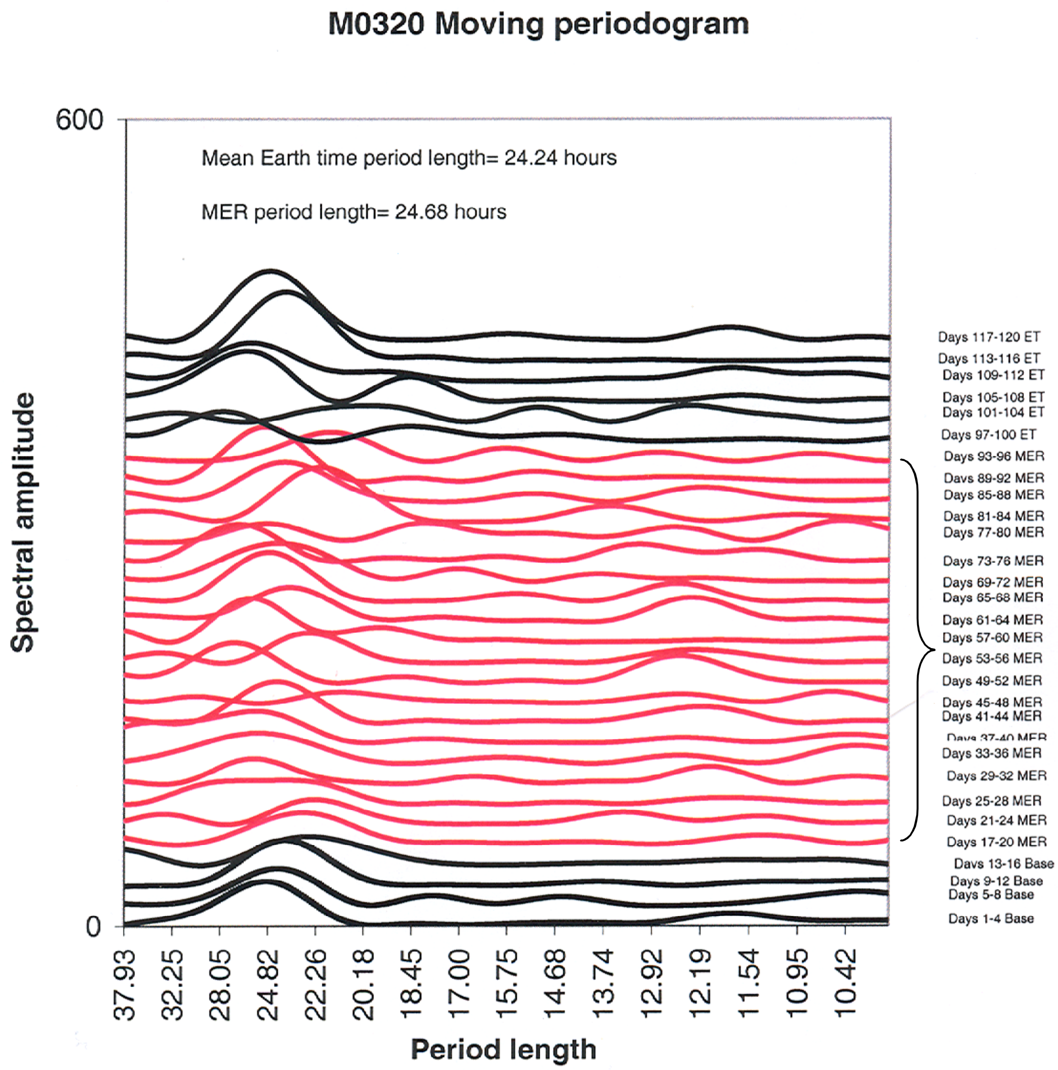


Figure 13i. Moving periodogram on locomotor activity data. Power spectra were computed on 4-day blocks of data incremented four days at a time. The graph starts with the baseline regime days 1–4. The MER regime starts on Days 17–20 and ends on Days 93–96 and was followed by earth time days starting at days 97–100. During the MER regime, the circadian rhythm progressively lengthens and shortens, with increasing power evidenced in the 12-hr (circasemidian) rhythm component. The circadian periodicity progressively lengthens and shortens over a wide range throughout the MER regime, with occasional regions of circadian rhythmic disruption or arrhythmia (days 45–48, days 77–80). The relatively large changes in circadian period length with occasional circadian rhythmic instability may have resulted from this participant switching back and forth between the rotating MER regime on work days and earth time on days off.

The responses of activity circadian periodicity during the MER regimes were highly individually specific. Some participants exhibit circadian rhythms with varying period lengths that progressively shorten and lengthen (Figures 13a, 13c, and 13d), some exhibit MER regimes with relatively stable circadian periodicity (Figures 13b and 13d), and some participants have transient 4-day segments that exhibit circadian arrhythmia and even two circadian rhythmic components (Figures 13c and 13d). Of particular interest was the appearance of relatively strong circasemidian (circa-12 hour) periodicities during the MER regime in some participants (Figures 13b and 13c). The important aspect of this "circasemidian" rhythm was that it was more marked in people who were relatively sleep deprived and resulted in increased performance errors (Hildebrandt, et al., 1974). The impact of circasemidian rhythms on circadian rhythmic stability was examined in the educed cycle analysis, in which four participants with relatively strong circasemidian periodicities during the MER regime were evaluated (Figure 14). In two participants (Figures 15a and b), the circasemidian rhythm is stronger (exhibits higher spectral amplitude) than the circadian rhythm.

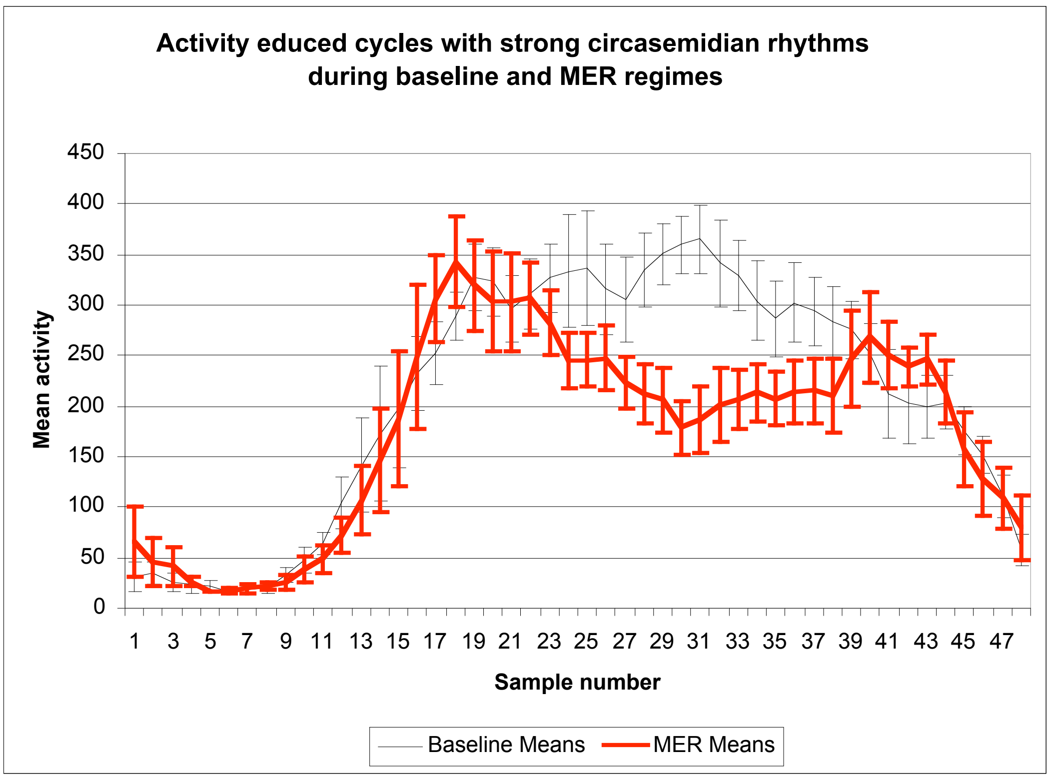


Figure 14. Comparison of activity circadian rhythm educed cycles during baseline and MER regimes. Represented were the mean +/- standard error of activity data from four participants with relatively strong circasemidian (circa 12-hour) rhythms. Sample number represents the number of sampling intervals in the educed cycle (e.g., for baseline data with a period length of 24.0 hours, there are 48 values and for MER data with a period length of 24.5 hours, there are 49 values). Therefore, sample 1 corresponds to the mean of the 00:00–00:30 interval, while sample 24 corresponds to the mean of the 12:00–12:30 interval for a 24.0 hour period and 12:30–13:00 for a 24.5 hour period. During the MER regime, activity assumes a bimodal waveform with a significant decline in activity levels during approximately the 11:00–20:00 time period (sample points 22–40).

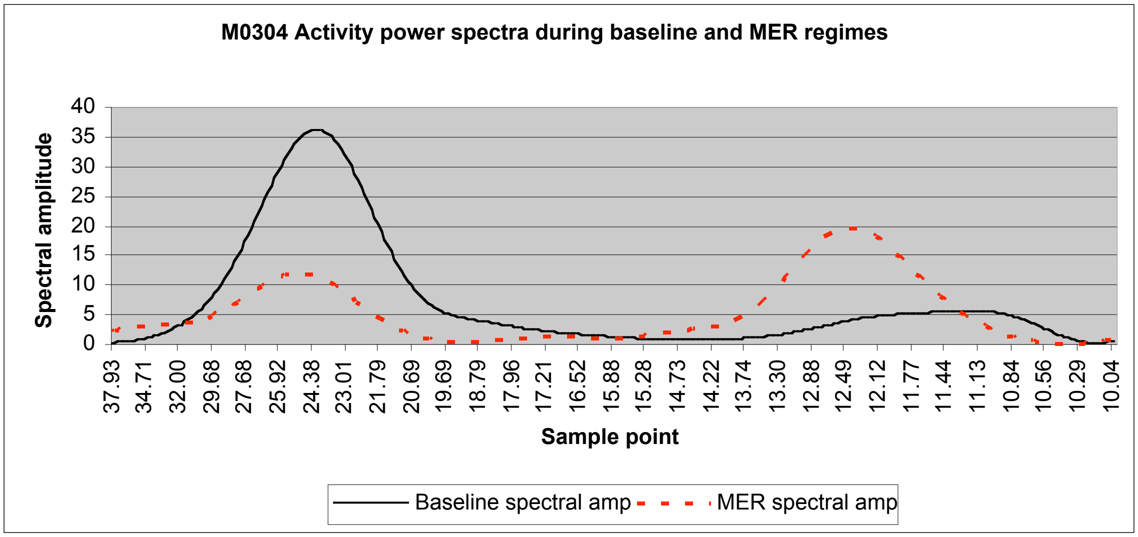


Figure 15a. Activity power spectra during baseline and MER regimes. In this participant, the circasemidian rhythm exhibits higher spectral power than the circadian rhythm during the MER regime.

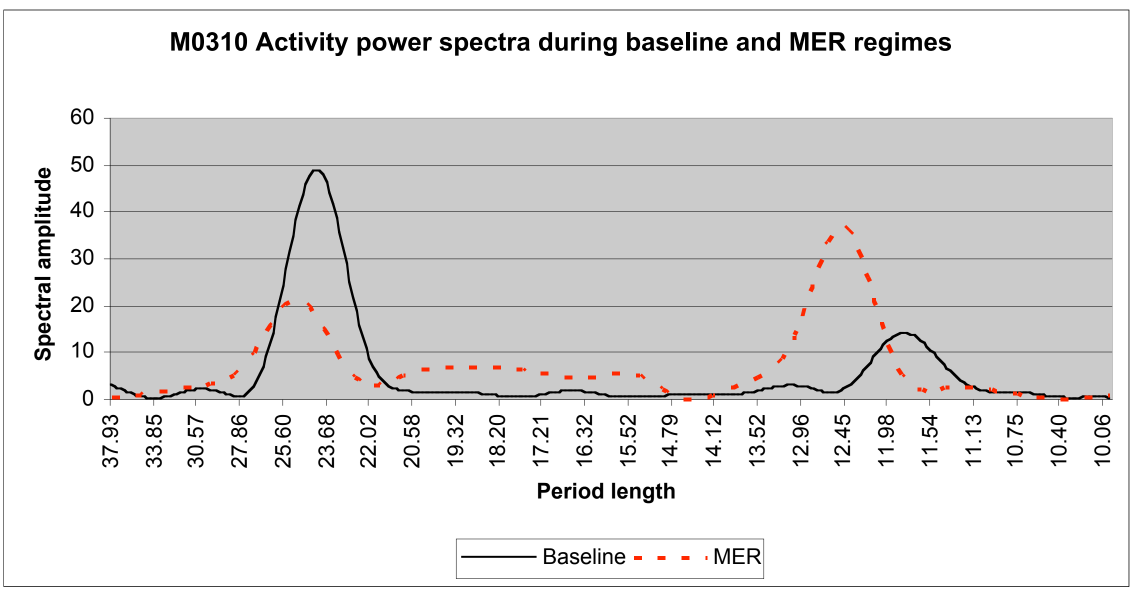


Figure 15b. Activity power spectra during baseline and MER regimes. In this participant, the circasemidian rhythm exhibits higher spectral power than the circadian rhythm during the MER regime.

Differences in circadian and circasemidian periodicities between baseline and MER regimes are presented in Figures 16a–d. Both power spectra and profilogram analysis show that the activity circadian rhythm strength was reduced during the MER regime, relative to baseline.

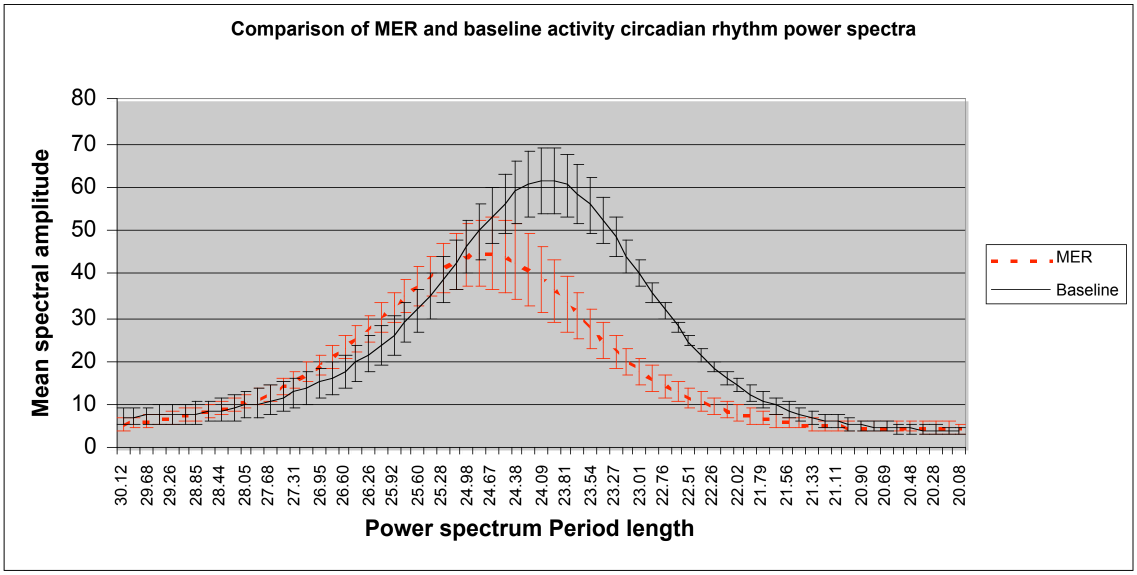


Figure 16a. Comparison of activity circadian rhythm spectral power means (+/- standard error) during baseline in 9 participants (mean = 23.98 hours) and MER regimes (mean = 24.9 hours).

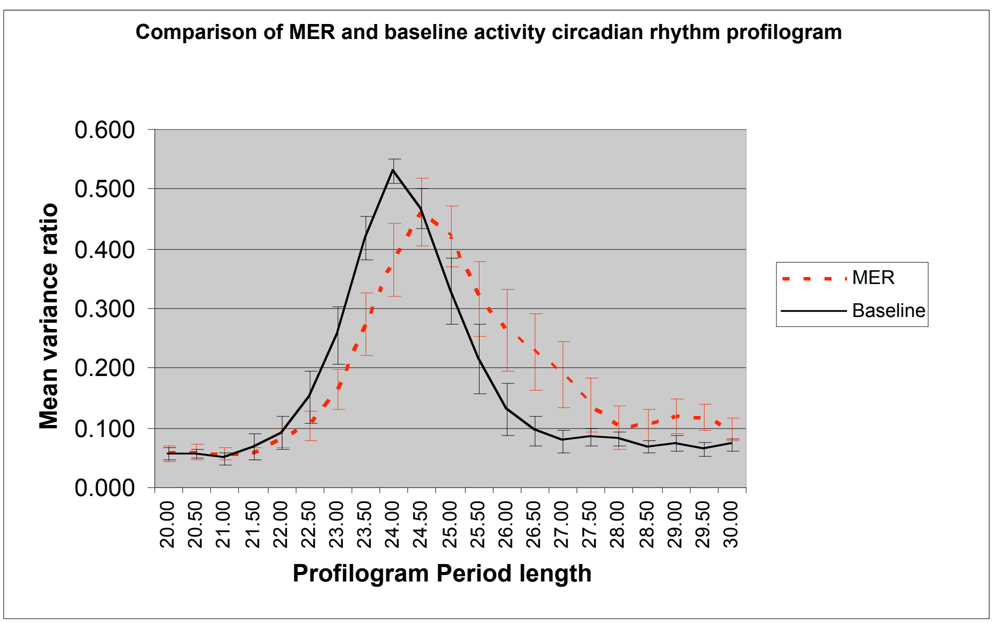


Figure 16b. Comparison of activity circadian rhythm periodicity (profilogram) means (+/- standard error) during baseline in 9 participants (mean = 24.17 hours) and MER regime (mean = 24.64 hours).

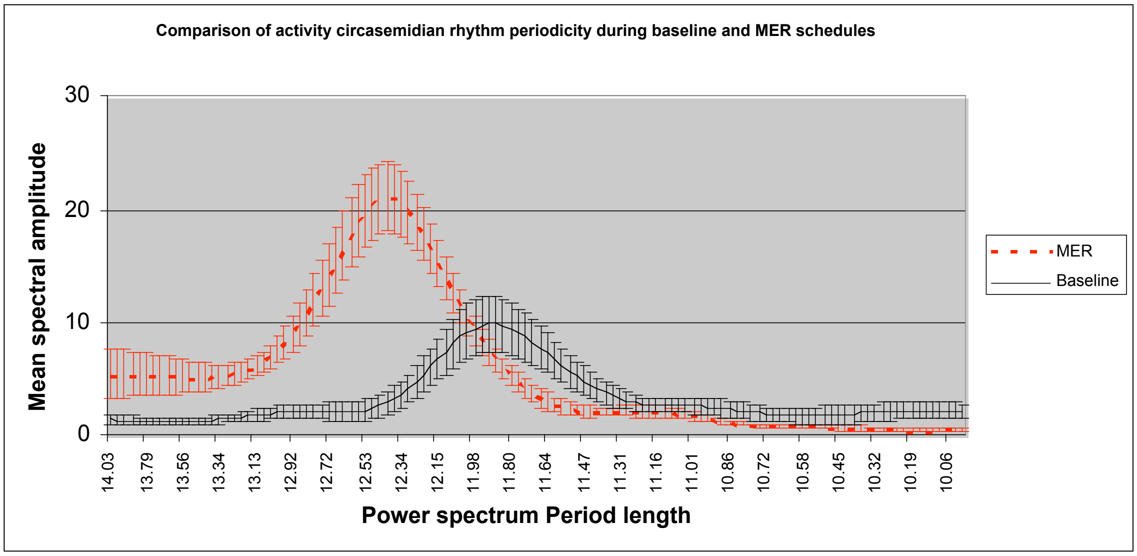


Figure 16c. Comparison of activity circasemidian rhythm spectral power means (+/- standard error) during baseline in 9 participants (mean = 11.91 hours) and MER regimes (mean = 12.41 hours).

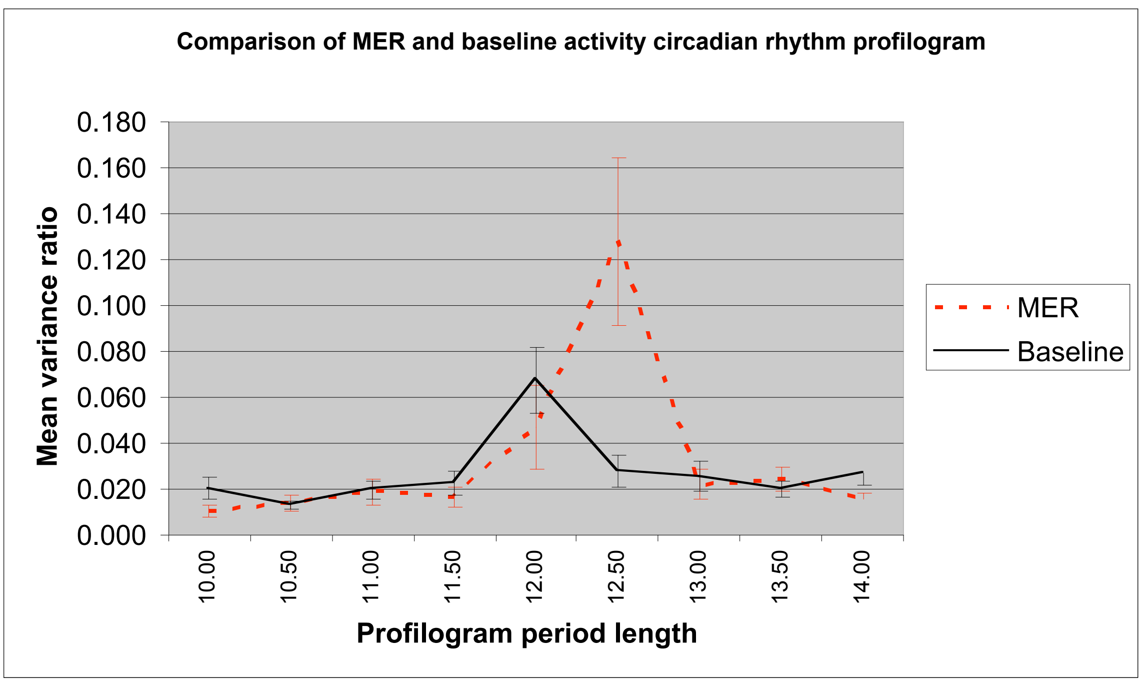


Figure 16d. Comparison of activity circasemidian rhythm periodicity (profilogram) means (+/- standard error) during baseline in 9 participants (mean = 12.12 hours) and MER regime (mean = 12.51 hours).

Both analyses also show that the circasemidian periodicity was substantially stronger during the MER regime than during the baseline regime (Figures 16c and d). The circasemidian periodicity also has a longer period length during the MER regime than during the baseline regime. The ratio between the activity circadian and circasemidian periodicities for baseline and MER regimes for both power spectra and profilogram methods ranges from 1.99–2.01. This ratio was therefore relatively constant, regardless of condition or periodicity method. The constant ratio for the power spectral analysis implies that the circasemidian rhythm was simply a harmonic of the primary circadian periodicity, but the presence of a strong circasemidian rhythm in the profilogram, which was a waveform based method independent of harmonic model assumptions, indicates that the circasemidian periodicity was a real biological periodicity. However the constant ratio between circadian and circasemidian periodicities indicates that the circasemidian rhythm was controlled or modulated by the circadian periodicity. When the subjective information on work shift duration and sleep duration means between earth time and MER regimes were compared in the four participants with strong circasemidian rhythms to the other participants, no substantial differences were found. Work shift durations were 10.04 hours for the circasemidian group and 10.38 hours for the other participants. Sleep durations were somewhat higher in the circasemidian group (7.7 hours) than in the other participants (6.9 hours). However, the composite fatigue scores showed no reported net fatigue symptoms in the circasemidian group (+0.7) but pronounced fatigue symptoms in the other participants (-3.8).

The effects of the MER regime on the activity circadian rhythm waveform are illustrated in Figures 17a–i. The educed activity circadian rhythm cycles exhibit considerable individual variability but there were distinct waveform pattern differences between baseline and MER regimens. The baseline cycles exhibit square wave type of waveform while the MER cycles show asymmetric waveforms with a rhythmic peak early in the subjective day (M0303, M0304), a predominantly bimodal waveform pattern with a pronounced post-lunch or afternoon decline in activity levels (M0309, M0310), and a similar waveform shape but with reduced activity levels during the subjective day in the two participants who maintained the MER schedule (M0332, M0325). Waveforms in which relatively high activity levels were maintained for a longer period of time during the subjective day were evident in all participants except M0309.

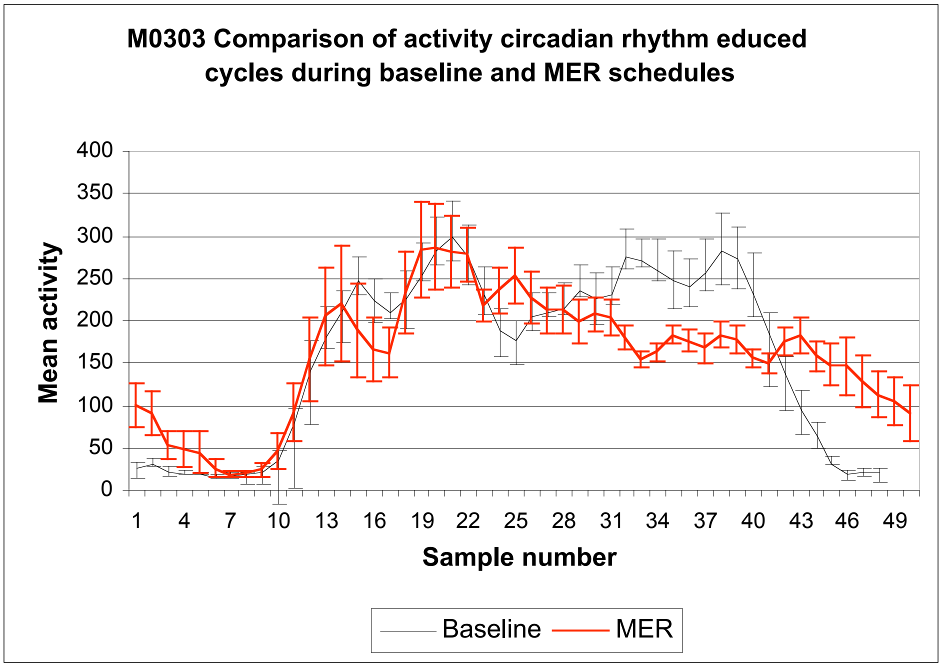


Figure 17a. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was more asymmetric with activity levels declining toward the end of the subjective day.

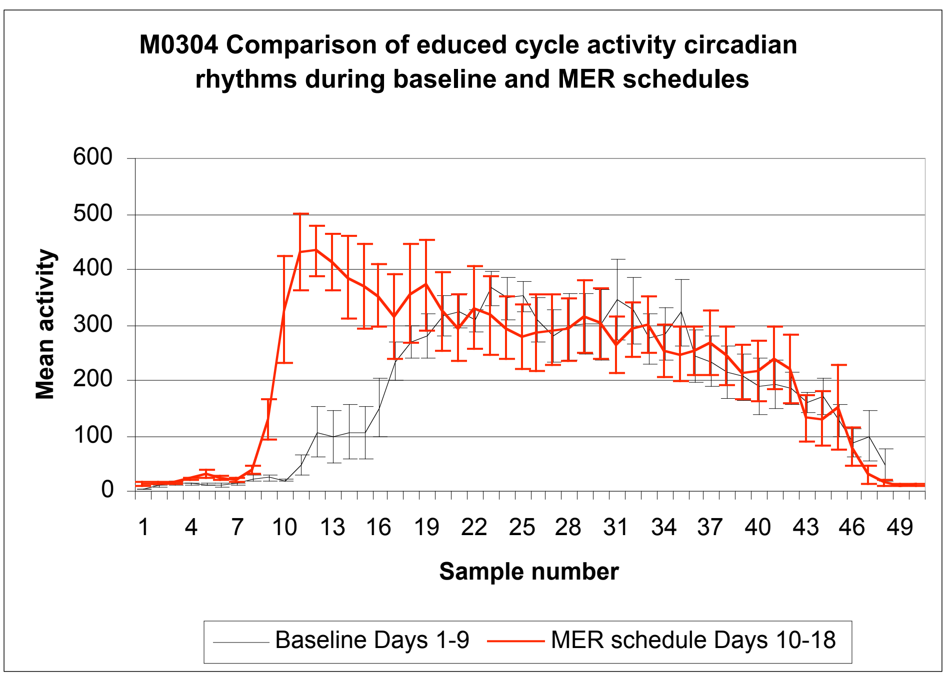


Figure 17b. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was more asymmetric with an early activity peak and activity levels declining toward the end of the subjective day.

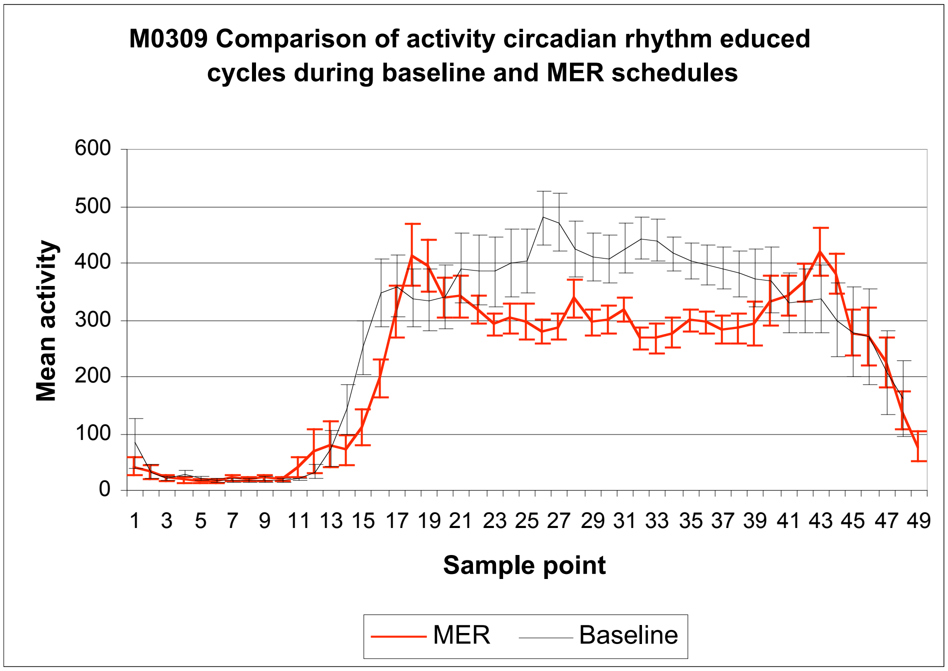


Figure 17c. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was bimodal with a substantial decline in activity levels corresponding to afternoon and early evening.

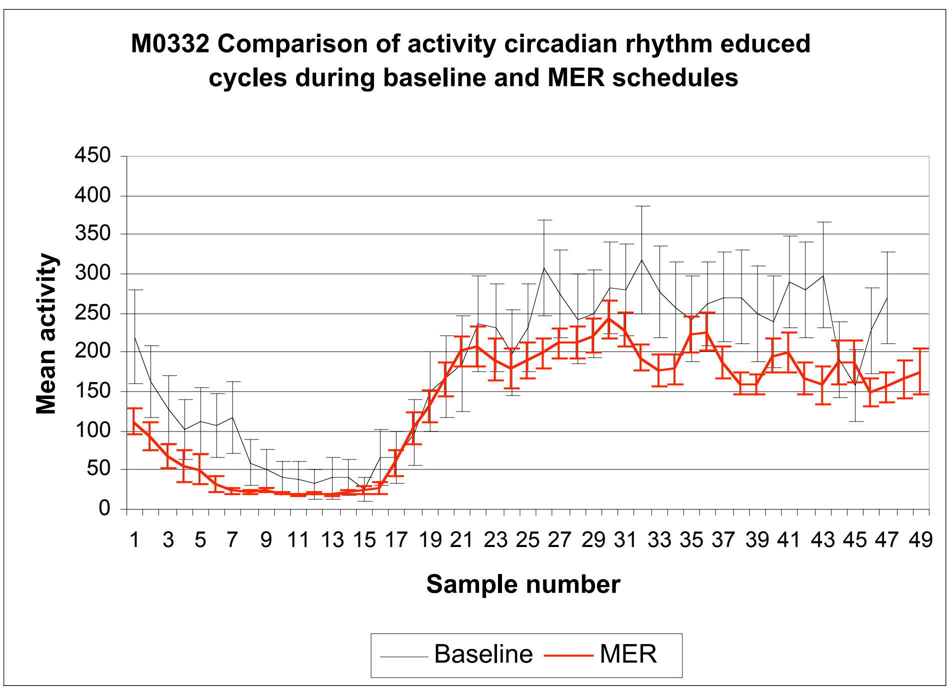


Figure 17d. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was similar to the baseline waveform with a decline in activity levels during the subjective day.

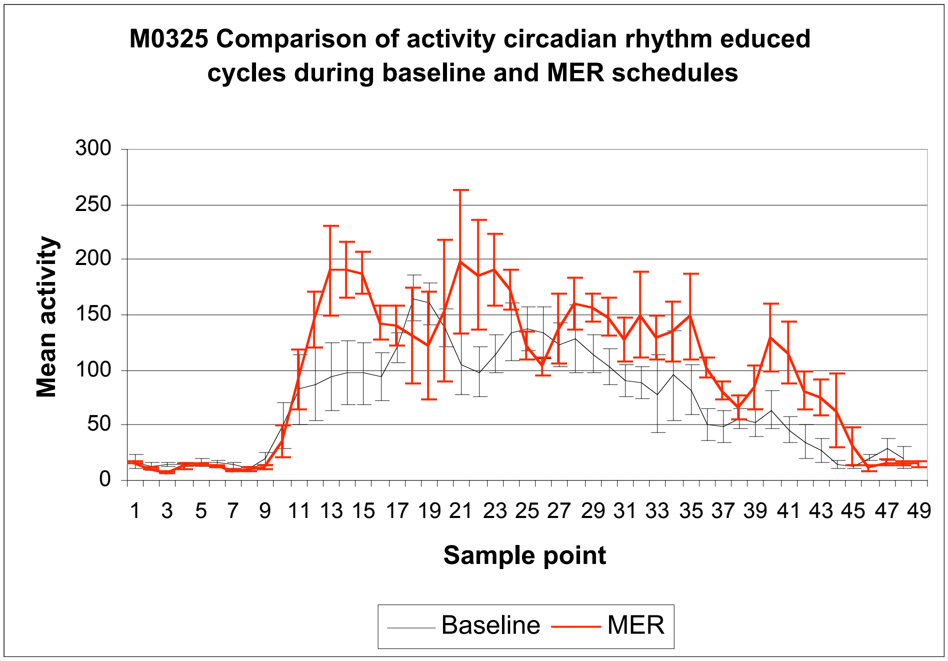


Figure 17e. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was similar to the baseline waveform with a decline in activity levels during the subjective day.

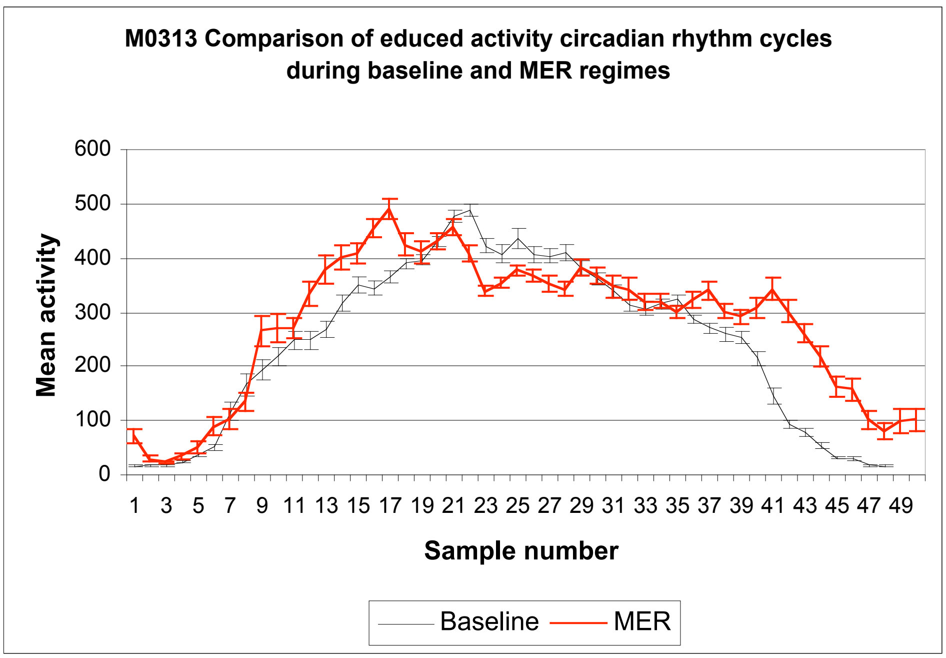


Figure 17f. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was similar to the baseline waveform but the high activity levels extend over a larger proportion of the subjective day.

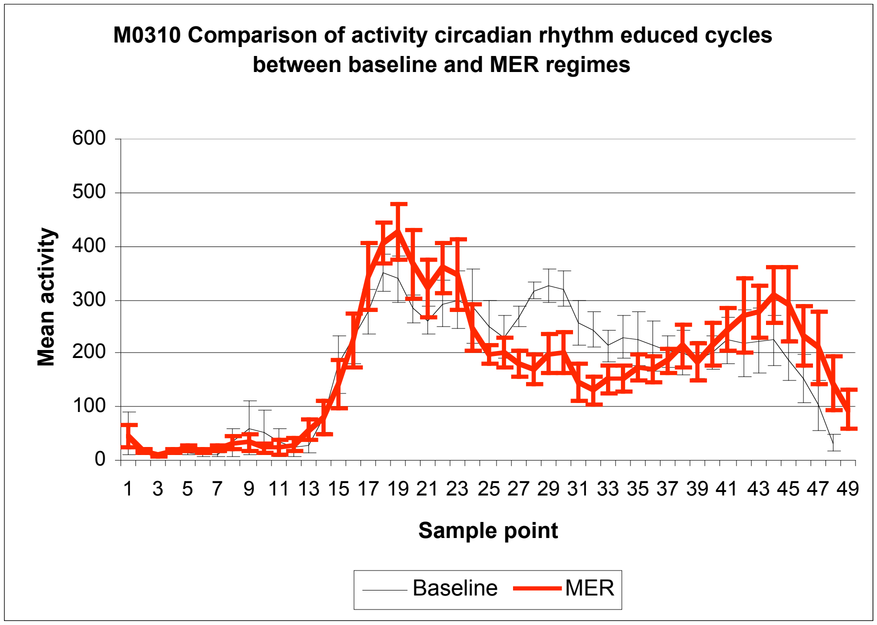


Figure 17g. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform exhibits a bimodal waveform with a decline in activity levels during the middle of the subjective day.

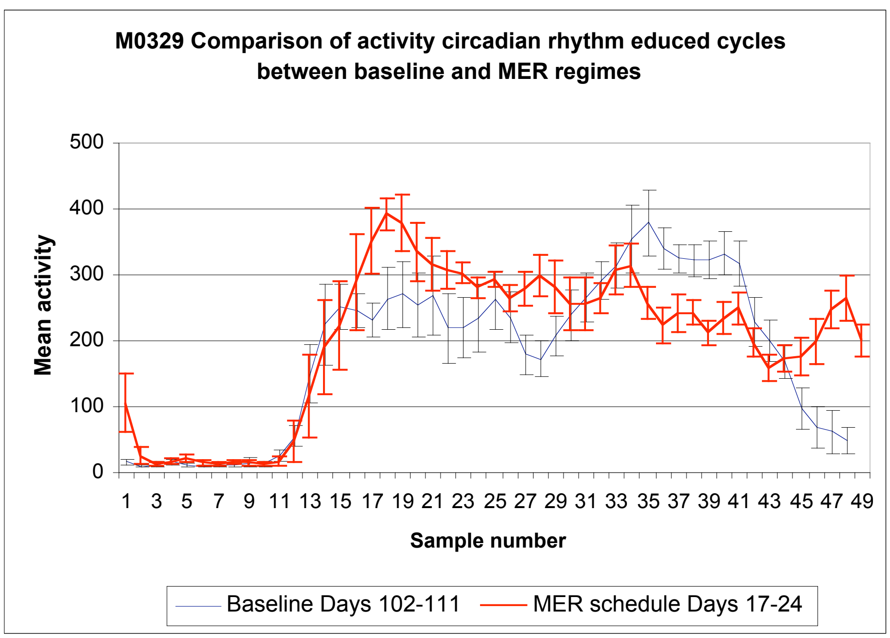


Figure 17h. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was more asymmetric with an early activity peak and activity levels declining toward the end of the subjective day. Relatively high activity levels extend over a larger proportion of the subjective day during the MER regime.

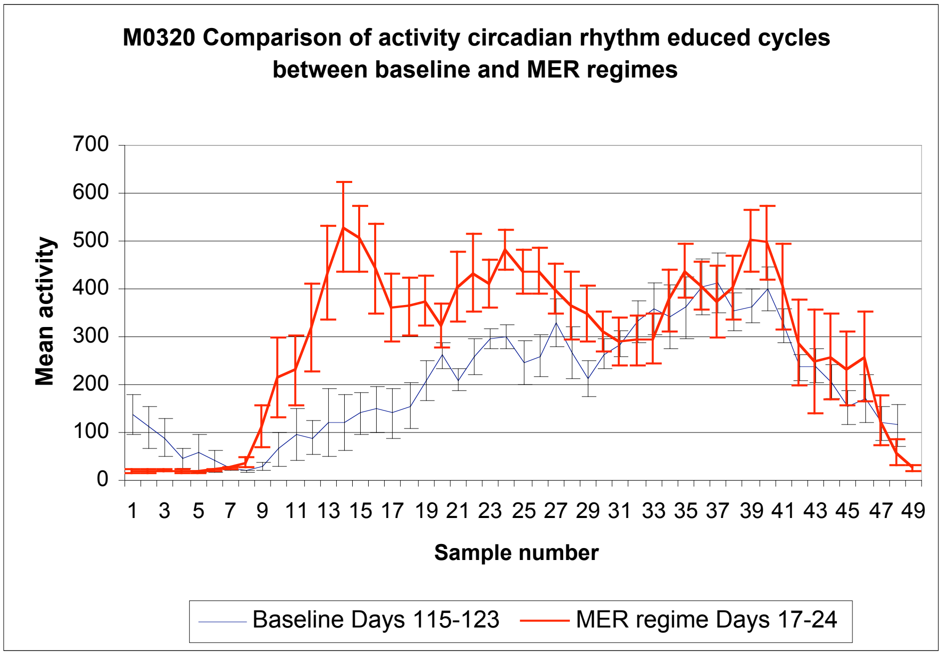


Figure 17i. Comparison of the activity circadian rhythm waveform means (+/- standard error) during the baseline and MER regimes. During the MER regime the circadian waveform was more symmetric, relative to baseline, with a high early activity peak, relative to baseline. Activity levels were higher during the MER regime, especially during the first half of the subjective day.

The comparison of activity circadian rhythms in four participants between MER regime day shifts (circadian acrophase peaks between 11:40 and 19:40) and MER regime schedules rotated to night shifts (circadian acrophase peaks between 23:40 and 07:40) is shown in Figures 18a–d. The circadian waveform differences were less pronounced between MER day and night shifts than between baseline and MER regimes but there was a tendency for reduced activity levels during the middle of the night shift in all four participants. Also, the length of the higher activity levels during the night shift was extended in 2/4 participants (M303 and M332) such that the ratio of subjective day to subjective night was larger. Circadian rhythm relative amplitude increased from 0.68 during day shifts to 1.02 during night shifts but circadian rhythm goodness of fit decreased from 0.72 to 0.64. These changes indicate that the activity circadian rhythm was robust during night shifts but that the waveform was less symmetric and sinusoidal, relative to day shifts.

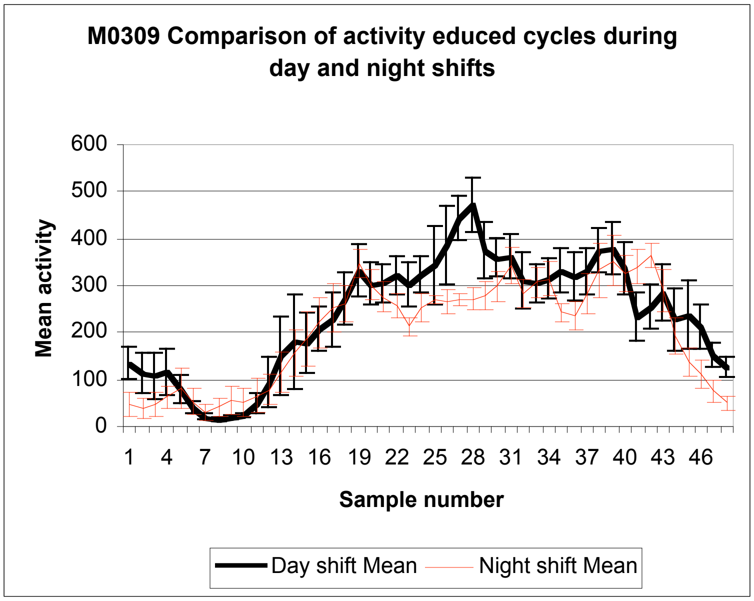


Figure 18a. Comparison of mean (n = 4) activity circadian rhythm waveform means (+/- standard error) during MER regime operations occurring during the subjective day (11:40–19:40) and rotated MER regime operations occurring during the subjective night shift (23:40–07:40). The circadian waveforms were very similar except for a reduction in activity levels during the middle of the night shift.

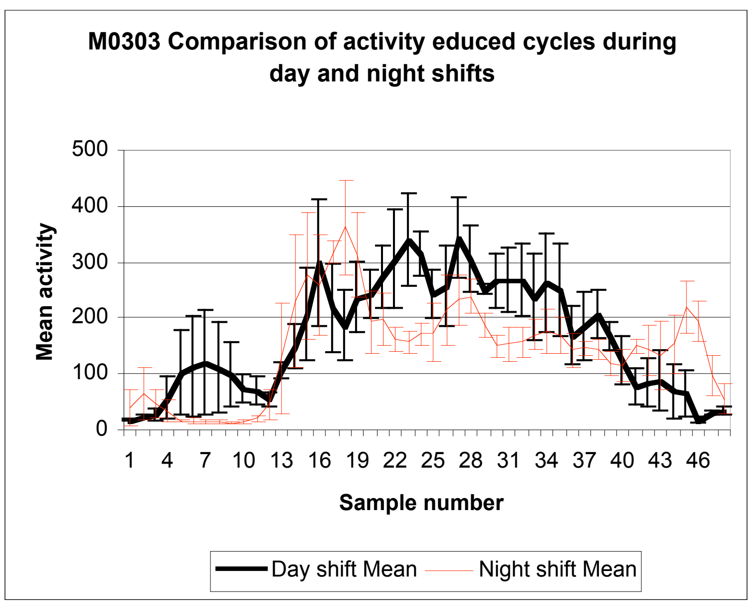


Figure 18b. Comparison of activity circadian rhythm waveform means (+/- standard error) during MER regime operations occurring during the subjective day (11:40–19:40) and rotated MER regime operations occurring during the subjective night shift (23:40–07:40). The circadian waveforms show a reduction in activity levels during the night shift associated with extension of the duration of the high activity levels during the night shift.

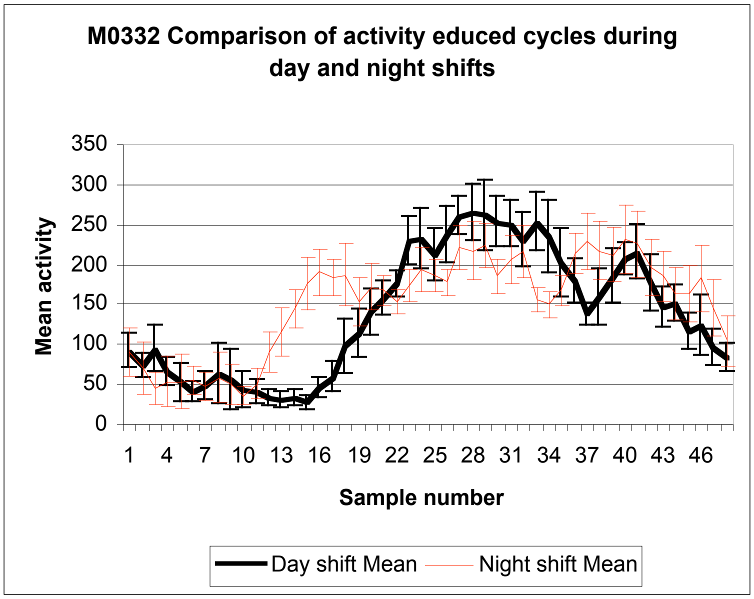


Figure 18c. Comparison of activity circadian rhythm waveform means (+/- standard error) during MER regime operations occurring during the subjective day (11:40–19:40) and rotated MER regime operations occurring during the subjective night shift (23:40–07:40). The circadian waveforms show a reduction in activity levels during the night shift associated with extension of the duration of the high activity levels.

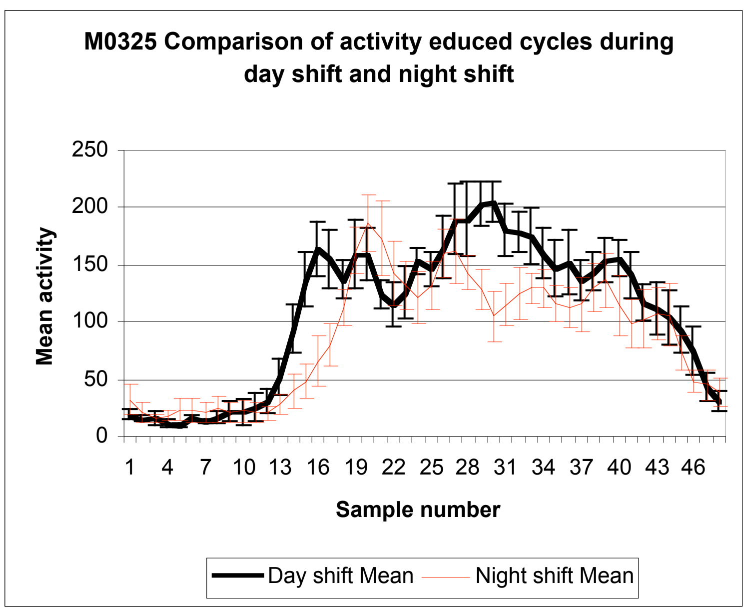


Figure 18d. Comparison of activity circadian rhythm waveform means (+/- standard error) during MER regime operations occurring during the subjective day (11:40–19:40) and rotated MER regime operations occurring during the subjective night shift (23:40–07:40). The circadian waveforms were very similar except for a reduction in activity levels during the middle of the night shift and a reduction of the duration of the higher activity levels during the night shift.

The consequences of a shift in MER operational work schedules from a MER-A shift with one Mars rover to a MER-B shift with the other rover was evaluated by examining the actigraph and periodicity analysis of activity circadian rhythms from one participant (Figures 19a–e). Since the second Mars rover was located on the other side of the planet, the switch in work shifts necessitated a 12-hour shift in the rest-activity schedule for this participant. The schedule shift occurred on days 33–36 of a 12-day MER regime.

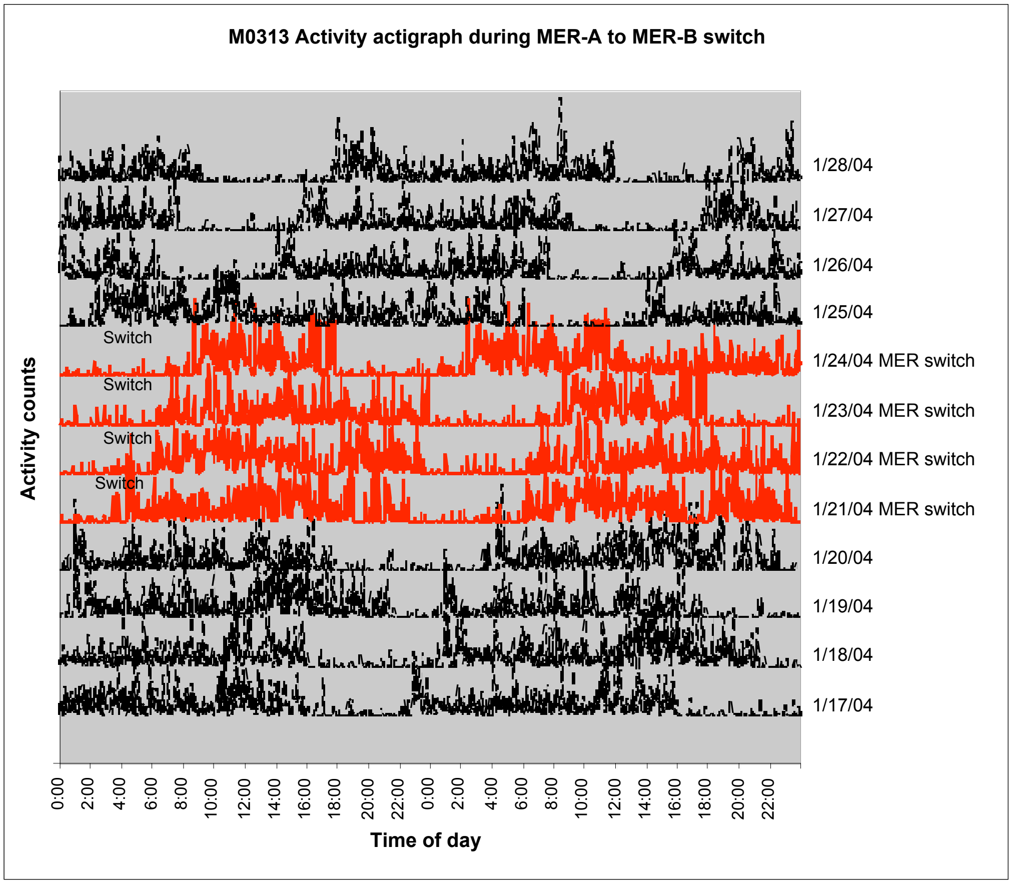


Figure 19a. Double raster plot actigraph of raw activity data from participant M0313 during a shift from a MER operational schedule with one Mars rover lander (MER-A) to another MER schedule with the other Mars rover (MER-B). The plot shows a major phase delay in the timing of the rest-activity cycle followed by extension of activity levels during the 5th day after onset of the schedule shift.

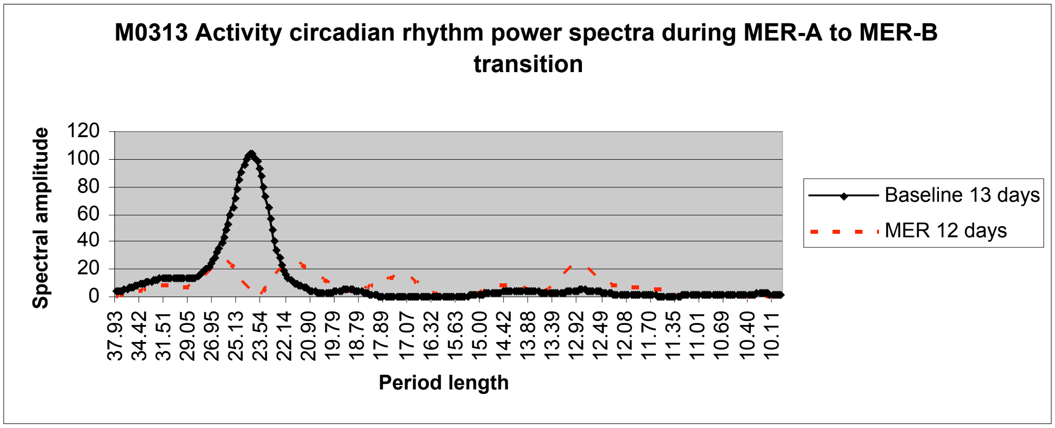


Figure 19b. Comparison of activity circadian rhythm power spectra between baseline and a MER regime in which the participant switched operational MER schedules between Mars rovers (MER-A to MER-B schedule).

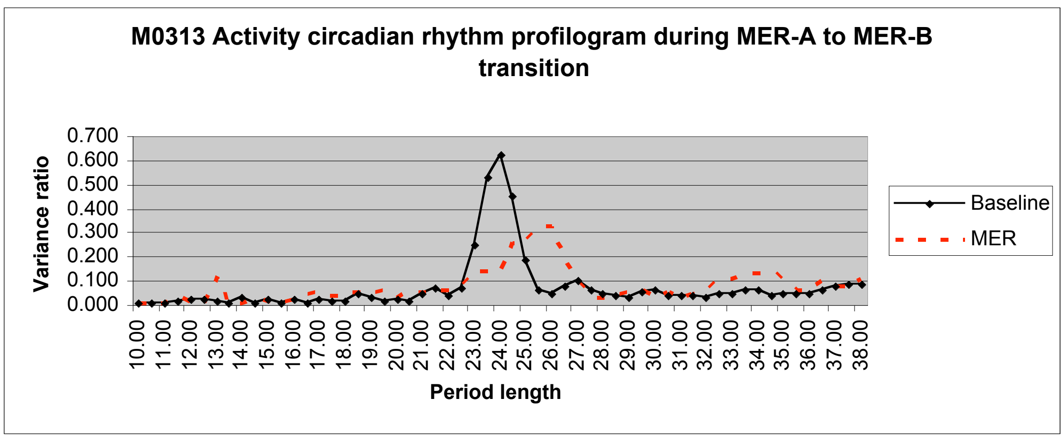
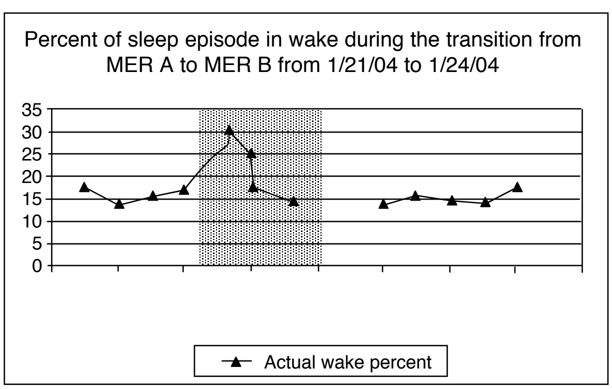


Figure 19c. Comparison of activity circadian rhythm profilogram periodicity between baseline and a MER regime in which the participant switched operational MER schedules between Mars rovers (MER-A to MER-B schedule).



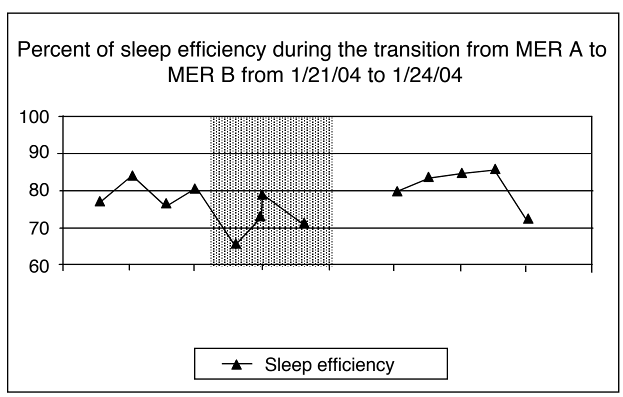
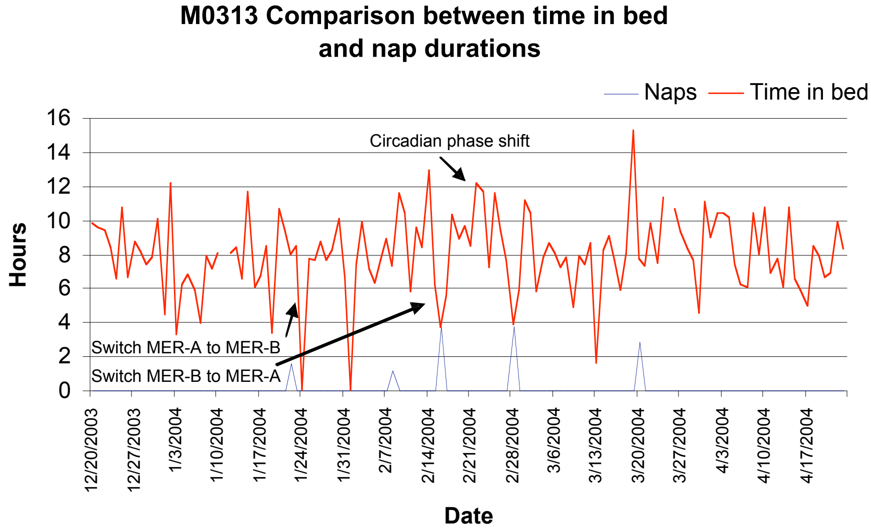


Figure 19d. Plots of actual wake percent and sleep efficiency suggests sleep disturbances occurred due to the transition between rovers. The participant has missing data on 1/25/04. Bedtimes were delayed starting from 1/18/04 at 16:00 until 1/26/04 at 6:00.



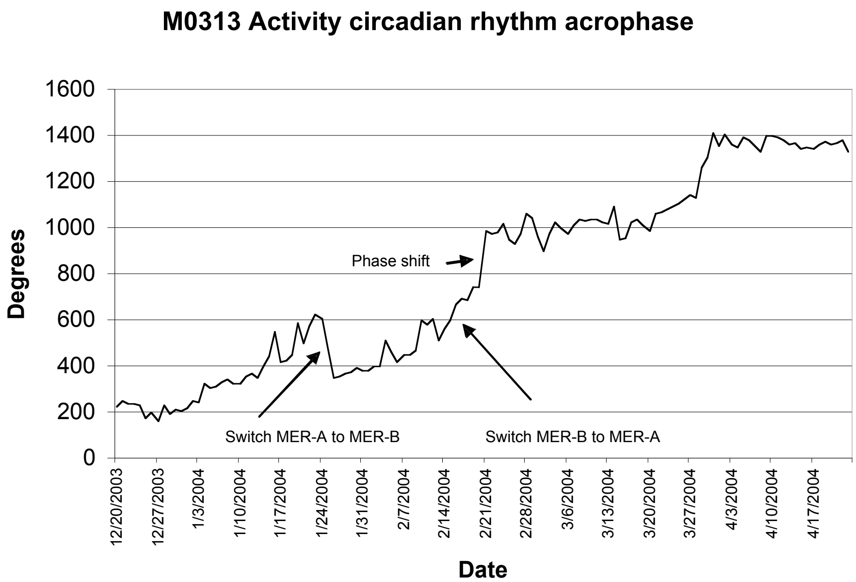
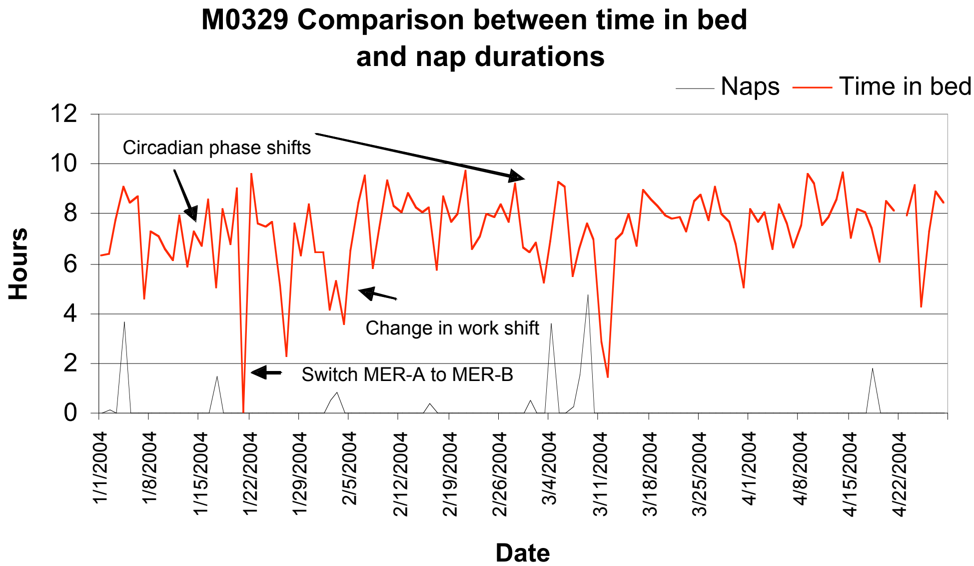


Figure 19e. Plots of daily time in bed and total daily nap durations (top) and locomotor activity circadian rhythm acrophase (bottom) show the consequences of a 12-hour work shift change that occurred when this participant switched from MER-A to MER-B operations during the period of 1/21 to 1/24 and from MER-B to MER-A operations on 2/16. The first MER operations shift was associated with a pronounced phase advance in the activity circadian rhythm peak time and a drastic reduction in time in bed. The second MER operations shift was associated with a circadian rhythm phase delay and reduction in time in bed. Other transient reductions in time in bed on 2/16 and 2/28 were associated with relatively long naps.

The periodicity analysis in M0313 showed that extreme circadian rhythm disruption occurred during the MER schedule switch regime. The power spectrum shows that either the participant was arrhythmic during this regime or that masking effects resulting from conflict between two different rest-activity times effectively occluded the rhythm, resulting in the appearance of a bimodal circadian rhythmic component (Figure 19b). The profilogram shows a weak broad band circadian periodicity (Figure 19c). The difference between the two periodicity estimates probably reflects the differential influences of masking effects and harmonic residuals on the spectral output. The circadian rhythm disruption was accompanied by reduced sleep efficiency and increased wake time in bed (Figure 19d), and a profound decline in time in bed, which was indicative of significant sleep loss in this subject (Figure 19e). The disruptive effects of changes in work shifts on circadian rhythmicity and sleep during MER operations were also evident in participant M0329, in which the changes in work shifts were associated with large circadian rhythm phase shifts and dramatically reduced time in bed (Figure 20). The extreme activity circadian rhythm disruption and reduced time in bed in these participants have deleterious implications for sleep loss, sleep disruption and fatigue during MER operations.



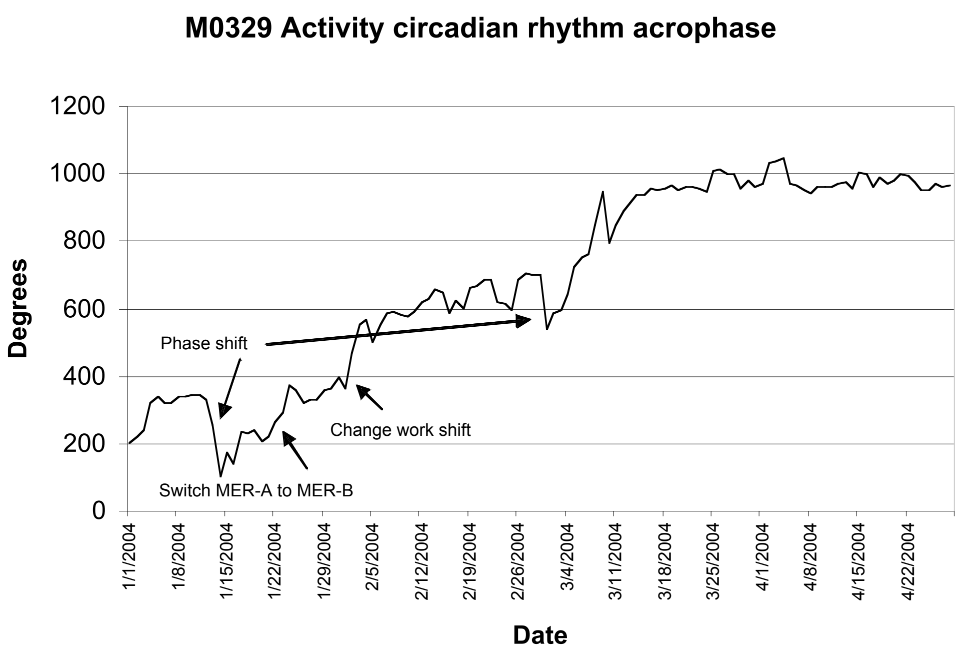


Figure 20. Plots of daily time in bed and total daily nap durations (top) and locomotor activity circadian rhythm acrophase (bottom) show the consequences of a 12-hour work shift change that occurred when this participant switched from MER-A to MER-B operations during the period of 1/21 to 1/24 and also from a large change in work shift times during MER operations on 1/31. The MER operations shift was associated with a phase delay in the activity circadian rhythm peak time and a drastic reduction in time in bed. The change in work shift timing was associated with a circadian rhythm phase delay and pronounced reduction in time in bed.

DISCUSSION

Adaptation to the MER Operations Regime

The decision to conduct MER operations on a Mars sol rotation schedule instead of conducting standard shift rotations on earth time has been documented (Bass, et al., 2005; Parke 2001). This decision was based upon the experience of the 1997 Mars Pathfinder mission, in which operations personnel agreed that working on a Mars time schedule had several advantages and disadvantages. The advantages of Mars time operations were ability to command every Mars sol operation, optimal time utilization, response to off-nominal situations, and little or no requirement for cross training. The disadvantages were the requirement for more crews to sustain Mars time operations and the potential deleterious effects of long duration Mars time operations on operational crew fatigue and well-being. Mars time operations were selected for the MER operational schedules in this study since Mars time provided the most efficient staffing solution and a fatigue/stress questionnaire completed by 43% of the Mars Pathfinder operations personnel indicated that the negative effects of both fatigue and the Mars time schedule were relatively low (Parke 2001).

The environment in which MER operations personnel were required to work presented challenges and placed unique demands on human circadian rhythm and sleep physiology that could influence the capacity of these personnel to adapt and perform during MER operations, where the maintenance of optimal levels of performance and alertness was critical to the success of the MER mission. In response, overall adaptation to the MER operational regime was relatively poor, as evidenced by the subjective report of moderate to strong increases in fatigue in 82% of the participants, and moderate to strong increases in sleepiness, with decreases in concentration and energy in most participants. In addition, participants reported several primary challenges to successful adaptation, including switching between Mars sol and earth time, switching work shift assignments between the two Mars rovers, working during the subjective night during MER rotations, sleep difficulty during the subjective day, the adverse effects of changes in the timing of social and daily living activities, and awakening by children. Participants reported the necessity of adopting several strategies to cope with the MER operational regime. These strategies primarily included the use of caffeinated beverages, naps, recovery days off, and exercise to maintain alertness and performance during MER operations. Naps tended to be clustered over periods of consecutive days in most participants, which could reflect an adaptive response to cumulative sleep loss and fatigue. There were also relatively long duration naps associated directly with large reductions in time in bed, in which these naps could represent a compensatory response to sleep loss. There was large individual variability in the capacity to adjust to the MER regimes since several participants expressed little or no difficulty in adaptation. There were several factors which could have affected individual adaptability to the MER regime, including workload duration, relative number of days off, sleep quality and duration, circadian rhythm stability, and individual response differences to MER mission stressors. In addition, there were large differences in the durations of consecutive MER operations work days and rest days in different participants. Personnel who needed to work from 17–31 consecutive days without a break would be expected to show higher incidences of accumulated sleep loss, stress, and fatigue. In general, work shift durations increased 1.6 hours from earth time to MER operations, while subjective sleep durations decreased by 1.3 hours. The increase in work shift durations during MER was likely the consequence of the requirement for 10-hour uplink and downlink shifts. Time in bed also decreased 0.4 hours during MER operations and was associated with higher variability of sleep episodes. The primary factor differentiating the relatively best adapters from the poorest adapters appeared to be sleep duration. The good adapters reported 8-9 hours of sleep, while the poorest adapters reported only 5-6 hours of sleep. Poor adaptation was also associated with frequent awakenings and changes in the timing of work shifts. The importance of this magnitude of sleep reduction for the maintenance of alertness and performance has been demonstrated in other studies. Sleep duration restrictions experienced by several MER personnel (i.e., less than 6-hr sleep per night) raises safety concerns because it has been documented in multiple ground based studies that such levels of sleep deprivation affect neurobehavioral functioning such as increased reaction times, memory difficulties, cognitive slowing, and increased lapses of attention (Bonnet 1994, Carskadon and Dement 1987, Dinges 1992, Dinges and Kribbs 1991, Dinges, et al., 1997, Naitoh 1975, Webb and Agnew 1965). When restriction continues over successive days, significant decrements in performance can appear in less than one week (Belenky, et al., 2003, Dinges, et al., 1997, Van Dongen, et al., 2003). Operational space flight simulation studies (Wright, et al., 1999), have also demonstrated that such chronic sleep reduction can result in performance decrements, subjective and objective sleepiness, decreased alertness and sleep disruptions. As a result, operations personnel can experience fatigue when trying to perform mission critical tasks and experience sleep disruption during daytime sleep, thus potentially compromising the mission and increasing the risk of accidents and possible mission failure. A slight reduction of sleep length to 7 hours per night was insufficient to maintain brain vigilance during schedules which precluded extra time for sleep recovery (Wright, et al., 2006). Van Dongen (Van Dongen, et al., 2003) has shown that even 8 hours per night may be insufficient to prevent the buildup of neurobehavioral impairment. Therefore, the reduction of subjective and objective sleep time during MER operations in our study has unfavorable implications for the maintenance of personnel well-being and mission performance.

The increase in work shift durations of 1.6 hours from baseline to MER operations was also of concern since increased workload durations subtract from time available for sleep. A recent survey showed that 63% of Americans work more than 40 hours per week, with some 40% exceeding the 50-hour a week mark (Sandweiss 2004). The average MER workload of 10.4 hours corresponds to a 5-day workload of 52 hours, which is comparable to the workload for 40% of the population. However, 26% of the MER workloads exceeded 12 hours in our study. In another study, a week with 12 hour work days was associated with greater exhaustion and lowered sleep quality (Dahlgren 2005). Fatigue also was predicted by high work demands and disturbed sleep (Akerstedt, et al., 2004). High workload combined with high stress levels increases sleepiness and impairs sleep (Dahlgren, et al., 2005). Since disturbed sleep was reported by several participants in our study as the consequence of awakenings due to children and difficulty sleeping during the subjective day, sleep disturbances may have contributed to fatigue resulting from high workloads during MER operations. The problems presented by attempts to obtain restful sleep during the subjective day are common in night work, which is associated with excessive daytime sleepiness, abnormal sleep duration, and poor/fair health (Paine, et al., 2005). Therefore, high workloads in our study during MER operations are predictive of potential sleep loss and deterioration in well-being and the resulting fatigue may have been exacerbated by stress and disturbed sleep. Two participants indicated that their adaptation improved during about the first month of MER operations. This adaptation may have resulted from the initial excessively long work MER shift durations. These work shift durations decreased during the mission due to improvements in automation, training and experience (Bass, et al., 2005).

Differences in adaptation to the MER regimes between personnel living local to JPL and those who moved to Pasadena from remote locations were not assessed due to the difficulty of evaluating the effects of all the other uncontrolled variables, such as age, sex, presence of children, and differences in MER consecutive work days and days off. However, it was reported that the remote personnel had less difficulty adapting to the MER sol schedule than the JPL local personnel (Bass, et al., 2005). This conclusion was not documented with specific evidence but was supported by specifying that the remote personnel had the advantage of having special housing arrangements with black-out shades and flexible house cleaning services. On the other hand, the JPL local personnel had the additional stress of managing tasks with their families such as child care and the additional workload of attending MER institutional meetings and meetings related to other aspects of their professional work. These demands could have resulted in increased stress levels in the JPL local personnel and reduced available time for sleep and recovery.

This study focused primarily on assessment of changes in sleep and circadian rhythmicity during MER operations. However, subjective reports indicated the occurrence of stress related responses in several participants. These responses were manifested by increases in irritability in most participants and individual reports of stress related problems with social isolation, lack of social camaraderie, and awakenings in response to children. The experience of social isolation in this study may be important since depression, irritability and hostility with some cognitive impairment were commonly reported during exposure to isolation in Antarctic missions (Palinkas 1988). One of the problems in subjective evaluations of fatigue is that dependent variables measured in survey responses to operational duty factors characterized as “stress”, “fatigue”, or “sleepiness” are not orthogonal or independent. (Galipault 1980; Chatoo, et al., 2006). However, the presence of documented stress responses in our study, in which several objective indicators of increased workload and reduced sleep time were obtained, is important to the degree that stress may exacerbate fatigue resulting from other factors. In flight attendants, end of duty stress was significantly correlated with end fatigue, start and end sleepiness, start stress, and miles walking required (Galipault 1980). Also, sleep problems in flight attendants were frequently attributable to family and personal problems, tension, and emotional stress (Galipault 1980). Physiological interrelationships between fatigue due to sleep loss and stress have been recently established since poor sleep quality is associated with higher blood pressure and blood pressure variability (Lanfranchi, et al., 2005). Therefore, it is possible that perceived stress in certain participants exposed to MER operations may have contributed to their problems in adaptation to the MER regime.

The reported incidences of increased fatigue and stress problems in the MER participants appear to be of higher magnitude than the incidences of problems experienced by operations personnel working on Mars time in the 1997 Mars Pathfinder study, in which subjective responses to Pathfinder operations were assessed by a post-mission questionnaire (Parke 2001). In this mission about 70% of the questionnaire respondents worked on the Pathfinder rover and 30% worked primarily on the Sojourner rover. The negative effects of fatigue and scheduling on work performance were reported as reduced during the second month of the Pathfinder mission. The differences in reported fatigue between the MER and Pathfinder studies can be attributed to changes in workload and days off during the second month of the Pathfinder mission. During the second month, Mars time work days were reduced from 23 to 11 days, daily workload was reduced from 12 hours/day to 10 hours/day, and days off increased from 5.5 to seven days. Fatigue was lower during the second month of operations in some workers despite increased workload on Mars time. Therefore, the increased Mars time workload effects upon fatigue may have been counteracted by shorter work shift durations and increased time off. The respondents said they could have sustained Mars time schedules for an additional two months with reduced hours and more days off. Fatigue had significantly less effect on performance at work in the Pathfinder workers than in the Sojourner workers. This difference was attributed to the fact that Pathfinder workers took nearly twice as many days off than the Sojourner workers. The implications of the Pathfinder questionnaire are that if the MER operations personnel had been reduced and they had more days off during the 2nd and 3rd month of MER operations, their adaptation to the rotating MER schedule would have been enhanced, with reduced fatigue, sleep loss, and stress. However, this was not possible to MER operational demands and limited personnel resources. Also, there was no indication in the Pathfinder report that operations personnel were subjected to the switches in MER rover work shift operations reported by several MER participants, which could have contributed to circadian rhythm and sleep disruption.

Circadian Rhythm Entrainment to the MER Regime

The circadian rhythm and sleep homeostatic systems represent two physiological processes which interact in a dynamic manner to regulate changes in alertness, performance and timing of sleep (Borbely 1982; Jewett and Kronauer 1999; Van Dongen and Dinges 2000; Broughton 1998). The circadian component is controlled by an endogenous biological clock, the circadian pacemaker, which is located in the suprachiasmatic nucleus of the hypothalamus (Klein, et al., 1991). A predictive mathematical model indicates that a vegetative class of circadian rhythm variables (body temperature and REM sleep) is controlled by one circadian pacemaker, whereas overt behavioral rhythms such as activity and sleep-wakefulness, are controlled by another pacemaker (Kronauer, et al., 1982). Circadian rhythms are entrained or synchronized by periodic environmental synchronizers, primarily the periodic light-dark cycle associated with the earth's daily rotation. The circadian pacemaker modulates waking alertness and performance in a sinusoidal rhythmic fashion of approximately 24-hr throughout the day. Light information is received via retinal ganglion cells of the eye and is then transmitted through the hypothalamic tract to the suprachiasmatic nucleus. Following this neural pathway, light acts as a powerful stimulus in the regulation of circadian rhythms, contributing to a stable phase relationship between circadian rhythms and the sleep/wake cycle (Czeisler and Wright 1999). Light pulses can also shift the phase of circadian rhythms to an earlier (phase advance, if provided shortly after the body temperature circadian rhythm minimum) or later (phase delay, if provided shortly before the body temperature minimum) time within the biological day. The degree to which light regulates circadian rhythms is dependent on the duration, intensity and frequency of light exposure as well as the phase of the circadian rhythms at which the light is received by the eye (Czeisler and Wright 1999). Research has also suggested that the wavelength of the light is equally critical, with shorter wavelengths having a greater effect on the pacemaker than longer wavelengths (Lockley, et al., 2003).

There exists a regular pattern of circadian rhythm peaks and troughs, in alertness and performance, throughout the 24-hr day, where on a normal 24-hr schedule, performance and alertness variables reach their low point around 0300-0500 and 1500-1700, Monk, et al., 1996). The circadian trough in performance and body temperature is associated with increased fatigue, i.e., a decline in arousal, alertness and reduced motivation (Frazier, et al., 1968; Waterhouse, et al., 2001). The sleep drive, a homeostatic process of exponential form, is primarily responsible for the timing of sleep and waking (Borbely 1982; Van Dongen and Dinges 2000). The drive to sleep is at its lowest point in the morning, upon awakening, and as the day progresses, the drive to sleep increases. Once sleep is initiated, this drive gradually decreases until awakening. Broughton (1998) suggests that this represents the output from the interaction between an endogenous brain rhythm, which provides a twice per day increase in sleep propensity due to accumulating wakefulness, and an opposing circadian arousal process, which counteracts the increasing sleep propensity process later during the wake phase.

The comprehensive human isolation studies by Wever (1979, 1986) showed that the average human circadian rhythm period is 25.0 hours. There is large individual variability in individual circadian rhythm capacity to entrain to non-24 hour zeitgebers. Some individuals can entrain their rhythms to 26.7 hour zeitgebers, some exhibit non-entrained free-running circadian rhythms, and others exhibit changes in rhythm periodicity dependent upon the phase relationship to the zeitgeber (relative coordination) (Wever 1986). Wever's finding of a 25.0 hour innate average circadian periodicity implies that personnel working on a 24.65 hour MER schedule in this study would have been able to easily entrain their circadian rhythms to this schedule. However, it was recently reported that the innate circadian periodicity was much closer to 24 hours than 25 hours (24.18 hours, Czeisler, et al., 1999). There are two published studies of circadian entrainment to a MER type work-rest schedule, in which entrainment to a 24.6 hour light-dark cycle was evaluated under controlled laboratory conditions (Wright, et al., 2001, 2006). In these studies, the melatonin circadian rhythm period lengths were less than 24.6 hours in all participants, i.e., the daily phase shifts in the melatonin rhythm were insufficient in low light intensity (ca. 1.5 lux) to maintain a constant phase relationship to the light-dark cycle and exhibited phase dissociation from the timing of the scheduled sleep episode. The authors concluded that the circadian rhythms of these participants were not entrained but showed evidence of relative coordination effects by the light-dark cycle (Wright, et al., 2001). The entrained participants in these studies also exhibited a change in phase angle in response to the weak environmental synchronizer and the 24.6 hour day length. The participants in our study also exhibited a 61 degree increase in phase angle during the MER regime. Such a change in circadian acrophase following a transition to a non-24-h work-rest schedule reflects an adjustment of the circadian system to a new zeitgeber periodicity and has been observed in other studies (Wright, et al., 2006). This change in acrophase could also be attributed in part to a change in time zone after moving to JPL from their home base (up to three hours time zone difference). More importantly, the synchronized participants in the Wright, et al. (2001, 2006) studies showed less reduction in total sleep time than the non-synchronized participants. The non-synchronized participants also exhibited impairment in cognitive and vigilance performance (Psychomotor Vigilance Task [PVT], Wright, et al., 2006). These deleterious changes in sleep and performance were attributed to changes in the phase relationship between internal biological time and scheduled sleep/wake timing which prevented the circadian system from counteracting the buildup of homeostatic sleep drive across the day, resulting in worse performance and shorter sleep latencies (Wright, et al., 2006). The reduction of sleep length in these participants to 7 hours per night was insufficient to maintain brain vigilance during schedules which precluded extra time for sleep recovery (Wright, et al., 2006). Dissociation between the circadian pacemaker and the sleep-wake schedule has been associated with the periodic appearance of fatigue symptoms (Shibui, et al., 1998). In a similar study, a 25-hour day work-rest schedule resulted in sleep and circadian disruption for 7/16 participants. Circadian rhythm disruption in these participants was associated with reduced cortisol levels, which may be related to circadian rhythmic amplitude disruption during rhythmic misalignment (Drake, et al., 2005). However, in a study using a zeitgeber combination of a 26 hour sleep-wake schedule and a 26 hour light-dark cycle containing evening bright light, the circadian rhythm of body temperature was entrained in most participants tested (Eastman and Miescke 1990). This study was conducted in the home environment of the participants, in which they were exposed to a conflicting 24.0 hour zeitgeber. The periodicity analysis showed circadian peaks at 24 and 26 hours, attributed to the 24 hour zeitgeber and masking by the 26 hour sleep-wake schedule. The study was similar to the present MER study in that participants were exposed to an imposed schedule with a differing zeitgeber period length than experienced in their home environment. The above studies indicate that circadian rhythm entrainment can occur to an imposed schedule of 24.65 hours, and even to a schedule of 26.0 hours in most individuals, assuming that zeitgeber strength is sufficient. The studies in which circadian rhythms failed to entrain to 24.6 and 25.0 hour cycles were characterized by weak zeitgeber (light intensity) strength and entrainment failed in the melatonin rhythm, which is a marker rhythm for the core circadian oscillator (Wright, et al., 2001, 2006). However, the rest-activity rhythm was found to have a wider range of entrainment (20–32 hours) than the core body temperature circadian rhythm (Wever 1979), and was more sensitive to non-photic entrainment (e.g., social) zeitgebers than was the body temperature rhythm (Honma, et al., 2003). We recognize that it was also not possible to validate entrainment in this study due to the potential masking effects upon the activity rhythm by uncontrolled environmental factors. However, the results from the Wright (Wright, et al., 2001, 2006) studies imply that individuals who fail to entrain to MER-like schedules were more likely to show reduced sleep time and deterioration in performance, which has unfavorable implications for the sleep quality and performance of participants in our study. In our study, we observed decreased time in bed, increased sleep length variability, and increased sleep during the subjective day during the MER rotation regimes.

Progressive deterioration in the psychomotor vigilance task in this study was documented in 4/10 tested participants following the transition from the MER schedule to an Earth time schedule (Appendix F, Brandt, et al., 2005). These effects may be attributable to lack of entrainment to the MER schedules, as in the Wright studies, or may reflect a direct negative impact of the rotating MER schedule on sleep quality and duration. The changes in circadian rhythm periodicity and amplitude during MER regimes may also reflect conflicts with the external 24.0 hour social and light-dark zeitgebers and possible dissociation of the rest-activity rhythm from the core circadian oscillator due to incomplete entrainment of the circadian oscillatory system and changes in the relative intensity and timing of exposure to light-dark cycles and social and behavioral zeitgebers. Behavioral zeitgebers (also referred to as sleep-wake schedule zeitgebers, Eastman and Miescke 1990), such as acoustically transmitted signals (e.g., alarm clock) which signal participants to wake up or go to bed, can be effective zeitgebers (Wever 1983). These zeitgebers can be even twice as effective as light-dark cycles (Wever 1986), which require at least three hours per day of bright light (>3000 lux) (Wever 1985). Changes in wake time were associated with much greater circadian phase shifts than changes in bedtime, which was most likely due to the associated reduction in morning light exposure (Burgess and Eastman 2005). It was likely that acoustic zeitgebers (alarm clock) served as the primary zeitgeber for the activity circadian rhythm in our study since exposure to ambient light-dark cycles was erratic due to the rotating MER schedule, the uncontrolled exposure to workplace, home and outside illumination, and the uncontrolled exposure to social interaction zeitgebers in the workplace and home environments.

Operational demands in missions such as the MER mission, require shifted work schedules and irregular sleep/wake cycles during operations. These shifts can induce a misalignment between the phase of the circadian pacemaker and the sleep/wake cycle, resulting in circadian rhythmic disruption. Subsequently, there is a dissociation between the timing of circadian physiological and performance rhythms. The consequences, as demonstrated in ground-based studies, can be increased sleep disruption, malaise, performance errors, uncontrollable sleep periods intruding into waking hours, a more negative mood and decrements in social interaction, inefficient communication and accidents (Holley, et al., 1981; Winget, et al., 1984). This overall impairment of performance proficiency results from the shifting of performance times to an unfavorable phase of the performance circadian rhythm. Certain individuals are more susceptible to sleep loss or to the debilitating effects of shifted work-rest cycles (Stepanova 1986). In our study, shifted work schedules resulted from 12-hr shifts in work schedules between the two Mars rovers, changes in job position schedules during MER operations, and shifts between Mars sol work shifts and earth time on days off. The maximum degree of activity circadian rhythm disruption in this study was seen in two participants who switched from a MER-A to a MER-B schedule, which necessitated a 12-hour shift in rest-activity patterns. The importance of this finding was the association of large circadian rhythm phase shifts with reduced time in bed and sleep efficiency. The large circadian phase shifts and circadian rhythm disruption in activity in these participants has serious implications for sleep disruption, performance deterioration and fatigue during MER operations, similar to that observed in the 'jet-lag" response to transmeridian flight (Winget, et al., 1984). The MER rover work shift transitions of 12 hours were similar to a procedure called "slam shifting," which involves abrupt shifts of up to 12-hr used to align the sleep/wake schedules of Space Shuttle and ISS crews upon docking (Neri, et al., 2003). Since all four participants in this study who were required to perform MER rover work shift transitions reported that these transitions were a major problem in adaptation to MER operations and the one participant evaluated showed profound circadian rhythm disruption during a MER rover transition, this practice has major implications for profound sleep disruption and performance decrements in MER operational personnel and space crews and should be avoided if at all possible. The shifts in rest-activity times between Mars sol work shifts and days off schedules also created adaptation problems for some participants and two participants elected to remain on a Mars sol schedule throughout MER operations. A preliminary study on two participants who worked three consecutive 13 hour night shifts per week followed by 4 four consecutive nights off showed that the one participant who maintained the same sleep/wake cycle on days off slept nearly two hours more per night than the other participant, who reverted back to normal night sleep times on days off (Hurlbert, et al., 2005). The implications of this study for the MER operations regime is that individuals who transition back and forth between Mars sol schedules and earth time are much more likely to experience chronic sleep loss than individuals who remain on the Mars sol schedule for the duration of the MER operations.

A number of individual circadian rhythm indices, including morningness-eveningness (Horne and Ostberg 1976), rhythm phase, amplitude and stability, have been evaluated as predictors of adaptability to circadian phase shifts (Minors and Waterhouse 1981). These individual differences in circadian rhythm characteristics suggest that there would be significant differences in the capacity of a given MER operations personnel to maintain adequate sleep and physiologically adapt to work-rest schedule shifts and lengthened sleep/wake cycle schedules. In the Wright studies (Wright, et al., 2001, 2006), failure to entrain was related to individual differences in intrinsic circadian period length. Research on circadian chronotypes showed that individuals with peaks in circadian rhythms that peak relatively early in the day tend to be morning active types and vice versa (Horne and Ostberg 1976). Additional studies demonstrated that circadian period was correlated with morningness-eveningnesss,, circadian phase and wake times (Duffy, et al., 2001), individuals with shorter circadian periods initiate sleep and awaken at later biological times than did individuals with longer circadian periods (Wright, et al., 2005), there were differences in the regularity of sleep satisfaction and sleep quality between morning and evening types (Kato, et al., 2006), and eveningness was associated with a greater need for sleep and less time in bed (Taillard, et al., 1999). In our study, about half of the participants exhibited entrainment to the MER 24.65 hour schedule, but the rest showed activity circadian periods of about 25 hours, which often diverged from expected MER schedule onsets, work time onsets and wake-up time onsets. These differences in MER schedule synchronization, along with the differences observed in circadian rhythm stability and waveform patterns during the MER regimes may reflect chronotype differences between the participants, who exhibited the expected wide distribution of chronotypes from morning to evening types. However, it was not possible to statistically evaluate the effects of chronotype differences in this study given the differences in participant work schedules, home environments, exposure to different zeitgeber influences, and the other uncontrolled variables. However, the literature indicates that individuals with morning active chronotypes would have more difficulty adjusting their work/rest schedules and synchronizing their circadian rhythms to a longer period day length such as the MER 24.65-hr day. One participant, who had a moderate morning chronotype, reported difficulty in adjusting to the MER regime. Individuals who have periods shorter than 24-hr, which is about 25% of the population, will have the greatest challenges in entraining to a Mars sol (Czeisler, et al., 2003). An investigation was conducted of the extent to which individual performance responses to extended duration mission demands were a function of recent sleep/wake history, trait-like neurobehavioral vulnerability and/or sensitization or adaptation as a consequence of previous exposure (Van Dongen, et al., 2003). The results revealed that there were differences in performance among individuals but performance responses were not related to sleep/wake history or previous exposure and there appeared to be trait-like characteristics within the individual for performance responses. The prospects for identifying individual traits which may be predictive of performance and physiological responses during operational missions have recently been evaluated, in which multivariate converging indicators provide a significantly more reliable method for assessing environmental effects upon performance and health than single indicators (Cowings, et al., 2006).

Circasemidian Rhythms

Several studies have reported the existence of 12-hour rhythms in several variables, including body temperature (Colquhoun, et al., 1978), melatonin (Maggioni, set al., 1999), slow-wave sleep (Hayashi, set al., 2002) and operational performance (Hildebrandt, et al., 1974). This rhythm has been characterized as a bimodal component of the circadian waveform, in which peaks in the evening and early morning are separated by about 12 hours, with the interval in between referred to as the post-lunch dip or performance decrement interval (Hildebrandt, et al., 1974), or afternoon nap zone, in which sleepiness increases (Broughton 1998). The important aspect of this “circasemidian” rhythm was that it was more marked in people who were relatively sleep deprived and results in increased performance errors (Hildebrandt, et al., 1974). This rhythm can represent the manifestation of a bimodal circadian rhythm, but the 12 hour rhythms detected in this study by spectral analysis could represent the output of circadian period harmonics generated by harmonic analysis of non-sinusoidal and asymmetric circadian activity waveforms, in which the residuals from the harmonic fit process would generate spectral peaks at submultiples of the circadian period (e.g., at 12, 6, 3 hours, etc). The verification of the 12 hour rhythm observed in several participants primarily during the MER regime by the waveform-based profilogram method, which was independent of harmonic waveform assumptions, suggests that the 12 hour rhythms were real biological periodicities. However, the ratio between the circadian and circasemidian rhythm period lengths detected was 2.0 in nearly all cases during baseline and MER regimes. This indicates that the circasemidian periodicity was either a harmonic of the circadian period or, more likely, was modulated by the circadian rhythm, or was the manifestation of a bimodal circadian wave form. A third explanation for the circasemidian rhythm phenomenon based upon the work of Broughton (1998) suggests that the bimodal 12 hour pattern was not a true rhythm but represented the output from the interaction between an endogenous brain rhythm, which provides a twice per day increase in sleep propensity due to accumulating wakefulness, and an opposing circadian arousal process, which counteracts the increasing sleep propensity process later during the wake phase. In this model, the circasemidian rhythm would not represent an independent oscillatory system, but would be the result of an evolutionary process which promotes energy efficiencies by the preferential selection of rhythmic processes that show simple fixed integer rations such as 2:1 (Broughton 1998). Sleep deprivation would then amplify the sleep propensity circadian rhythm, resulting in increased sleepiness and fatigue during the nap zone (Lack and Lushington 1996). The finding of substantially reduced activity levels in the mean activity educed cycle waveforms during the period from about noon to early evening in participants with pronounced circasemidian rhythms in this study suggests that the reduced activity may have resulted from fatigue or increased sleepiness. This suggestion is supported by previous studies in which increased fatigue was associated with reductions in activity circadian rhythm amplitude (Liu, et al., 2005; Mormon, et al., 2000). Students who had experienced sleep loss indicated that they were less likely to participate in daily activities and to be less active (Engle-Friedman, et al., 2005), which would likely result in lower daily activity levels. However, in our study, the increased circasemidian rhythm strength was not associated with increased workload and sleep durations were actually 0.8 hours higher in the circasemidian group. Another unexpected result was the finding that the four participants analyzed in the strong circasemidian group adapted well, as evidenced by a positive composite fatigue score. Two of these participants reported that their adaptation to the MER regime was enhanced by attempting to obtain at least 8-hr sleep per night. Therefore, the increased circasemidian rhythm strength in these participants may have resulted not from increased fatigue levels, but from an attempt by these participants to conserve energy during the MER regimes by reducing activity levels during the MER work shifts. However, the finding of increased performance errors associated with circasemidian rhythms (Hildebrandt, et al., 1974) implies that the circasemidian group may have had reduced performance capacity during MER work shifts. Monk (Monk, et al., 1996) indicated that participants showing a post-lunch performance dip had higher circadian amplitude than those not showing the dip. Therefore, the post-lunch dip is likely linked to individual endogenous circadian rhythm characteristics (Monk, et al., 1996). Finally, we cannot eliminate the possibility that the activity reductions observed in our study may be due in part to differences in MER schedule related changes in workload patterns which could have affected activity levels at certain phases of the MER schedule.

In most participants, the reduced activity levels were associated with an extension of high activity levels, such that the ratio between subjective day and night activity was higher. Aschoff (1971) showed a negative correlation between duration of wakefulness and mean activity levels, in which extended wakefulness was associated with lower activity levels. He attributed this finding to a homeostatic process, which tends to maintain relatively constant levels of daily activity. The extensions of the subjective day during the MER shifts would result in increased activity levels. This would reduce available sleep time and may have resulted in sleep loss and subsequent fatigue in these individuals, with reduced activity as a compensatory response. This conclusion was supported by the report of a reduction in total sleep time under night shift conditions in another study (St. Hilaire and Klerman 2006). Aside from the absence of evidence for increased fatigue in the strong circasemidian rhythm group, the assumption that reduction in activity levels during the subjective day, particularly during the post-lunch phase of the activity circadian rhythms, represents evidence for increased fatigue levels was supported by the subjective mood reports in our study. The mood data show an increase in subjective fatigue, sleepiness, and irritability during MER operations, relative to baseline. Also, circadian rhythm waveforms became less symmetric and sinusoidal during night shifts. However, we cannot eliminate the possibility that these waveform changes may be due in part to differences in MER schedule uncontrolled changes in workload patterns which could have affected activity levels at certain phases of the MER schedule.

Countermeasures to MER Operational Schedule Effects Upon Circadian Rhythms and Sleep

Maintenance of the MER schedule throughout the MER operation would likely result in reduced fatigue and circadian rhythm disruption resulting from shifting back and forth between the MER schedule and weekend schedules. Circadian period length was significantly longer following entrainment to a 24.65 hour day than to a 23.5 hour day, which demonstrates an aftereffect of entrainment on circadian period length (Scheer, et al., 2005) which could have a disruptive effects on circadian rhythm stability in personnel shifting back and forth between the longer day MER schedule and the 24.0 hour non-MER work or weekend schedules. Using weekend breaks for fatigue recovery by sleeping-in later results in circadian rhythm phase delays and longer sleep onset latencies (Taylor, et al, 2006). Adaptation to the MER regime was facilitated in four participants by attempting to obtain at least 8-hr sleep per night. A recent study by Monk and Buysse (2006) showed that advancing bedtime by two hours was associated with increased sleep time and greater daytime alertness. Vigilance performance was also improved by increasing time in bed by two hours per night (Wright, et al., 2006). A sleep extension period also resulted in substantial improvements in daytime alertness, vigilance performance, and mood (Kamdar, et al., 2004). Therefore, MER personnel could be encouraged to retire to bed earlier or strive to spend more time in bed during MER regimes to maintain alertness and reduce fatigue levels.

Caffeinated beverages were used by the majority of MER personnel to counteract fatigue effects during MER operations. Caffeine is successful in overcoming the midday dip in physiological alertness (Dijk and Edgar 1999). Caffeine stimulates the nervous system, generally taking effect in 15–45 minutes after ingestion and it usually remains active for 3–5 hours, although the effects can continue for up to 10 hours in sensitive individuals. However, caffeine should not be ingested before sleep since it interferes with sleep quality (Rosekind, et al., 1996).

Naps were used as a strategy to aid in adaptation to the MER regime by half the participants. Anchor sleep is sleep obtained on days off during normal night sleep times. Nighttime anchor sleep, in combination with daytime nap sleep, does increase neurobehavioral functioning (Maislin, et al., 2001). It is not only the duration of the nap that determines the magnitude of effect on performance but the placement of the nap within the circadian cycle, as well as the time at which the nap is taken relative to beginning of the sleep restriction period (Rogers, et al., 2003). A nap reduces the duration of continuous wakefulness before a work period and can be particularly beneficial before a period of night work, when the challenge of working through the circadian trough is also a factor (Rosekind, et al., 1996). The duration of naps is very important since in a recent study of the efficacy of 5 min to 30 min naps, the 10-minute nap produced immediate improvements in all outcome measures, including sleep latency, subjective sleepiness, fatigue, vigor, and cognitive performance. However, the 30-minute nap resulted in a period of impaired alertness and performance immediately after napping, indicative of sleep inertia, followed by improvements lasting up to 155 minutes after the nap. Therefore, 10-min naps would be recommended to MER personnel as a restorative measure for fatigue resulting from sleep restriction. Other investigators (Rosekind, et al., 1996) recommend limiting naps to 45 minutes to avoid disruption of sleep architecture during normal sleep periods.

Exercise was used by one third of the participants in this study as a strategy to aid in adaptation to the MER regime, although one participant indicated that exercise contributed to fatigue. Although exercise can have adverse effects on sleep, it can also induce phase shifts in the melatonin circadian rhythm, in which late afternoon or early evening exercise regimens induced phase advances and late evening exercise induced phase delays (Buxton, et al., 2003, Eastman, et al., 1995). Therefore, repeated exposure to appropriately timed exercise sessions during MER operations could be used to facilitate the adaptation of circadian rhythmicity (Barger, et al., 2004, Buxton, et al., 2003) and thus serve as a countermeasure to circadian rhythm disruption.

Five participants reported that they used days off to recover from fatigue and sleep loss and adapt their work/rest times for their return to the MER regime. Repeated sleep loss in humans appears to be cumulative, as indicated by the tendency to make up for lost sleep on days off (Carskadon and Dement 1981). The effective use of days off and rest periods to catch up on sleep generally requires two nights of unrestricted sleep (Rosekind, et al., 1996). The timing of sleep periods is critical since sleeping-in later on days off can result in circadian rhythm phase delays, which could interfere with adaptation to the subsequent MER regime (Taylor, et al, 2006). The problem in the MER study was that the distribution and number of consecutive days off was highly variable, which implies that sleep recovery and MER schedule adaptation was feasible for some participants but not for other participants.

The results of this study showed that excessive work shift schedules and work shift transitions between MER rovers were associated with increased fatigue levels and/or circadian rhythm disruption. In addition, there was one instance where one of the most extreme morningness chronotypes was associated with difficulty in adaptation to the longer Mars sol. Therefore, future MER operations schedules should strive to schedule sufficient personnel to avoid excessive MER shift durations and eliminate the necessity to require major work shift schedule transitions to minimize fatigue and reduce the potential for mission operational performance errors. Individuals with extreme morning chronotypes should be assigned to reduced-rotation MER missions or non-MER rotation duties instead of the full rotation 24.65-hr day missions.

Melatonin skin patches were effective in improving daytime sleep in other studies by increasing REM sleep and decreasing waking after sleep onset (Aeschback, et al., 2006). Bright blue light (3450 lux) was effective, even more so than bright white light, in producing phase shifts in circadian rhythms (Smith, et al., 2006). Such phase advances were enhanced by the combined use of intermittent morning light and afternoon melatonin doses (Revell, et al., 2005). Such treatments could be used to promote circadian rhythm phase advances in personnel transitioning from normal work-rest schedules to a MER regime which starts at an earlier time than the normal work-rest schedule. Short time (30 min) exposure to natural bright light in the afternoon improved arousal levels in the afternoon (Kaida, et al., 2005), which suggests that personnel on MER daytime rotations would benefit from brief sunlight exposures. MER operations personnel who had rotated to night time shifts were probably exposed to much lower light levels than during daytime shifts. An increase in bright light exposure during night shifts could be beneficial since bright light exposure during nighttime has been shown to result in significant improvement in performance and alertness levels (Campbell and Dawson 1990, Daurat, et al., 1993, Hannon, et al., 1991). Exposure to bright light can also facilitate entrainment to rotating work schedules (Czeisler and Allan 1987). Exposure to 30-min of natural bright light in the afternoon improved arousal levels (Kaida, et al., 2005). This treatment could be useful in counteract fatigue and the decline in locomotor activity observed in several participants during MER operations.

Other countermeasures suggested to improve sleep quality and duration include: a) regular pre-sleep routines which can condition relaxation in preparation for falling asleep; b) the use of various physical and mental relaxation techniques such as meditation, autogenic training, yoga, and progressive muscle relaxation; c) giving priority to sleep time and keeping sleep time as free as possible from other commitments and activities; and d). sleeping in a dark, quiet room, with the use of eyeshades to screen unwanted light and earplugs or background white noise to reduce noise (Rosekind, et al., 1996).

A comprehensive approach in the management of fatigue and alertness for MER operations personnel needs to be employed, which includes: 1) educational efforts; 2) effective scheduling policies and procedures; and 3) implementation of specific fatigue remedies and countermeasures. These workshops can be tailored specifically for MER operations and based on the original Fatigue Education and Training Module (ETM) developed by the NASA Ames Fatigue Countermeasures Group (Rosekind, et al., 2002).

Suggestions for Future MER Operational Studies

1. Obtain marker rhythm measures (e.g., body temp, melatonin), if possible and also obtain more comprehensive pre-and-post MER operations mood tests and surveys to establish potential predictive factors for MER adaptation.

2. Evaluate light exposure by utilizing Actiwatches with built-in light meters to evaluate the range and timing of light exposure (Oyung 2003; Heil and Mathis 2002) which could modulate circadian rhythm entrainment and stability. These devices are ideal for unobtrusive use in field studies.

3. Evaluate activity rhythms in a control group working in the same environment but not on the MER rotating schedule.

4. Obtain more complete participant information on work schedules and daily mood and subjective sleep reports.

5. Incorporate more measurements of cognitive performance levels during MER regimes. This could be done by incorporating shorter versions of cognitive tests such as a 3-min version of the psychomotor vigilance task (William, et al., 2006), which could provide test data without significant intrusion into the operational work schedule of the participant.

6. Evaluate countermeasures such bright light exposure, exercise regimes, and fatigue countermeasures training to improve sleep quality.

7. Evaluate relative changes in activity levels and circadian activity wave form in individuals subjected to varying degrees of chronic sleep loss.

8. Compare differences in mood, performance, and circadian rhythmicity between participants who are chronically synchronized to a Mars sol schedule and participants who transition back and forth between a Mars sol schedule and earth time on days off.

CONCLUSIONS

This study documented reduced sleep durations associated with increased work shift durations and changes in circadian rhythm stability with reduced activity levels, the appearance of pronounced 12-hr (circasemidian) rhythms and extended high activity level durations during MER operational schedules. In response, overall adaptation to the MER operational regime was characterized by increases in fatigue, sleepiness, and irritability and decreases in concentration and energy in most participants. In addition, participants reported several primary challenges to successful adaptation, which necessitated the adoption of several strategies to cope with the MER operational regime. The assessment of adaptation to the MER rotating schedule by evaluation of circadian rhythm changes in locomotor activity was important since high circadian rhythm mesor and circadian amplitude were associated with better neuropsychological function (Martin, et al., 2001) and there is a high correlation between actigraph and EEG estimates of sleep duration and efficiency (Monk, et al., 1999). The entrainment limits of the human circadian pacemaker have important implications for the entrainment not only of MER operations personnel but also in astronauts during normal spaceflight operations and during future Mars missions, in which space crews will be exposed to a mars sol of 24.65 hours and potential conflicts with ground control personnel working on 24.0 hour earth days.

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APPENDIX A
Schedule for Baseline Data Recording and MER Operations

Participant M0303

Baseline data	12/18/03–1/2/03	16 days	Days 1–16
MER regime	1/3/04–3/17/04	77 days	Days 17–91
Earth time	3/18–4/5/04	19 days	Days 92–110

Baseline data segment	12/18–12/31/03	14 days	Days 1–14
MER data segment	1/4/03–1/17/04	14 days	Days 8–31

Participant M0304

Baseline data	12/17/03–1/4/04	19 days	Days 1–19
MER regime	1/5/04–3/28/04?	80 days	Days 20–99?

Baseline data segment	12/21–1/28/03	8 days	Days 4–11
MER data segment	1/5–1/12/04	8 days	Days 19–26

Participant M0309

Baseline data	12/20/03–1/2/04	14 days	Days 1–14
MER regime	1/3/04–4/5/04	94 days	Days 15–108

Baseline data segment	12/20–12/31/03	12 days	Days 1–12
MER data segment	1/6/–1/17/04	12 days	Days 18–29

MST from 12/19/03 to 1/1/04	Time changes
PST from 1/2/04 to 3/23/04	-1 hr
CST from 3/24/04 to 3/27/04	+2 hr
PST from 3/28/04 to ?	

No additional time zone data available

Notes: This person seemed to be impaired by the schedule based on personal correspondences. Missing post-study data and sleep difficulties data.
Missing data 4/4/04 from 02:00 to 02:59 replaced by data folding. A note referring to missing data on 1/13/04 was not verified since no missing data blocks were identified on this date.

Participant M0310

Baseline data	12/20/03–1/2/04/03	14 days	Days 1–14
MER regime	1/3/04*4/3/04	10 days	Days 15–106

Baseline data segment	12/20–12/30/03	11 days	Days 1–11
MER data segment	1/4–1/13/04	10 days	Days 16–25

Participant M0313

Baseline data 12/20/03–1/2/04 14 days Days 1–14
MER data 1/3-3/28/04* 86 days Days 15–100

Baseline data segment 4/13/04–4/24/04 12 days Days 116–127
MER data segment 1/17–1/28/04 12 days Days 29–40

*participant switched from MER-A to MER-B schedule 1/21–1/24/04
and from MER-B to MER-A on 2/16/04

Time changes

CST from 12/19/03 to 12/20/03
EST from 12/21/03 to 12/26/03
CST from 12/27/03 to 1/1/04
PST from 1/2/04 to 2/19/04
AZT from 2/20/04 to 2/27/04*
*Note: Unsure whether in AZ or PST time zones
PST from 2/28/04
to 3/13/04
CST from 3/14/04 to 3/19/04
PST from 3/20/04 to 4/2/04
PDT from 4/3/04 to 4/24/04

Notes: Switched to MER B on 1/24/04
Switched to MER A on 2/16/04
Sick 2/22-2/25/04 and 3/21/04

Participant M0325*

Baseline data 12/23/03–1/4/03 13 days Days 1–13
MER regime 1/5/04–4/5/04 72 days Days 14–105

Baseline data segment 12/24–12/29/03 6 days Days 2–7
MER data segment 2/15–2/20/04 6 days Days 55–60

*participant remained on MER regime throughout MER operations phase

Time changes

EST from 12/23/03 to 12/30/03
PST from 12/31/03 to 4/3/04
PDT from 4/4/04 to 4/18/04

Notes: This participant stayed on a Mars schedule
Flew to Las Vegas on 3/1/04 for overnight trip
Missing data 4/9/04 02:00–02:59, 2/10/04 10:27-2-12:04, replaced by data folding
Missing data 3/24/04 21:00 to 3/25/04 14:00, replaced by averaging across two adjacent days.

Participant M0332
Baseline data: No pre-MER regime baseline data available prior to 1/3/04
MER regime 1/2/04 to 3/19/04 78 days Days 1–78
Post-baseline 3/19/04 to 4/22/04 35 days Days 79–112

Baseline data segment 4/4–4/21/04 18 days Days 94–111
MER data segment 2/1–2/18/04 18 days Days 31– 48

Time changes
PST from 1/3/04 to 4/3/04
PDT from 4/4/04 to 4/22/04

Notes: –Worked overtime on 3/29-3/30/04 which affected sleep pattern. Removed this sleep period since interested in normal operations.

M0329
Baseline data: No pre-MER regime baseline data available prior to 1/5/04
MER regime 1/5/04–4/10/04 97 days Days 5–101*
Baseline 4/11/04–4/30/04 35 days Days 102–121

Baseline data segment 4/11–4/20/04 10 days Days 102–111
MER data segment 1/5–1/11/04 10 days Days 5–11

*participant switched from MER-A to MER-B schedule 1/21–1/24/04

M0320
Baseline data 12/17–1/3/04 18 days Days 1–18
MER regime 1/4/04–3/20/04 77 days Days 19-95
Post-baseline 4/11/04–4/30/04 35 days Days 102–121

Baseline data segment 4/10–4/18/04 9 days Days 102-111
MER data segment 2/16–2/24/04 9 days Days 62–70

APPENDIX B
Circadian Rhythm Metrics

Table 2. Circadian Rhythm Metrics (Means) for the Baseline Data for the Fatigue Countermeasures Group Working a Day Schedule

ID	No. days	Per-iod	Ampli-tude	% Rhythm	Acrophase Degrees	Mesor	Relative Ampli-tude	Good-ness of fit	Inter-daily Stability	Rhythm Sig Prob	95% CL
LC	44	23.97	161.53	38.62	214.20	210.46	0.76	0.60	0.47	3.12E-20	19.14
CWD	19	23.96	89.62	37.40	196.91	110.48	0.80	0.61	0.30	2.97E-11	19.56
DR	11	23.96	107.41	44.12	251.14	139.36	0.78	0.66	0.64	4.80E-09	25.55
SB	11	24.10	143.96	43.74	260.09	186.33	0.80	0.64	0.50	8.20E-06	22.50
S1014	6	24.24	345.64	58.26	174.82	379.98	0.92	0.76	0.58	2.07E-03	53.73
S1008	8	24.10	249.23	53.53	174.87	275.87	0.91	0.72	0.51	4.46E-05	36.72
S1006	14	23.96	318.80	55.85	184.72	358.42	0.90	0.74	0.55	4.46E-05	36.72
	Means	24.04	202.31	47.36	208.11	237.27	0.84	0.68	0.51	3.10E-04	30.56

Table 3. Circadian Rhythm Metrics (Means) for MER Personnel at Baseline before the Rovers Landed

ID	No. days	Per-iod	Ampli-tude	% Rhythm	Acrophase Degrees	Mesor	Relative Ampli-tude	Good-ness of fit	Inter-daily Stability	Rhythm Sig Prob	95% CL
M0303	13	23.96	105.51	28.85	195.71	118.37	0.95	0.60	0.21	1.52E-08	51.41
M0304	8	24.10	117.24	58.31	217.74	215.97	0.57	0.77	0.46	1.96E-03	101.80
M0309	12	24.10	180.58	68.99	258.47	293.83	0.75	0.86	0.53	8.45E-08	78.33
M0332	18	23.80	117.25	46.84	200.02	161.78	0.74	0.73	0.48	6.34E-10	71.17
M0325	6	24.10	41.34	58.40	199.98	75.06	0.58	0.74	0.52	2.21E-03	134.55
M0313	13	24.24	143.40	68.17	207.78	271.87	0.54	0.83	0.55	1.32E-07	36.93
M0310	10	24.10	97.87	43.20	253.05	169.18	0.60	0.66	0.53	1.95E-05	45.25
M0329	7	24.09	124.11	54.00	253.67	190.90	0.66	0.79	0.61	6.71E-05	74.20
M0320	9	24.24	249.95	41.01	306.00	246.75	1.09	0.64	0.51	6.45E-04	77.46
	Means	24.08	115.91	53.35	223.30	187.12	0.67	0.75	0.49	5.44E-04	74.56

Table 4. Circadian Rhythm Metrics (Means) for Personnel during the MER Regime

ID	No. days	Per-iod	Ampli-tude	% Rhythm	Acrophase Degrees	Mesor	Relative Ampli-tude	Good-ness of fit	Inter-daily Stability	Rhythm Sig Prob	95% CL
M0303	13	25.29	129.40	27.93	240.55	123.82	1.09	0.60	0.32	4.90E-07	52.93
M0304	8	24.83	150.28	25.50	309.69	134.46	1.12	0.62	0.53	2.74E-05	49.03
M0309	12	24.82	256.20	47.28	328.02	198.46	1.30	0.78	0.68	3.82E-08	20.85
M0332	18	24.53	108.04	45.93	225.58	123.82	0.90	0.77	0.51	2.44E-10	21.35
M0325	6	24.68	101.08	49.99	285.63	97.45	1.08	0.75	0.23	3.00E-04	55.74
M0313	9	25.13	238.35	48.72	259.20	227.48	1.06	0.75	0.50	1.60E-06	4.63
M0310	10	24.98	151.76	18.00	313.76	137.33	1.11	0.61	0.51	1.08E-05	31.76
M0329	7	24.58	198.17	50.79	310.15	169.18	1.16	0.77	0.74	3.76E-04	33.75
M0320	9	24.68	164.04	52.81	256.41	195.39	0.85	0.75	0.51	3.80E-05	31.01
	Means	24.84	166.66	39.27	284.07	151.50	1.10	0.71	0.50	8.38E-05	33.45

Table 5. Circadian Rhythm Variability (Standard Deviation) for MER Personnel during Baseline before the Rovers Landed

ID	Amplitude	% Rhythm	Acrophase Degrees	Mesor	Relative Amplitude	Goodness of fit
M0303	34.60	11.35	106.92	24.75	0.34	0.11
M0304	24.89	16.01	19.57	53.87	0.12	0.09
M0309	34.59	17.24	41.41	81.41	0.13	0.11
M0332	36.33	17.54	144.26	27.51	0.27	0.10
M0325	36.33	17.54	144.26	27.51	0.27	0.10
M0313	43.29	17.19	25.81	49.44	0.15	0.09
M0310	26.33	14.77	25.58	39.24	0.18	0.11
M0329	18.91	11.71	15.54	23.87	0.16	0.05
Means	33.77	15.95	72.54	43.39	0.21	0.10

Table 6. Circadian Rhythm Variability (Standard Deviation) for Personnel during the MER Regime

ID	Amplitude	% Rhythm	Acrophase Degrees	Mesor	Relative Amplitude	Goodness of fit
M0303	25.42	10.99	38.25	23.51	0.35	0.07
M0304	43.20	22.31	63.14	91.93	0.29	0.16
M0309	28.55	4.35	20.60	15.21	0.18	0.02
M0332	28.72	13.08	16.00	20.25	0.29	0.08
M0325	14.98	10.95	17.37	25.59	0.24	0.05
M0313	43.46	17.85	26.08	20.14	0.23	0.11
M0310	39.21	7.12	15.92	23.16	0.25	0.08
M0329	53.93	15.04	10.64	21.60	0.19	0.08
M0320	33.10	16.69	22.94	26.96	0.18	0.10
Means	34.51	13.15	25.66	29.82	0.25	0.08

APPENDIX C
Background Questionnaire

BACKGROUND QUESTIONNAIRE

This background questionnaire is being provided to all those who have agreed to participate in the MER activity study.

DO NOT WRITE YOUR NAME ON THIS SURVEY. This will ensure anonymity for you. This survey will be administered to as many as 40 subjects and will be held in the strictest confidence.

<u>For research purposes only</u>

We very much appreciate your participation.

GENERAL SURVEY DIRECTIONS:

I. Please answer all questions, and please be as accurate as possible. All information is confidential and anonymous.

II. Please mark boxes and lines as follows:

Small boxes should get a checkmark or an “x”: ☐ ➪ √ or X

Large boxes should get a number: ☐ ➪ 204

Lines should get text: ______ ➪ kids

III. Watch for special instructions relating to a question or set of questions.

A. GENERAL

1. Do you have children? ☐ yes ☐ no

If you answered yes, how many children do you have in each age category:

_____ < 1 yrs old _____ age 1 to 5 _____ age 6 to 13 _____ age 14 to 18 _____ > 18 yrs old

How many children will reside in your place of residence during MER operations? ________

2. Do you have a bed partner or roommate? ☐ yes ☐ no

3. According to him or her, or to your knowledge, how often in the past 3 months have you had:

	never less than once/week	rarely 1–2 times week	sometimes	frequently 3–4 times week	always 5–7 times week	don’t know
a. loud snoring	☐	☐	☐	☐	☐	☐
b. long pauses between breaths while sleeping	☐	☐	☐	☐	☐	☐
c. legs twitching or jerking	☐	☐	☐	☐	☐	☐
d. episodes of disorientation or confusion during sleep	☐	☐	☐	☐	☐	☐

e. other sleep problems, please describe ______________________________________

4. What is your usual amount/frequency of caffeine consumption? (Enter number of cups of coffee/caffeinated soft drinks)

☐ daily ☐ weekly

5. Do you exercise on a regular basis? If no, skip to **Section B**.

☐ yes ☐ no

6. How often do you exercise?

less than once/week	1–2 times/ week	3–4 times/ week	over 4 times/ week
☐	☐	☐	☐

a. List type(s) of exercise you do: ____________________

____

B. SLEEPING AT HOME

Based on **an average night of sleep at home** , please give one best answer to each of the following questions. **Use your local 24-hour clock.**

7. What time do you usually go to bed?

☐ time, 24-hr clock

8. How long after going to bed do you usually fall asleep?

☐ hr and ☐ min

9. How many times on average do you wake up?

☐ times

10. If you wake during the night, what most often awakens you? (Check **ONLY** one answer.)

☐ bathroom ☐ can't sleep
☐ children/spouse ☐ noise
☐ other ____________________

11. If you wake during the night, on average, how long does it take you to go back to sleep?

☐ hr and ☐ min

12. What is the amount of total sleep you get on average? ☐ hr and ☐ min

13. On your days off, what time do you usually get out of bed? ☐ Time, 24-hr clock

On your work days, what time do you usually get out of bed? ☐ Time, 24-hr clock

14. On average, how much sleep per 24 hr day have you obtained during the past 30 days? ☐ hr and ☐ min

15. How much sleep per 24 hr day do you usually need to feel fully alert for the day? ☐ hr and ☐ min

16. Do you consider yourself a morning person or evening person? ☐ morning person ☐ evening person

17. At what time of day do you feel most alert? (please shade/circle your alert times below)

0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200

18. How often do you take a nap at home? (If "never," skip to #20.)

never	rarely 1-10 /yr.	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

19. On average, how long are your naps? ☐ hr and ☐ min

20. How often do you have problems problems getting to sleep?

never	rarely 1-10 /yr.	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

21. How often do you take medication to help you sleep?

never	rarely 1-10 /yr.	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

22. How often do you use alcohol to help you sleep?

never	rarely 1-10 /yr.	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

23. Overall, what kind of sleeper are you?

very poor	poor	good	very good
☐	☐	☐	☐

D. DUTY & HOUSING

24. Is your home local to JPL? ☐ yes ☐ no

25. If "no", what timezone do you typically live? _________

26. Where will you stay during MER operations? ☐ house ☐ apartment ☐ hotel ☐ other

    If you selected "other", please specify: _____________

27. Typically, how long will it take to commute to JPL during MER operations? [ ] hrs [ ] mins

28. If you had your own choice to schedule your duty day, what time would you pick to work your shift? (24 hr clock) [ ] begin time [ ] end time

E. DEMOGRAPHICS

29. Age? ☐ 18 – 29 ☐ 30 – 39 ☐ 40 – 49 ☐ 50+

30. Gender? ☐ male ☐ female

APPENDIX D
Post-Study Questionnaire

POST-STUDY QUESTIONNAIRE

This questionnaire is being provided to all those who have agreed to participate in the MER Sleep/Wake Cycles of MER Personnel in Working a Mars Sol Schedule study, protocol HRII-03-44.

DO NOT WRITE YOUR NAME ON THIS SURVEY. This will ensure anonymity for you and your company. This survey will be administered to as many as 40 subjects and will be held in the strictest confidence.

For research purposes only

We very much appreciate your participation.

GENERAL SURVEY DIRECTIONS:

I. Please answer all questions, and please be as accurate as possible. All information is confidential and anonymous.

II. Please mark boxes and lines as follows:

Small boxes should get a checkmark or an "x": ☐ ➪ √ or X

Large boxes should get a number: ☐ ➪ 204

Lines should get text: ______ ➪ kids

III. Answer these questions based on the time period during MER operations. Watch for special instructions relating to a question or set of questions.

A. GENERAL

1. Describe typically times and reasons for removing the Actiwatch. (e.g., to shower at night) ______________________ ______________________

2. On which wrist did you wear the Actiwatch? non-dominant hand ☐ dominant hand ☐

3. Age ☐

4. What was your usual amount/frequency of caffeine consumption during the MER operation? (Enter number of cups of coffee/caffeinated soft drinks) ☐ daily ☐ weekly

5. Did you exercise on a regular basis during MER operations? yes ☐ no ☐
If no, skip to Section B.

6. How often did you exercise? less than once/week ☐ 1–2 times/week ☐ 3–4 times/week ☐ over 4 times/week ☐

a. List type(s) of exercise you did: ______________________ ______________________

B. SLEEPING DURING MER OPERATIONS

Based on **an average night of sleep <u>during MER operations</u>**, please give one best answer to each of the following questions. **Use your local 24-hour clock.**

7. How long after going to bed did you usually fall asleep? ☐ hr and ☐ min

8. How many times on average did you wake up? ☐ times

9. If you woke during the night, what most often awakened you? (Check **ONLY** one answer.)
   - ☐ bathroom
   - ☐ couldn't sleep
   - ☐ children/spouse
   - ☐ noise
   - ☐ other ______________________ ________

10. If you woke during the night, on average, how long did it take you to go back to sleep? ☐ hr and ☐ min

11. What is the amount of total sleep you got on average per 24-hrs on <u>your days off duty</u>? ☐ hr and ☐ min

12. What is the amount of total sleep you got on average per 24-hrs on your days <u>working a Mars sol</u>? ☐ hr and ☐ min

13. How often did you have problems getting to sleep?

never	rarely 1 or 2 /times	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

14. How often did you take a nap? (If "never," skip to #15.)

never	rarely 1 or 2 /times	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

15. On average, how long were your naps? ☐ hr and ☐ min

16. How often did you take medication to help you sleep? (If "never," skip to #19.)

never	rarely 1 or 2 /times	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

17. If you took medication to help you sleep, please specify the medication.

name: ____________________

18. Rate the effectiveness of the medication.

not at all effective		moderately effective		very effective
☐	☐	☐	☐	☐

19. How often did you use alcohol to help you sleep?

never	rarely 1 or 2 /times	sometimes 1-3 /mo.	often 1-4 /wk	very often 5-7 /wk
☐	☐	☐	☐	☐

20. On average, how much sleep per 24-hr period did you obtained during MER operations?

☐ hr and ☐ min

21. Overall, what kind of sleeper were you during MER operations?

very poor	poor	good	very good
☐	☐	☐	☐

C. FATIGUE DURING MER OPERATIONS

22. How difficult was it working a Mars Sol?

very difficult	somewhat difficult	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

Please explain:

____

____

____

23. What day did you start working a Mars Sol? ☐ mm/dd/yy

24. What day did you stop working a Mars Sol? ☐ mm/dd/yy

25. Specify how your mood changed during the MER operations:

Mood	Strongly Increased	Moderately Increased	Neither Increased Nor Decreased	Moderately Decreased	Strongly Decreased
Fatigue	☐	☐	☐	☐	☐
Irritableness	☐	☐	☐	☐	☐
Concentration	☐	☐	☐	☐	☐
Energy	☐	☐	☐	☐	☐
Sleepiness	☐	☐	☐	☐	☐

26. List in rank order three strategies that you used to cope with fatigue during the MER operations.

1. ____________________________

2. ____________________________

3. ____________________________

27. What did you find most challenging about your schedule?

____

____

____

____

____

28. Please add any additional comments or recommendations about MER scheduling

____

____

____

____

____

APPENDIX E
Analysis of Sleep and Circadian Rhythm Metrics from Actigraphy Data

The reliability of actigraphy in extracting reliable sleep metrics is controversial. Some studies have validated actigraphy for number of awakenings (Lichstein, et al., 2006; Pollak, et al., 2001), total sleep time (Lichstein, et al., 2006), sleep efficiency (Lichstein, et al., 2006; Tworoger, et al., 2005), and total wake time (Tworoger, et al., 2005) but actigraphy has been deemed unreliable by other studies for time in bed (Tworoger, et al., 2005), total sleep time (Vallieres and Morin 2003; Tworoger, et al., 2005), sleep onset (Tworoger, et al., 2005), sleep efficiency (Vallieres and Morin 2003; Signal, et al., 2005a,b; Pollak, et al., 2001), sleep latency (Signal, et al., 2005a,b) and total wake time (Vallieres and Morin 2003). The reliability of the sleep efficiency metric was likely dependent upon the setting of the sensitivity threshold from which actual sleep time was calculated from the actigraphy data. We decided to use the sleep efficiency metric since its reliability was supported by two publications (Lichstein, et al., 2006; Tworoger, et al., 2005). We selected time in bed as the primary dependent measure of sleep for group analyses and sleep efficiency, percentage of actual wake time, bed times and wake-up times were used to further examine sleep disturbances observed in circadian rhythm analyses of individuals.

CIRCADIAN RHYTHM DATA ANALYSIS

Previous studies criticized the use of harmonic-based methods, especially single harmonic cosinor analysis, for the analysis of circadian rhythms in activity, since rest-activity rhythms obtained by actigraphy were highly non-sinusoidal, and daytime activity levels were considerably longer in duration than nighttime activity levels, resulting in very poor fits to the data (Teicher, et al., 1997; Van Someren, et al., 1999). In normal subjects, the goodness of fit was only 0.49 for data sampled every five minutes (Satlin, et al., 1995). However, in another study, hourly activity measures showed very good correlations (0.8-0.95) with cosine models, which suggests that data sampling rates may significantly affect goodness of fit and appropriateness of given data sets for harmonic analysis. Activity circadian rhythm goodness of fit estimates averaged 0.75 for the baseline regimes in this study. This value was well above goodness of fit estimates reported in a previous study using 5-min sampling (0.49, Satlin, et al.,1995) and was comparable to the highest estimates reported (0.8-0.95, Teicher, et al., 1997). There was no doubt that the utilization of multiple harmonic fits to activity circadian rhythm data (Van Someren, et al., 1999; Martin, et al., 2001) provides better fits to the data and probably more reliable estimates of circadian rhythm metrics. However, in this study the methodology employed in processing the raw activity data (clipping, robust locally weighted regression, followed by conversion from 1-min to 5-min samples) was fully adequate to provide extraction of reliable activity circadian rhythm wave forms which could be reliably processed by single harmonic analysis. In addition, the utilization of non-parametric methods such as the profilogram periodicity analysis and educed cycle analysis provided means of evaluating changes in circadian rhythmicity which were free of potential artifacts or misinterpretation of results based upon the parametric methods.

APPENDIX F
Transitioning from a Mars Day to an Earth Day: Effects on Psychomotor Vigilance Performance*

Mars Exploration Rover (MER) Surface Operations personnel were required to complete mission critical tasks on work schedules coinciding with a Mars sol (day) of 24h and 39m for a minimum of 3 months, while being exposed to 24h Earth-based exogenous cues. Once operations extended beyond 3 months, personnel were required to revert back to an Earth-day schedule. Research has shown that changes in circadian rhythms and accumulated sleep loss caused by disruptions in sleep/wake cycles can lead to reduced daytime alertness and impaired neurobehavioral performance. The purpose of the current study was to document performance changes associated with transitioning from a 24h and 39m Mars sol to a 24h Earth day.

Ten participants (8 male, 2 female) MER Surface Operations personnel aged 27–54 ($M = 39.7$, $SD = 8.73$) performed the Psychomotor Vigilance Task (PVT), 10-minute simple, visual reaction time task. Trials were self-administered prior to major sleep periods, when time permitted. Actigraphy (Minimitter, OR) and sleep logs with work schedules were collected. Participants completed between 9 and 32 trials over the protocol period. However, three participants did not complete a sleep log and/or work schedules and therefore, only data from seven participants were analyzed. The following variables were examined:

- number of lapses during trials and progressive changes thereof over the protocol period
- mixed effects ANOVA with age and recency of work
- subjective reports of symptoms indicative of sleep problems (loud snoring, long pauses between breaths, and/or leg twitching or jerking)
- sleep/wake estimates obtained from actigraphy (Actiware-Sleep version 3.3) and verified with sleep log.

Results found that four participants showed degradations over the protocol period reaching levels of > 4 lapses (RT > 500ms) per trial. Two participants showed progressive degradations in performance over time [$t(21) = 4.7$, $p < 0.01$; $t(9) = 3.4$, $p < 0.01$; see Figure 21].

*Brandt, S.L., L.M. Colletti, H. Van Dongen, D.F. Dinges, and M.M. Mallis. Associated Professional Sleep Societies, 19th Annual Meeting, Denver, CO, June 18-23, 2005. Sleep 28: A356.

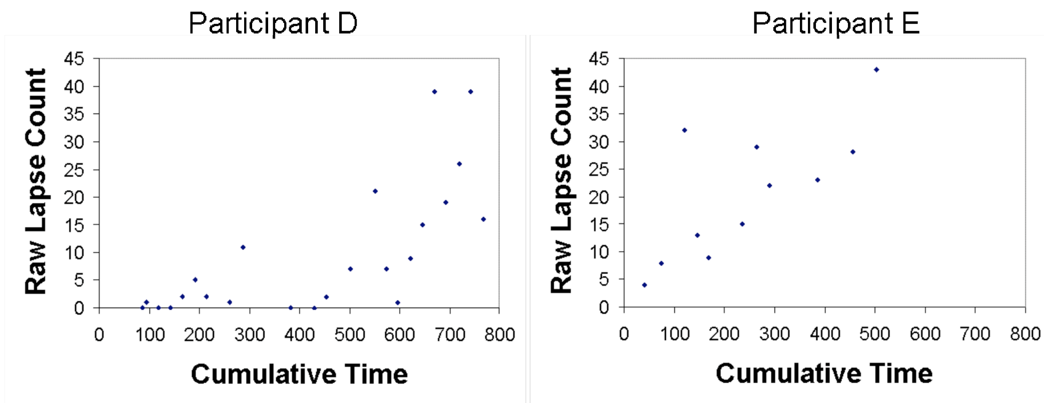

Figure 21. Raw lapse count on the PVT for participants D and E showing severe, progressive degradations in performance over the protocol period. Cumulative time is in hours.

A mixed effects ANOVA suggested that age and recency of work, which was defined as whether the participant worked in the preceding wake period, did not contribute significantly to performance impairment [$F(1,98) = 1.10$, $p = .30$; $F(1,98) = 0.10$, $p = .75$]. Four participants reported subjective symptoms indicative of sleep problems occurring 1-2 times per week or more (loud snoring, long pauses between breaths, and/or leg twitching or jerking). Two of these participants were the same participants who showed progressive degradations in performance over the protocol period (as shown in Figure 21).

Although only descriptive, Figure 22 demonstrates potential variance in sleep/wake patterns between an impaired and a non-impaired participant based on available sleep/wake data.

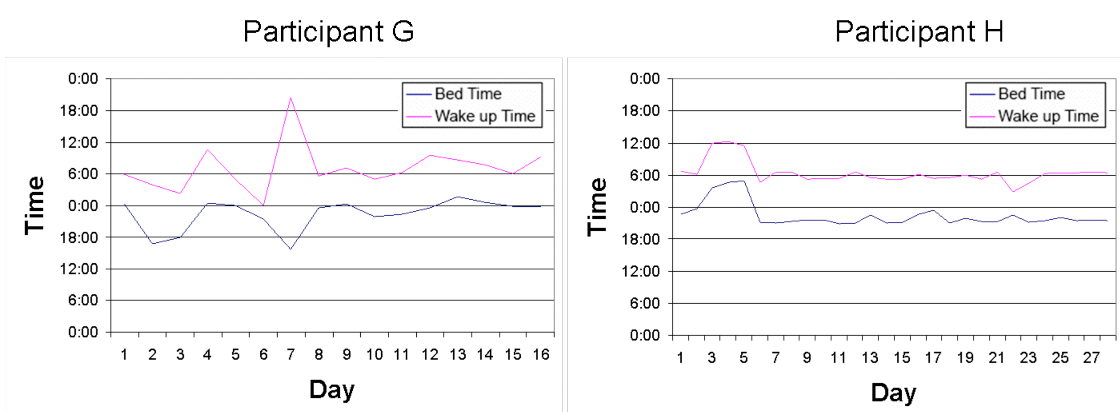

Figure 22. Bed times and wake up times for one impaired participant (G) and one non-impaired participant (H).

Overall, data indicate wide variability in performance across participants transitioning from a Mars sol to an Earth day. It is unclear whether the variability was due to transitioning from a Mars sol to an Earth day or some other factors. Age and recency of work did not significantly affect performance. There is slight evidence that sleep problems and sleep/wake patterns were contributing factors to the degraded performance; however, the limited number of samples per day precludes conclusive statements

This unique opportunity to collect data on MER Surface Operations personnel in the field was limited by operational constraints in this field study. In order to make conclusive statements about performance changes associated with the transition from a Mars sol to an Earth day, a more controlled study including baseline and post-study measures as well as better experimenter control over data acquisition is needed.

APPENDIX G
Participant Demographics

ID	Age Category	Gender	Home Time Zone	Date started MER rotation	Date ended MER rotation
M0301	30-39	male	Pacific	1/3/2004	4/4/2004
M0302	50+	male	Pacific	1/8/2004	2/23/2004
M0303	50+	male	Central	1/3/2004	3/29/2004
M0304	18-29	female	Central	1/4/2004	4/11/2004
M0305	30-39	male	Pacific	1/30/2004	4/2/2004
M0306	18-29	female	Pacific	1/3/2004	2/8/2004
M0307	50+	male	Eastern	1/4/2004	4/5/2004
M0308	18-29	male	Pacific	1/15/2004	4/5/2004
M0309	18-29	male	Eastern		
M0310	18-29	male	Mountain	1/3/2004	3/26/2004
M0312	50+	male	Arizona	1/2/2004	4/11/2004
M0313	18-29	male	Central	1/3/2004	3/29/2004
M0314	40-49	male	Eastern		
M0315	40-49	male	Eastern	1/3/2004	4/15/2004
M0316	18-29	male	Arizona	1/3/2004	4/1/2004
M0317	50+	male	Pacific	1/2/2004	5/15/2004
M0318	40-49	male	Eastern	1/4/2004	4/15/2004
M0319	40-49	male	Pacific	1/3/2004	4/12/2004
M0320	18-29	female	Pacific	1/28/2004	3/20/2004
M0321	30-39	male	Pacific	1/4/2004	3/24/2004
M0322	18-29	female	Pacific		
M0323	40-49	male	Pacific	1/6/2004	3/13/2004
M0324	18-29	female	Eastern	1/3/2004	4/9/2004
M0325	30-39	male	Pacific	1/5/2004	4/5/2004
M0326	30-39	female	Pacific	1/4/2004	3/6/2004
M0329	30-39	male	Pacific	1/4/2004	4/10/2004
M0330	30-39	female	Pacific	1/21/2004	4/1/2004
M0331	30-39	male	Pacific	1/4/2004	4/3/2004
M0332	40-49	male	Pacific	1/6/2004	3/29/2004
M0333	30-39	male	GMT -3	1/3/2004	3/10/2004

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14. ABSTRACT This study assessed human adaptation to a Mars sol by evaluating sleep metrics obtained by actigraphy and subjective responses in 22 participants, and circadian rhythmicity in locomotor activity in 9 participants assigned to Mars Exploration Rover (MER) operational work schedules (24.65 hour days) at the Jet Propulsion Laboratory in 2004. During MER operations, increased work shift durations and reduced sleep durations and time in bed were associated with the appearance of pronounced 12-hr (circasemidian) rhythms with reduced activity levels. Sleep duration, workload, and circadian rhythm stability have important implications for adaptability and maintenance of operational performance not only of MER operations personnel but also in space crews exposed to a Mars sol of 24.65 hours during future Mars missions.							
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