

Circadian variation in swim performance

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Kline CE, Durstine JL, Davis JM, Moore TA, Devlin TM, Zielinski MR, Youngstedt SD. Circadian variation in swim performance. *J Appl Physiol* 102: 641–649, 2007. First published November 9, 2006; doi:10.1152/jappphysiol.00910.2006.—Previous findings of time-of-day differences in athletic performance could be confounded by diurnal fluctuations in environmental and behavioral “masking” factors (e.g., sleep, ambient temperature, and energy intake). The purpose of this study was to examine whether there is a circadian rhythm in swim performance that is independent of these masking factors. Experienced swimmers ($n = 25$) were assessed for 50–55 consecutive hours in the laboratory. The swimmers followed a 3-h “ultra-short” sleep-wake cycle, involving 1 h of sleep in darkness and 2 h of wakefulness in dim light, that was repeated throughout the observation. The protocol distributes behavioral and environmental masking factors equally across the 24-h period. Each swimmer was scheduled to perform six maximal-effort 200-m swim trials that were distributed equally across eight times of day ($n = 147$ trials). Each trial was separated by 9 h. A cosine fit of intra-aural temperature data established the time of the lowest body temperature (T_{\min}). Swim performances were z -transformed and compared across the eight times of day and across twelve 2-h intervals relative to T_{\min} . Analysis of covariance, controlling for trial number, revealed a significant ($P < 0.001$) pattern in swim performance relative to environmental and circadian times of day. Performance peaked 5–7 h before T_{\min} (~2300) and was worst from 1 h before to 1 h after T_{\min} (~0500). Mean swim performance was 169.5 s; circadian variation from peak to worst performance was 5.8 s. These data suggest a circadian rhythm in athletic performance independent of environmental and behavioral masking effects.

body temperature rhythm; swimming; ultra-short sleep-wake cycle

CIRCADIAN RHYTHMS ARE INTERNALLY generated phenomena with periodicity of ~24 h (3). Most mammalian circadian rhythms originate from an endogenous pacemaker located in the suprachiasmatic nucleus (SCN) of the anterior hypothalamus (37). Neural and humoral outputs from the SCN communicate with other centers in the hypothalamus and the endocrine system. These centers drive a multitude of behavioral and physiological rhythms (17).

Demonstration of circadian rhythms requires chronobiological techniques that separate the measurement of circadian rhythms from environmental and behavioral factors that might “mask” the measurement (e.g., energy intake, activity, posture, sleep, ambient temperature, and light) (21). These “unmasking” techniques have included the constant routine (21), data purification (51), forced desynchrony (19), and ultra-short sleep-wake protocols (15).

There has been speculation that there may be a circadian rhythm in athletic performance. The theoretical rationale for

expecting such a rhythm stems, in part, from the observation that numerous biological and behavioral functions that could influence athletic performance, such as pulmonary function (49), core body temperature (50), mood (12), reaction time (52), memory and alertness (29), and cognitive functioning (19), have been shown to exhibit circadian rhythmicity. Indirect support for a performance rhythm is also provided by anecdotal evidence that athletic performance is impaired after transmeridian travel (44).

Time-of-day (diurnal) variations in athletic performance have been reported in numerous studies. Generally, peak performance has been found to occur in the early evening, at approximately the peak of the body temperature rhythm, and worst performance has been found in the morning (see Refs. 4 and 20 for reviews). However, because these studies failed to employ circadian unmasking techniques, diurnal differences in performance could be attributed to a number of environmental and behavioral factors independent of circadian regulation. For example, worse performance in the morning than in the evening could be attributed to nutritional status (≥ 12 -h fast in the morning), joint stiffness following bed rest, sleep inertia (i.e., prolonged sleepiness and lethargy) on arising, lower ambient temperature, and lack of muscle “warm-up” (53). Conversely, given increases in physical and mental fatigue that occur throughout the daytime, previous studies might have underestimated the superiority of evening athletic performance.

Another limitation of previous studies of diurnal variation in athletic performance is that they have generally involved small numbers of untrained or unskilled athletes who performed novel experimental tasks of dubious generalizability to athletic competition (e.g., grip strength) (53). Moreover, performance has been described strictly with respect to environmental time of day. If athletic performance is regulated by the circadian system, then description of performance relative to a known marker of the circadian system (e.g., body temperature peak) should more precisely characterize the rhythm, since interindividual variation in timing of circadian phase can be profound (31).

The aim of this study was to examine whether there was a circadian rhythm in swim performance in highly trained swimmers ($n = 25$). Swimming is a highly suitable mode for assessment of athletic performance rhythmicity because environmental conditions can be easily standardized, repeated swim trials induce less fatigue than repeated trials of other exercise modes (e.g., cycling and running), and performance analogous to competition (i.e., time trials) can be assessed. The swimmers were assessed over 50–55 consecutive hours during adherence to a 180-min ultra-short sleep-wake schedule. The

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protocol distributed multiple masking factors equally across the 24-h day and allowed multiple performance assessments over a short period of time with relatively little sleep loss.

METHODS

Participants

Twenty-five volunteers [13 female and 12 male, 20.7 ± 0.6 (SE) yr of age] participated in the study. Inclusion in the study required participation in regular (>2 days/wk) swim training. Exclusion criteria included depressed mood [i.e., Beck Depression Inventory II (9) score >13], poor sleep quality [i.e., Pittsburgh Sleep Quality Index (16) global score >5], recent shift work or travel across multiple time zones, and extreme chronotype [i.e., Horne-Östberg Morningness-Eveningness Questionnaire (28) score >69 or <31] and risk factors (>1) and/or symptoms (>0) of cardiovascular disease (1). The study protocol was approved by the Institutional Review Board at the University of South Carolina, and each participant provided signed informed consent before participating.

Home Observation

During the week before laboratory observation, participants maintained stable sleep-wake schedules (i.e., ≤ 1.5 -h variation in bed and wake times) that were consistent with their usual sleep habits. Adherence to the sleep schedule was verified by continuous wrist actigraphic recording (Octagonal Basic Motionlogger, Ambulatory Monitoring, Ardsley, NY) and completion of a daily sleep diary. Participants were asked to refrain from alcohol and caffeine during the 2 days before laboratory observation. Early in the home observation week, participants practiced two to three swim trials to help establish optimal pacing for the experimental swim trials.

Participant Randomization and Scheduling

Immediately after home observation, each participant spent 50–55 h completing a weekend laboratory protocol. Time of arrival was determined by the time of the first scheduled swim trial, which occurred at one of eight times of day (i.e., 0200, 0500, 0800, 1100, 1400, 1700, 2000, or 2300; Fig. 1). Participants were randomized to these start times in blocks of three. Most participants ($n = 19$) arrived in the laboratory 4 h before *swim trial 1* to allow acclimation to the laboratory protocol and reduce any transient influences of the pre-laboratory environment on the laboratory measures. To avoid sleep

interruption, participants scheduled to perform *swim trial 1* at 0500 or 0800 ($n = 6$) were required to arrive in the laboratory 1 h before their usual bedtimes and to remain in the laboratory for 2–5 h longer than the other participants.

Participant randomization was structured to obtain 18 swim performances at each of the eight possible time points to distribute fatigue associated with multiple trials evenly across the 24-h day. Thus, for example, three swim performances during each time point were *swim trial 1* for some participants, and three swim performances during each time point were *swim trial 2* for some participants (Fig. 1).

Laboratory Observation

Laboratory environment. Laboratory observation was conducted in the University of South Carolina's Clinical Research Laboratory. We converted the ~ 130 -m² room, which normally is a fitness center, to a chronobiology laboratory by clearing the center space of equipment, adding inflatable camping mattresses to the room, and reducing lighting by spreading dimly lit lamps across the room. Approximately six participants participated per experimental weekend.

Ultra-short sleep-wake schedule. For the duration of laboratory observation, all participants followed a 180-min ultra-short sleep-wake schedule involving 120 min of out-of-bed wakefulness in dim (<30 -lux) light followed by 60 min of attempted sleep in darkness (<1 lux); this regimen was repeated throughout the 50–55 h experiment. At *minute 90* of each 120-min wake period, participants ate a standardized meal that was designed by a registered dietitian (TAM) on the basis of each participant's individual energy intake needs [i.e., body weight, age, sex, and activity level (24)]. Water and noncaffeinated, calorie-free beverages were allowed ad libitum. Sleep/wakefulness was continuously monitored by wrist actigraphy.

Participants were free to engage in sedentary activities of their choice during wake periods, including visiting with friends. Aside from swim performances, exercise was not allowed. Participants left the laboratory only to use the restroom or to perform swim trials. When participants left the laboratory, they were required to wear dark sunglasses [Uvex Genesis (dark gray lenses, 10% available light transmittance), Smithfield, RI] to keep light exposure relatively constant.

Body temperature measurements. Intra-aural temperature (T_{aur}) was assessed at *minutes 15, 60, and 105* of each 120-min wake period throughout laboratory observation (5). Laboratory staff members used a hospital-grade infrared ear thermometer (Braun ThermoScan 4000,

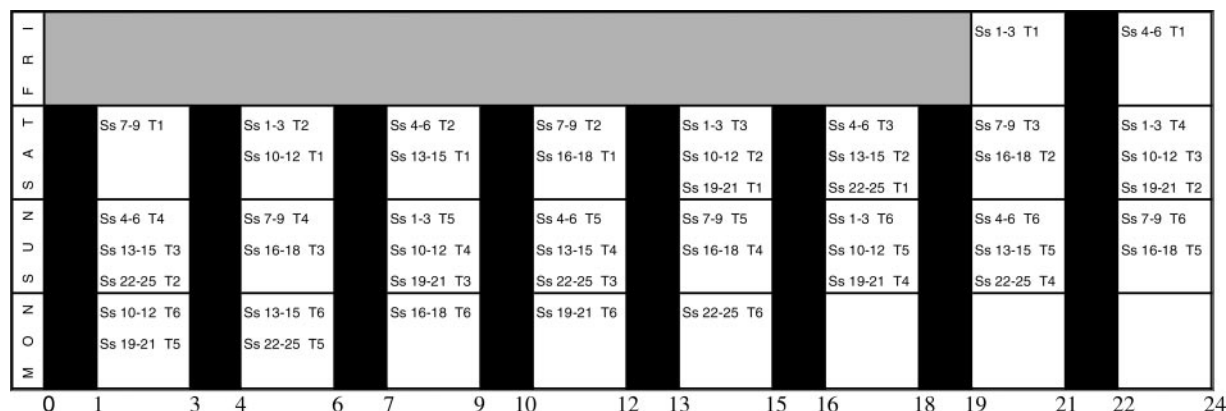


Fig. 1. Laboratory observation and performance trial schedule. Ss followed by number indicates participant; T followed by number designates trial number. Open bars, 120 min of wakefulness in dim (<30 lux) light; solid bars, 60 min of sleep (<1 lux). Days of observation are shown at *left*; environmental time of day is shown at *bottom*. Most participants entered the ultra-short sleep-wake protocol 1 cycle before their scheduled 1st performance and remained in the protocol for 50 h. However, if the randomly assigned time of entry was to occur during the participant's normal hours of sleep (e.g., 0100 or 0400), he/she began laboratory observation 1 h before his/her usual bedtime. Participants were randomized into groups of 3, with each group performing a swim trial every 9 h. Possible fatigue effects of multiple swim trials were evenly dispersed over each wake period. For each of the 8 wake periods, ~ 18 trials were performed, and each group of performances was at a different point in the progression of trials.

Welch Allyn, San Diego, CA) to measure each participant's T_{aur} . Three measurements were taken at each time point and averaged.

Swim performances. As described above, most participants performed *swim trial 1* after completing the first 180-min ultra-short sleep-wake cycle (i.e., ~4 h after entrance into the laboratory protocol). However, participants who arrived in the laboratory 1 h before their usual bedtimes were in the laboratory 6–9 h before *swim trial 1*. All swim trials occurred at approximately *minute 60* of the 120-min wake periods, and trials were each separated by 9 h (i.e., every 3rd ultra-short sleep-wake cycle). Participants completed six swim trials, except for three participants who completed five trials (see below).

Participants were escorted to the pool at the appropriate times while wearing dark sunglasses to limit light exposure. For each trial, participants swam the 200-m freestyle with maximum effort in an individual time-trial format. Because warm-ups could enhance performance (11) and could mask an internally driven circadian rhythm of performance, warm-up swims were not allowed. Before each trial, participants were given standardized instructions reminding them to treat each trial as a race and to give maximal effort for each trial, regardless of performance expectations for that time of day.

Swim trials were conducted in a 50-m pool. Participants performed a push-off start (which is typical for training intervals), and final 200-m times were obtained by the same timer throughout the six trials. For a subset of participants (~25%), water temperature was verified to be constant throughout all six swim trials. Immediately after the swim performance, participants rated their exertion using the Borg [6–20] Perceived Exertion Scale [rating of perceived exertion (RPE)], which ranges from 6 (“no exertion”) to 20 (“maximal/very, very hard exertion”) (13). After each trial, participants performed a “cooldown” of up to 200 m to recover from the swim performance. Each participant kept his/her cooldown consistent through all six trials. Performance times were disclosed to the participants if they requested them. After each swim trial, participants returned to the laboratory and continued to follow the ultra-short sleep-wake schedule.

Psychological state assessments. At *minutes 15* and *105* of each wake period, sleepiness was assessed with the Stanford Sleepiness Scale (SSS) (27). The SSS is a single-item scale on which participants rate their sleepiness “at that very moment” on a scale of 1 (“feeling active and vital, alert, wide awake”) to 7 (“almost in reverie, sleep onset soon, lost struggle to remain awake”).

At *minute 15* of each wake period, mood was assessed with the Profile of Mood States Questionnaire (POMS) (35) using the “right-now” prompt. The POMS assesses the present intensity of 65 different emotions/feelings on a five-point scale: 0 for not at all, 1 for a little, 2 for moderately, 3 for quite a bit, and 4 for extremely. Subscale scores for tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment and a global total mood disturbance score were calculated.

At *minute 105* of each wake period, participants completed Part II of the Mental and Physical State and Trait Energy and Fatigue Scales Questionnaire (MPSTEFs; P. J. O'Connor, personal communication). On this part of the questionnaire, participants used 100-mm visual analog scales to rate their feelings of energy and fatigue on the basis of “how-you-feel-right-now” instructions. Six questions relate to feelings of energy and fatigue regarding physical activity. Six similar questions relate to feelings of energy and fatigue regarding mental activity. Subscale scores were calculated for physical energy, physical fatigue, mental energy, and mental fatigue.

Data Analysis

All statistical comparisons were performed using SPSS (version 13.0.1, SPSS, Chicago, IL) software. Values are presented as means \pm SE, and significance was set at $P < 0.05$.

Circadian rhythm of T_{aur} . To avoid possible transient effects of the environment or initiation of the 180-min ultra-short sleep-wake cycle

on circadian assessment, an a priori decision was made to exclude temperature data during the first 4 h of laboratory observation. Similarly, because of the effects of swimming and water temperature on body temperature, temperature data taken immediately after the swim trials were also excluded from analysis. In addition, an a priori decision was made to exclude individual data points if there was $>1^{\circ}\text{F}$ (0.56°C) difference compared with measurements taken immediately before and after the data point in question. The circadian rhythm of body temperature was determined by least-squares estimation of the best-fitting cosine curve of temperature data using Action4 (version 1.12, Ambulatory Monitoring, Ardsley, NY) software. The circadian nadir [time of the lowest value of the cosine-fitted rhythm (T_{\min})], acrophase (24-h cosine-fitted time of peak value), mesor (mean value of the fitted curve, expressed in $^{\circ}\text{C}$), and amplitude (difference between mesor and acrophase values, expressed in $^{\circ}\text{C}$) of body temperature were calculated. Student's two-tailed t -tests analyzed sex differences in body temperature rhythm parameters.

Within-individual rhythms of swim performance. Within-individual circadian rhythms of swim performance across the six trials were determined by least-squares estimation of the best-fitting 24-h cosine curve of swim performance times using Action4 software. Acrophase, mesor (expressed in seconds), and amplitude (expressed in seconds) of each individual rhythm were calculated. Student's two-tailed t -tests analyzed sex differences in swim performance rhythm parameters. The Rayleigh test (7) was used to test the null hypothesis that swim performance acrophases were randomly distributed across the 24-h day.

z -Transformations of individual swim performances. So that variations in performance could be determined relative to each participant, swim performances for each trial were subjected to z -transformation as follows

$$\frac{(\text{time for specific trial} - \text{mean time across all 6 trials})}{(\text{standard deviation of set of 6 trials})}$$

z -Transformations were used for all subsequent analyses regarding swim performance.

Time-of-day variation in swim performance across all participants. Analysis of covariance (ANCOVA), with trial number as the covariate, was used to compare swim performance between eight times of day across all participants. When significant between-group differences were found, Bonferroni's post hoc tests were used to compare performance between individual times of day.

Variation in swim performance relative to T_{\min} . The circadian time of each individual swim trial was determined relative to the time at which the participant's body temperature was lowest (T_{\min}). Relative timing of the swim trials was calculated into twelve 2-h intervals. ANCOVA, with trial number as the covariate, was used to compare performances between the intervals across all participants. When significant between-interval differences were found, Bonferroni's post hoc tests were used to compare performance between individual intervals.

Fatigue effects on swim performance. Fatigue effects associated with multiple trials were measured by one-way ANOVA comparing swim performance across *trials 1–6*, collapsed across all times of day. Trial number was included as a covariate in the swim performance analyses (see above).

Sleep. Sleep-wake state was recorded over the course of home and laboratory observation by wrist actigraphy. Sleep-wakefulness was estimated from a statistical algorithm using Action4 software. For home observation, bed and wake times, sleep onset (i.e., bedtime + sleep onset latency), midsleep (i.e., midpoint between sleep onset and wake time), and total sleep time were determined for each night. For laboratory observation, total sleep time per 24 h was calculated. Circadian rhythm of sleep during laboratory observation was determined by least-squares estimation of the best-fitting 24-h cosine curve of the raw data using Action4 software.

Pearson's post hoc product-moment correlation analysis was performed between total sleep time per 24 h and change in swim performance from trials 1–3 to trials 4–6 to examine the association between fatigue effects and sleep.

Correlations of swim performance with temperature and psychometrics. Pearson's product-moment correlations were used to correlate swim performance rhythm parameters (i.e., acrophase, mesor, and amplitude) with body temperature rhythm and swim performance acrophases with acrophases of each of the psychological variables.

Body temperature assessments immediately before each swim were expressed relative to each participant's mesor to standardize values across participants. Pearson's product-moment correlations were used to correlate preswim body temperatures with swim performances.

Psychological variables were subjected to *z*-transformation. Associations of *z*-transformed swim performances with psychometric measures obtained 45 min before the swim trials (POMS and SSS), with RPE assessed immediately after the trials, and with MPSTEFs data obtained ~45 min after the trials were assessed with Pearson's product-moment correlations collapsed across all times of day.

RESULTS

Participants

Demographic information regarding the participants is included in Table 1. Only height and weight were significantly different between males and females. One participant withdrew from the study after 8 h of laboratory observation because of a persistent headache. Data associated with this participant were excluded.

At the time of the study participants averaged 4.2 ± 0.4 days/wk of swim training. Most of the participants were on the university intercollegiate team ($n = 7$) or on a competitive summer club team ($n = 6$). On the basis of the Horne-Östberg Morningness-Eveningness Questionnaire (MEQ) (28), 10 participants were moderate morning types, 13 were intermediate types (neither morning nor evening types), and 2 were moderate evening types. Mean MEQ score was 54.0 ± 1.8 , further indicating that the group was, on average, intermediate in terms of morningness-eveningness.

Body Temperature

On average, 38.8 ± 0.3 body temperature data points were obtained for each participant over the 50–55 h of laboratory

observation. Mean coefficient of variation for the three measurements at each time point was $0.16 \pm 0.01\%$. Cosine fits of individual T_{aur} measurements produced significant cosine fits for 23 of 25 participants. For the two nonsignificant cosine fits, visual inspections of the temperature rhythms were insufficient for estimation of T_{min} . To estimate T_{min} for these 2 participants, we determined the correlations of T_{min} with various actigraphic sleep parameters measured during home observation (i.e., median bed and wake times, sleep onset, and mid-sleep) of the other 23 participants (14). The highest correlation was that of bedtime and T_{min} ($r = 0.459$, $P = 0.028$), with a median time lag of 4.16 h. In the remaining two participants, T_{min} was estimated by addition of this time lag to the respective median bedtimes (obtained from home observation) of each participant. Average T_{min} for the group was 0357 ± 0021 . Similar T_{min} averages were found between men (0408 ± 0019) and women (0347 ± 0036). Mesor was significantly higher [36.71 ± 0.07 vs. $36.49 \pm 0.06^\circ\text{C}$, $t(23) = 2.335$, $P = 0.029$] and body temperature rhythm amplitude was lower [0.21 ± 0.02 vs. $0.30 \pm 0.02^\circ\text{C}$, $t(23) = -3.017$, $P = 0.006$] in the women than in the men. The average circadian profile of T_{aur} is included in Fig. 5.

Swim Performance

A total of 147 swim performances (of the intended 150 for 25 participants) were obtained for analysis. The sixth trial for three of the participants was not performed because of an unexpected pool closure for reasons unrelated to this study.

Individual swim times for the 200-m trials ranged from 127.90 to 246.94 s; mean swim performance was 169.50 ± 2.56 s. The mean within-individual standard deviation for performance was 3.18 s. The median swim performance acrophase was 1802 (range 0305–2243). Significant individual cosine-fitted swim performance rhythms were found for only 4 of the 25 participants. However, the Rayleigh test indicated that the performance acrophases obtained from cosinor analysis were not randomly distributed across the 24-h day ($r = 0.80$, $P < 0.001$). In addition, group cosinor analysis also indicated a highly significant swim performance rhythm (acrophase = 1803, $P < 0.001$). There were no sex differences for mesor, amplitude, or acrophase of the swim performance rhythms.

Time-of-day variation in swim performance. Swim performances across all participants differed significantly by environmental time of day, regardless of whether trial number was included as a covariate [$F(7,138) = 9.776$, $P < 0.001$; Fig. 2]. Post hoc analysis revealed that performance was significantly worse at 0200, 0500, and 0800 than at 1100, 1400, 1700, 2000, and 2300.

Variation in swim performance relative to T_{min} . Swim performances across all participants also differed significantly when expressed relative to T_{min} and grouped into 12 equally spaced intervals, regardless of whether trial number was included as a covariate [$F(11,134) = 6.607$, $P < 0.001$; Fig. 3]. Post hoc analysis revealed that performances at -1 to $+1$ h (i.e., 1 h before to 1 h after T_{min}) and $+1$ to $+3$ h relative to T_{min} were significantly worse than those at -9 to -7 h, -7 to -5 h, -5 to -3 h, $+9$ to $+11$ h, and $+11$ to $+13$ h relative to T_{min} .

Table 1. Participant characteristics

	Means \pm SE ($n = 25$)
Age, yr	20.68 \pm 0.61
Height, cm	176.23 \pm 2.28
Weight, kg	73.92 \pm 2.46
BDI-II, total score	1.60 \pm 0.39
MEQ, total score	54.04 \pm 1.75
PSQI, global score	3.33 \pm 0.34
Bedtime, h	23.90 \pm 0.20
Wake-time, h	7.72 \pm 0.29
Sleep onset, h	0.15 \pm 0.21
Midsleep, h	3.81 \pm 0.22
Swimming, days/wk	4.16 \pm 0.40
Top swim time, s	166.60 \pm 6.13

BDI-II, Beck Depression Inventory II; MEQ, Horne-Östberg Morningness-Eveningness Questionnaire; PSQI, Pittsburgh Sleep Quality Index. Bedtime, wake time, sleep onset, and midsleep midpoint between sleep onset and wake time represent median sleep parameters obtained from week of home observation. Top swim time is best (of 6 possible trials) 200-m freestyle time recorded during laboratory observation.

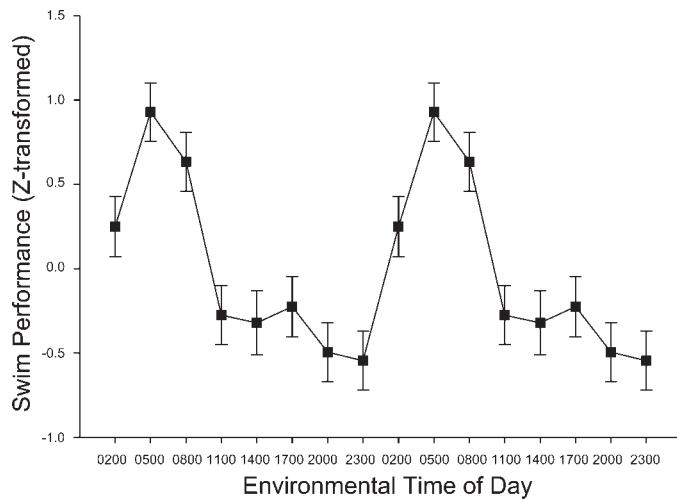


Fig. 2. Swim performances vs. environmental time of day. Values (means \pm SE) are double plotted to convey cyclical nature of the rhythm. Higher z scores indicate worse performance. Analysis of covariance (ANCOVA), controlling for trial number, revealed a significant difference in performance between times of day ($P < 0.001$). Performances were significantly worse at 0200, 0500, and 0800 than at 1100, 1400, 1700, 2000, and 2300.

Fatigue effects on swim performance. ANOVA revealed a significant trial effect for performance [$F(1,112.286) = 4.022$, $P = 0.047$; Fig. 4]. Post hoc curve-fitting analyses revealed a significant linear pattern indicating a general worsening of performance across trials, as well as a significant quadratic pattern [$F(1,112.286) = 7.085$, $P = 0.009$], indicating better performance in the beginning and end trials than in the middle trials. Similarly, ANOVA revealed that performances were significantly better in trials 1–3 than in trials 4–6 [$F(1,48) = 6.513$, $P = 0.014$].

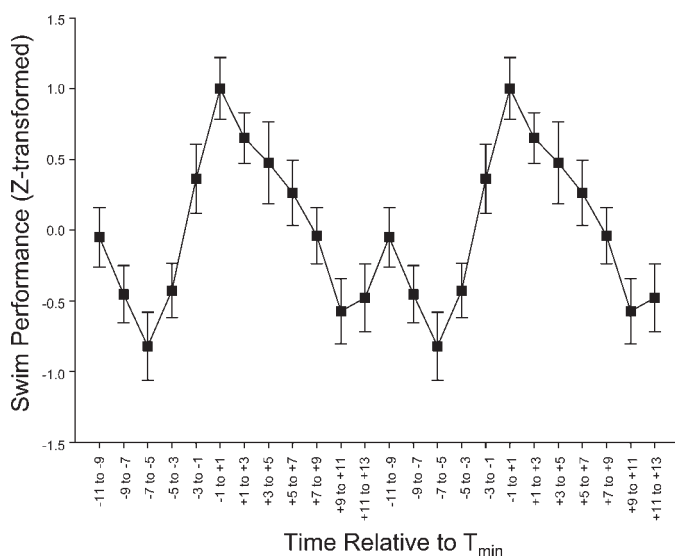


Fig. 3. Swim performances relative to time of lowest value of cosine-fitted rhythm (T_{\min}). Values (means \pm SE) are double plotted. Higher z scores indicate worse performance. ANCOVA, controlling for trial number, revealed a significant difference in performance between times relative to T_{\min} ($P < 0.001$). Performances were significantly worse at -1 to +1 h and +1 to +3 h than at -9 to -7 h, -7 to -5 h, -5 to -3 h, +9 to +11 h, and +11 to +13 h.

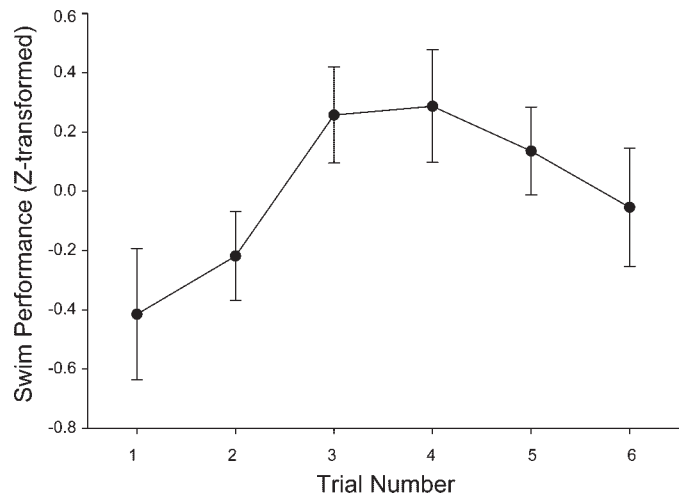


Fig. 4. Swim performances between trials collapsed across all times of day. Values are means \pm SE. Higher z scores indicate worse performance. Regression analysis revealed linear ($P = 0.047$) and quadratic ($P = 0.009$) fatigue effects across trials.

Sleep

The mean amount of sleep per 24 h of laboratory observation was 5.10 ± 0.20 h. Significant individual cosine-fitted sleep rhythms were found in 19 of the 25 participants. Mean sleep acrophase was 0630 ± 0024 , and amplitude was 0114 ± 0007 .

Fatigue effects in the swim trials (i.e., performance change from trials 1–3 to trials 4–6) were not significantly correlated with the amount of sleep per 24 h of laboratory observation ($r = -0.232$, $P = 0.265$).

Correlations of Swim Performance With Temperature and Psychometrics

Swim performance amplitude was significantly correlated with body temperature rhythm amplitude ($r = 0.464$, $P = 0.019$). There was a trend for a significant association between swim performance and body temperature acrophases ($r = 0.364$, $P = 0.074$). The relation between body temperature and swim performance rhythms is plotted in Fig. 5. Collapsed across all times of day, increased preswim body temperature

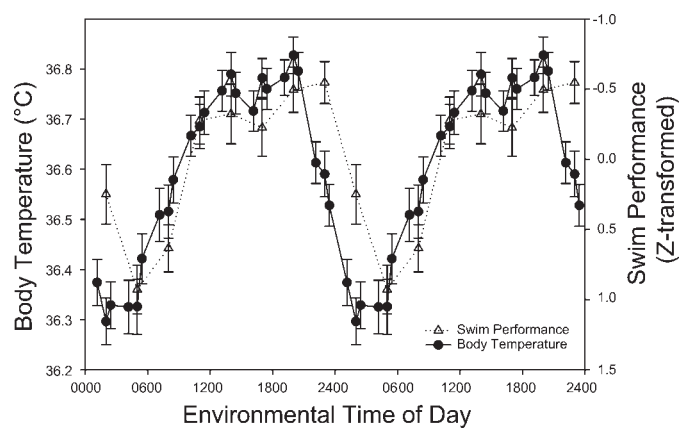


Fig. 5. Relation between body temperature (\bullet) and swim performance rhythms (Δ). Both rhythms are double plotted. Swim performance rhythm consistently lagged behind body temperature rhythm. Preswim body temperature was significantly associated with swim performance ($r = -0.427$, $P < 0.001$).

was significantly associated with faster swim performance, i.e., lower z scores ($r = -0.427$, $P < 0.001$).

Collapsed across all times of day, swim performance was significantly correlated with 1) POMS measures of total mood disturbance ($r = 0.476$, $P < 0.001$), anger ($r = 0.175$, $P = 0.035$), vigor ($r = -0.437$, $P < 0.001$), fatigue ($r = 0.426$, $P < 0.001$), and confusion ($r = 0.513$, $P < 0.001$); 2) the SSS measure of sleepiness ($r = 0.385$, $P < 0.001$); and 3) MPSTEFs measures of physical fatigue ($r = 0.263$, $P = 0.001$), mental energy ($r = -0.252$, $P = 0.002$), and mental fatigue ($r = 0.301$, $P < 0.001$). In general, improved swim performance was associated with decreased levels of total mood disturbance, anger, fatigue, confusion, sleepiness, physical fatigue, and mental fatigue and increased levels of vigor and mental energy. However, swim performance was not significantly correlated with RPE.

DISCUSSION

Swim Performance

The primary finding of this study was significant circadian variation in swim performance when expressed relative to environmental time of day or T_{\min} . When expressed relative to environmental time of day, swim performance was impaired from 0200 to 0800 compared with all other times of day, with peak performance at 2300 (Fig. 2). When expressed relative to T_{\min} , swim performance was worst from 1 h before to 1 h after T_{\min} and best from 9 h after to 5 h before T_{\min} (Fig. 3).

These results are consistent with numerous other studies comparing maximal swim performance at different times of day (8, 18, 46). Clear superiority of swim performance in the afternoon/evening compared with the morning has been reported in most, but not all, of these studies. Moreover, as in our study, other investigations of swim performance at multiple times of day have reported linear improvements in performance from the early morning to the evening. For example, in a counterbalanced study involving teen-aged competitive swimmers, Baxter and Reilly (8) found progressive improvements of 3.5% and 2.5% in 100- and 400-m swim performance, respectively, as the performance was assessed across five times of day (0630, 0900, 1330, 1700, and 2200). In a more recent study of experienced swimmers, Deschodt and Arzac (18) found progressive improvement in 50-m swim performance from 0800 to 1300 to 1800, with a total improvement of 4% from morning to evening.

In other types of athletic performance lasting 2–4 min (the approximate range of performance duration in this study), performance has consistently been superior in the afternoon/evening than in the morning. For example, Hill (26) found that time to exhaustion in a ~3.5-min constant-power cycling test was significantly better at 1600 than at 0800. Furthermore, in a test involving cycling at 95% of maximal O_2 uptake, Reilly and Baxter (43) found that time to exhaustion was significantly greater at 2200 than at 0630.

In summary, the results of the present study confirm previous findings of a significant diurnal, or time-of-day, variation in swimming performance. Of considerable interest to many investigators is whether this pattern is mediated by the circadian system. As reviewed previously, prior studies have not adequately addressed this question, because they have not employed appropriate chronobiological techniques that allow one to conclude whether time-of-day differences in perfor-

mance can be attributed to circadian regulation or to a host of environmental and behavioral masking factors (e.g., sleep-wakefulness, food ingestion, light exposure, and ambient temperature) (53). To our knowledge, the present study, using the ultra-short sleep-wake cycle, provides the first clear evidence of circadian regulation in athletic performance.

Fatigue Effects on Swim Performance

There was a significant linear decline in performance across trials, suggesting a fatigue effect (Fig. 4), as well as a quadratic fatigue pattern, which indicated improved performance in the early and late trials compared with the middle trials. The improvement toward the latter trials is consistent with anecdotal evidence that athletes often exert more effort as they approach the end of a set of trials. Importantly, fatigue was not so extreme that it prevented participants from performing better in their final two trials. Furthermore, ANCOVA, controlling for trial number, revealed significant circadian patterns, and post hoc ANOVA showed no significant trial \times time-of-day or trial \times circadian time interactions. This suggests that the study design adequately distributed these fatigue effects across the 24-h day.

The extent to which the fatigue effect can be attributed to swimming six trials over a short time period or to following the tiring ultra-short sleep-wake cycle is unclear. The opinion of the coach for most of the swimmers was that the swimmers could easily perform the six maximal trials without fatigue, inasmuch as this is commonly required in swim meets and in training. Although the swimmers averaged only ~5 h of sleep per 24-h period, there is little compelling evidence that such moderate short-term sleep loss impairs anaerobic (38) or aerobic (25) athletic performance. For example, Sinnerton and Reilly (48) found that the diurnal variation in 50- and 400-m swim performance was significantly greater than any effect of sleep loss on performance. Furthermore, we did not find a significant association between the amount of sleep and performance decrement ($P = 0.265$) in a post hoc analysis. Nonetheless, it is plausible that moderate sleep restriction combined with multiple swim trials contributed to fatigue.

Body Temperature Rhythm

T_{aur} measurements had acceptable precision. Average coefficient of variation for the three measurements at each time point was $0.16 \pm 0.01\%$. T_{aur} showed a robust circadian profile (Fig. 5), as expected.

The average T_{\min} (0357 ± 0021) for the participants in this study was somewhat phase advanced compared with that for young adults in other studies. Although protocols, measurement sites, and analysis techniques differ between studies, most chronobiological studies have found a T_{\min} of ~0400–0630 in young adults (22, 33). The relative phase advance of our participants may be partially explained by the proportion of participants classified as “moderately morning types” (13 of 25) by the MEQ, inasmuch as T_{\min} occurs earlier in morning types than in intermediate and evening chronotypes (6). Although morningness-eveningness is partly genetic (30), it seems plausible that early-morning training (e.g., early time of arising and morning exposure to light and/or exercise) could be partially responsible for the advanced circadian phase of the participants in the present study.

Association of Swim Performance With Temperature and Mood

Because many measures of athletic performance peak in the late afternoon or early evening, they naturally occur near the body temperature peak. Thus there has been speculation that diurnal variation in athletic performance might be moderated by the circadian rhythm in core body temperature (4, 20). Conclusions regarding causality cannot be made on the basis of our correlational data. Across all data points, preperformance body temperature was significantly correlated with better swim performance, i.e., less time to complete the swim trials ($r = -0.427$, $P < 0.001$). Moreover, the near-significant correlation between acrophases of swim performance and body temperature might have been underestimated, because most of the individual cosine fits of swim performance were nonsignificant. Nonetheless, as displayed in Fig. 5, the data suggest similar, but not coincident, timing of the rhythms of swim performance and T_{aur} . Rather, the swim performance acrophase lagged behind the temperature acrophase by ~ 90 min, which is consistent with the results of Baxter and Reilly (8) showing progressively better performance from early morning to late evening. Thus one interpretation of the data is that rhythms of temperature and athletic performance reflect parallel outputs from the SCN with a phase lag of ~ 90 min.

Other studies have indicated that although body temperature might contribute to the diurnal rhythm in athletic performance, it is unlikely to be the sole determinant of performance. For example, large increases in body temperature via passive heating have been necessary to elicit modest improvements in strength and anaerobic performance (10). Thus it has been argued (34) that the diurnal rhythm in muscular strength is more likely to be attributable to intracellular processes involved in excitation-contraction coupling than the small diurnal variation in body temperature.

Similarly, it seems unlikely that the small range of the circadian rhythm in temperature noted in the present study (0.5°C) can completely account for the large variation in performance (3.4%). In support of this interpretation, the diurnal rhythm in performance has commonly persisted after the elimination of the diurnal rhythm in temperature (2, 5).

Analogous to the thermogenic hypothesis, it could be posited that the circadian rhythm in swim performance might be partly mediated by circadian rhythms in mood, which indicate optimal mood near the body temperature maximum (12, 36). Our correlational data are inconclusive. Collapsed across all times of day, we found significant associations of swim performance with POMS measures of total mood disturbance, anger, vigor, fatigue, and confusion, SSS scores, and MPSTEFs measures of physical fatigue, mental energy, and mental fatigue. These findings are in agreement with other studies that have found an association between positive mood state and superior athletic performance (39). However, swim performance acrophase was not significantly correlated with acrophases of any of the psychological variables, even though the estimates of swim acrophase were not reliable (i.e., not significant) for most participants. The quadratic fatigue effect (Fig. 4) suggests that swim performance was partly influenced by effort/motivation. However, the performance rhythm clearly persisted after ANCOVA control for trial number. Of potential relevance to the present results, recent studies of diurnal

variation in muscular strength have reported peripheral (i.e., at the muscular level), rather than central (i.e., neural activation), changes over the course of the day (34), casting doubt that time-of-day variations are a result of motivation. Thus, as with associations with body temperature, the significant associations of swim performance with psychological variables in the present study might reflect parallel SCN regulation of performance and mood.

Methodological Strengths of the Study

One strength of this study was the use of the ultra-short sleep-wake cycle, which allowed equal distribution across the 24-h day of many potential masking factors that could possibly moderate diurnal variations in athletic performance (e.g., sleep, ambient temperature, energy intake, and light exposure). Previous research has indicated that this protocol is quite useful for assessing circadian rhythms (15, 47). Moreover, the ultra-short sleep-wake schedule allowed multiple performance assessments over a short period of time with relatively little sleep loss.

Another strength of the experiment was that it involved a sport-specific performance marker in highly trained participants. Furthermore, performance was assessed relative to body temperature (circadian time) as well as environmental time of day.

Limitations of the Study

There are several limitations to this study. Six maximal swim trials over a 50-h period were too many to avoid fatigue, yet too few to establish significant individual circadian performance rhythms, in most of the participants. Because the results did not differ significantly when trial number was added as a covariate in data analysis, it appears that the experimental design adequately distributed fatigue effects across the 24-h day. Furthermore, sleep duration was not found to be significantly associated with the fatigue effects. Nevertheless, fatigue contributed to increased variability of the data.

Notwithstanding the robustness of the grouped data (Figs. 2 and 3), it is noteworthy that significant cosine fits of swim performance were found in only 4 of the 25 participants. Nevertheless, the Rayleigh test revealed that the acrophases of swim performance were not randomly distributed. Given the variability in measurement, six data points distributed over 50 h are probably insufficient for establishing significant circadian rhythmicity in individual data. We illustrated this point by performing cosine fits of the T_{aur} data, restricting the analyses to the six temperature data points that immediately preceded the swim trials. Although the circadian rhythm of body temperature is the best-established human circadian rhythm, significant cosine fits were found for only 5 of the 25 participants in this restricted analysis. It has been more common to show mean (between subjects) circadian patterns for various data, including neurobehavioral performance (52), body temperature (32), and melatonin (45).

Despite standardized pretrial instructions to avoid altering effort on the basis of preconceived notions about performing at different times of day, expectations might still partly explain the superior performance in the evening compared with the morning. However, we do not believe this explanation is likely. In responding to a question on the MEQ (28), 13 participants indicated that they would be in "good form" or "reasonable form" if they decided to engage in hard physical exercise from

2200 to 2300, whereas 12 participants answered that they would find it “difficult” or “very difficult.” Conversely, in response to another MEQ question, all the participants indicated that they would be in “good” or “reasonable” form if asked to exercise from 0700 to 0800. Thus, contrary to performance results, the MEQ data suggest that the participants generally expected that they would perform particularly well in the morning and particularly poorly in the late evening.

An unfortunate study flaw was the nonstandardization of knowledge of swim performance, which may have impacted performance. We cannot assess the impact of this limitation, because we did not keep records of who was informed, but we believe that the impact on the results was minimal.

Although T_{aur} was an adequate marker of circadian phase, other markers may have been more advantageous. Although T_{aur} has been used often in recent studies involving diurnal rhythms of athletic performance (5), rectal temperature is still regarded as the “gold standard” for measurement of core body temperature. Most importantly, however, the more frequent sampling available with gastrointestinal (ingestible telemetric capsules) or rectal temperature measurement would allow for greater resolution of the circadian rhythm in core body temperature.

Light exposure of even lower intensity than the present study (<30 lux) can have circadian phase-shifting effects (23). However, light levels in the ultra-short sleep-wake schedule were distributed evenly across the 24-h day. Evidence suggests that circadian rhythms oscillate at their endogenous period (i.e., free run) in this protocol, even with higher light levels, social interaction, and knowledge of time of day (40). Exposure to 100- to 150-lux light when participants traveled to the restroom was reduced by 90% (to <15 lux) by dark eyewear and was also evenly dispersed across the 24-h day. Thus we do not believe that light exposure had significant phase-shifting effects in this experiment.

Implications of Study Results

The circadian range from best to worst performance in this study (5.84 s), a 3.4% difference from the mean, could have considerable importance in athletic competition. For example, among females competing in the 200-m freestyle final at the 2004 Olympics, first and third place were separated by only 0.42 s, and first and eighth place were separated by only 1.17 s. Among the men, 0.61 s separated the winner from third place, and 3.69 s separated first from eighth place (42).

Demonstration of a circadian rhythm in athletic performance provides a stronger theoretical rationale for expecting decrements in performance following circadian desynchronization (e.g., multiple-time-zone travel). Thus practical recommendations for resynchronizing the circadian system after rapid transmeridian travel (e.g., receiving bright light at appropriate times and avoiding bright light at inappropriate times) may be helpful (44).

By knowing the circadian time of peak performance, athletes may be better able to shift their circadian systems so that the peak of their performance rhythms coincides with the time of desired peak competition (41). This would be especially useful for athletes after rapid travel across multiple time zones, inasmuch as there is often insufficient time to gradually acclimate to the new time zone. Depending on the time of day of

competition, number of time zones crossed, and amount of time available before competition, athletes might perform better if they delay travel until just before competition. In addition, there could be implications for scheduling of training, which might be most efficient at the circadian time of peak performance. Exercise may also be most enjoyable at this time, which could have implications for exercise adherence.

Future Directions

Different modes and types of exercise should be examined in future studies. Some evidence suggests that anaerobic performance may exhibit even greater diurnal changes than endurance activity (see Ref. 4 for review). Furthermore, research should establish whether the circadian pattern exists when athletes are permitted warm-ups and interathlete competition. If these variables override circadian variations in performance, this study's findings may be of little practical value. Finally, future research should attempt to address whether rhythms in athletic performance are due to central (i.e., neural command/activation or motivation) or peripheral (i.e., intramuscular) factors. For instance, the rhythm in muscular strength could be investigated using voluntary and electrically induced contractions (34) during an ultra-short sleep-wake schedule.

In conclusion, this study used a chronobiological technique that allows for 24-h standardization of various environmental and behavioral masking factors to demonstrate circadian variation in athletic performance. A significant circadian pattern was noted, with worst performance at around the T_{min} and peak performance ~6 h before T_{min} . These circadian times corresponded to environmental times of day of 0500 and 2300, respectively. These data suggest a significant circadian rhythm in swim performance lasting 2–4 min.

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