How jet lag impairs Major League Baseball performance

Alex Song[a], Thomas Severini[b], and Ravi Allada[a,1]

[a]Department of Neurobiology, Northwestern University, Evanston, IL 60208; and [b]Department of Statistics, Northwestern University, Evanston, IL 60208

Edited by Joseph S. Takahashi, Howard Hughes Medical Institute, University of Texas Southwestern Medical Center, Dallas, TX, and approved December 13, 2016 (received for review June 1, 2016)

Laboratory studies have demonstrated that circadian clocks align physiology and behavior to 24-h environmental cycles. Examination of athletic performance has been used to discern the functions of these clocks in humans outside of controlled settings. Here, we examined the effects of jet lag, that is, travel that shifts the alignment of 24-h environmental cycles relative to the endogenous circadian clock, on specific performance metrics in Major League Baseball. Accounting for potential differences in home and away performance, travel direction, and team confounding variables, we observed that jet-lag effects were largely evident after eastward travel with very limited effects after westward travel, consistent with the >24-h period length of the human circadian clock. Surprisingly, we found that jet lag impaired major parameters of home-team offensive performance, for example, slugging percentage, but did not similarly affect away-team offensive performance. On the other hand, jet lag impacted both home and away defensive performance. Remarkably, the vast majority of these effects for both home and away teams could be explained by a single measure, home runs allowed. Rather than uniform effects, these results reveal surprisingly specific effects of circadian misalignment on athletic performance under natural conditions.

jet lag | circadian rhythms | athletic performance | Major League Baseball

Although we know much about circadian clock function from highly controlled laboratory studies, less is known about the specific functions of these clocks under natural conditions, especially in humans. In constant laboratory conditions, clocks drive a wide range of behavioral and physiological rhythms, which are approximately, but not exactly, 24 h (1). In addition, these near-24-h rhythms can be synchronized to and aligned with the 24-h environment via light. Rapid long-distance east–west travel can desynchronize internal clocks from the external 24-h environment, resulting in symptoms collectively known as "jet lag" (2, 3). These include poor sleep, fatigue, gastrointestinal disturbance, and impaired motor performance. To discern the role of circadian alignment under natural conditions in humans, researchers have examined the effects of jet lag on athletic performance and have found effects on broad aggregate performance parameters such as winning percentage or total points scored (4–11). It has been widely assumed that jet lag impacts a broad range of parameters under a wide variety of conditions. Here, we mined 20 seasons of Major League Baseball (MLB) data to examine the precise aspects of human performance that underlie the effects of jet lag. Specifically, we asked whether jet lag differentially affects the home and away teams and whether it affects all or only specific features of performance, and if so, which ones?

Results

To ensure sufficient statistical power and robust conclusions, we analyzed 20 y of data from MLB (1992–2011), encompassing 46,535 games analyzed for effects of jet lag on performance. From the perspective of both the home and away teams, we found 4,919 instances of teams having at least 2 h of jet lag (Tables S1 and S2). Jet lag was determined by the number of time zones crossed and the number of days since travel, following the general rule of thumb that human circadian clocks resynchronize toward their destination time at a rate of ~1 h/d (12, 13). Given the relatively small number of games involving jet lag of 3 h (Table S1) and the fact that the International Classification of Sleep Disorders diagnosis of Jet Lag Disorder requires travel across at least two time zones (14), we defined jet lag as those games where a team had at least a 2-h jet lag, that is, teams that traveled across at least two time zones, accounting for adaptation to the new time zone (*Methods*). Teams that were shifted 1 h or less after adaptation were not considered to be jet lagged. Combining the 2- and 3-h jet-lag groups allowed us to maximize the size of the jet-lag group and thus the power to detect jet-lag effects.

Importantly, we also accounted for potential confounding variables, such as home-field advantage and team effects. Because home teams were less often jet lagged, i.e., upon return travel home (Table S1), differences attributed to jet lag could be due to home-field advantage, i.e., the general advantage a team displays at home. In our analysis, we analyzed home- and away-team jet-lag effects separately. In addition, it is possible that high-performing teams may not be randomly distributed between the jet-lag and non–jet-lag groups and thus, differences between the two groups may instead be due to the differential composition of team quality between those groups. By controlling for the home team, this approach also controls for potential park effects. Thus, we controlled for many potential confounding factors when analyzing game data; see *Methods* (and below) for further details.

We also considered jet-lag effects as a function of eastward or westward direction of travel. Because the human endogenous circadian period is longer than 24 h (15, 16), it is generally thought to be easier to adjust to westward travel that delays sunrise/sunset, than eastward travel (17). Nonetheless, westward travel has been found to be more deleterious in some cases

Significance

Although circadian clocks have been studied extensively in controlled laboratory settings, examining the function and misalignment of these biological clocks in natural settings has been more challenging. Here, we examined data from Major League Baseball (MLB) where players frequently travel long distances in the east–west direction. By using 20 years of MLB data, we found the effect of jet lag to be context dependent and remarkably specific. Overall, our findings demonstrate how circadian misalignment can impact specific features of human performance in natural settings.

NEUROSCIENCE

Author contributions: T.S. and R.A. designed research; A.S. and T.S. performed research; A.S., T.S., and R.A. analyzed data; and A.S., T.S., and R.A. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

[1]To whom correspondence should be addressed. Email: r-allada@northwestern.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1608847114/-/DCSupplemental.

Table 1. Effect of travel direction on the impact of jet lag on home and away winning and aggregate offensive performance

	Home jet lag					Away jet lag				
Offense	West	West *P* value	Average	East	East *P* value	West	West *P* value	Average	East	East *P* value
Winning, %	−0.02 ± 0.016	0.112	0.539 ± 0.002	−0.035 ± 0.019	0.0335*	−0.01 ± 0.013	0.2295	0.461 ± 0.002	−0.021 ± 0.015	0.075
Runs scored	−0.098 ± 0.104	0.173	4.787 ± 0.015	−0.15 ± 0.121	0.1065	−0.018 ± 0.087	0.4165	4.652 ± 0.015	−0.011 ± 0.096	0.456
Batting average	−0.001 ± 0.003	0.372	0.265 ± 0.0004	−0.004 ± 0.003	0.074	−0.001 ± 0.002	0.2425	0.254 ± 0.0003	−0.001 ± 0.002	0.408
On-base, %	−0.001 ± 0.003	0.419	0.334 ± 0.0004	−0.003 ± 0.003	0.191	−0.002 ± 0.002	0.195	0.319 ± 0.0004	−0.00009 ± 0.002	0.486
Slugging, %	−0.002 ± 0.005	0.327	0.420 ± 0.0007	−0.01 ± 0.006	0.0415*	−0.002 ± 0.004	0.3215	0.400 ± 0.0007	−0.001 ± 0.004	0.412

Home and away jet lag show the regression coefficients indicating the effect of jet lag on home- and away-team offensive performance, respectively. Regression coefficients are adjusted for team effects. Parameters are expressed on a per-game basis with error indicating SE of the estimated effect. *P* values are one tailed, derived from the regression analysis testing whether jet lag adversely impacts performance.
*Metrics where $P < 0.05$. Average is over all 46,535 games.

(7, 10, 11). This latter effect has been attributed to the teams traveling west performing further from their optimal time-of-day than their host teams that are not typically jet lagged do, enhancing jet-lag effects.

We performed a multivariate linear regression analysis, including home- and away-team jet-lag variables considering travel direction (greater than or equal to two or more time zones with one time zone/day adjustment) and home- and away-team variables, to determine whether away- or home-team jet lag contributed to performance independent of each other and team (Table 1, and see *Methods*). A detailed description of the model used is provided in *Methods*. In general, the effects of eastward travel on winning percentage exceeded those of westward travel, which were consistent with the >24-h endogenous period. However, only eastward travel by the home team reached statistical significance (home eastward travel, $P < 0.05$). It is well established that the home team has a systematic advantage over the away or visiting team. In terms of winning percentage over the time period of our analysis, the home team won 53.9% of its games, corresponding to an advantage of +3.9%. In fact, the home-team eastward travel effect (−3.5%, $P < 0.05$) was comparable in magnitude to this home-field advantage (+3.9%). Thus, if the home team traveled two time zones east, and the away team was visiting from the same time zone, the home-field advantage was essentially nullified. On the other hand, the effect of traveling west was smaller and did not reach statistical significance (−2.0%, $P = 0.11$), suggesting direction selectivity. Interestingly, for the away team, the effects of traveling east on winning percentage were also larger than those traveling west, although eastward effects did not reach statistical significance (−2.1%, $P = 0.075$). The direction-selective effects, at least for the home team, suggest that they are due to circadian misalignment and not due to a general effect of travel.

To determine the basis of these effects, we examined the effects of jet lag on major parameters of home- and away-team offense, such as runs scored and batting average. Surprisingly, we found that home- and away-team offenses were differentially impacted by jet lag on one of these parameters, slugging percentage (total bases/at-bats). Like winning percentage, these home-team effects were direction selective, evident after eastward ($P < 0.05$) but not westward travel ($P = 0.327$), suggesting a circadian etiology. On the other hand, neither eastward ($P = 0.412$) nor westward travel ($P = 0.3215$) impacted away-team slugging percentage. Although the effects did not reach statistical significance, a similar pattern was also evident for runs scored. It is noteworthy that these effects were detected even though there are both fewer eastward travel and home-team jet-lag games and thus, less statistical power.

We then examined additional more specific offensive metrics to identify the underlying basis of these changes to major

Table 2. Effect of travel direction on the impact of jet lag on home offensive performance

	Home jet lag				
Offense	West	West *P* value	Average	East	East *P* value
At-bats	0.218 ± 0.138	0.113	33.497 ± 0.019	−0.141 ± 0.16	0.38
Singles	0.047 ± 0.088	0.7035	6.017 ± 0.012	−0.01 ± 0.103	0.46
Doubles	−0.015 ± 0.045	0.369	1.769 ± 0.006	−0.146 ± 0.053	0.003*
Triples	−0.003 ± 0.015	0.4295	0.205 ± 0.002	−0.031 ± 0.018	0.037*
Home runs	0.001 ± 0.035	0.525	1.033 ± 0.005	−0.01 ± 0.041	0.4
Walks	0.054 ± 0.071	0.777	3.435 ± 0.010	0.028 ± 0.083	0.6345
Strikeouts	0.057 ± 0.089	0.2595	6.202 ± 0.013	−0.05 ± 0.103	0.686
Stolen bases	−0.04 ± 0.031	0.0995	0.634 ± 0.004	−0.062 ± 0.036	0.0425*
Caught stealing	−0.032 ± 0.017	0.9725	0.262 ± 0.002	−0.002 ± 0.02	0.531
Stolen base attempts	−0.072 ± 0.036	0.022*	0.896 ± 0.005	−0.063 ± 0.041	0.0635
Sacrifice hits	−0.008 ± 0.02	0.349	0.348 ± 0.003	0.01 ± 0.023	0.674
Sacrifice flies	−0.011 ± 0.018	0.2685	0.295 ± 0.003	0.002 ± 0.021	0.5455
Grounded into double plays	0.032 ± 0.028	0.1235	0.762 ± 0.004	0.062 ± 0.032	0.0285*

Home jet lag shows regression coefficients indicating effects on home offensive performance. Regression coefficients are adjusted for team effects. Parameters are expressed on a per-game basis with error indicating SE of the estimated effect. *P* values are one tailed, derived from the regression analysis testing whether jet lag adversely impacts performance.
*Metrics where $P < 0.05$. Average is over all 46,535 games.

Table 3. Effect of travel direction on the impact of jet lag on away offensive performance

	Away jet lag				
Offense	West	West *P* value	Average	East	East *P* value
At-bats	−0.047 ± 0.117	0.685	35.086 ± 0.020	0.019 ± 0.129	0.883
Singles	−0.021 ± 0.075	0.3875	6.131 ± 0.013	−0.02 ± 0.082	0.403
Doubles	−0.029 ± 0.038	0.221	1.802 ± 0.007	0.03 ± 0.042	0.766
Triples	0.01 ± 0.012	0.808	0.179 ± 0.002	−0.016 ± 0.013	0.099
Home runs	−0.00004 ± 0.029	0.4995	1.029 ± 0.005	−0.001 ± 0.032	0.491
Walks	−0.03 ± 0.057	0.295	3.303 ± 0.010	0.019 ± 0.063	0.621
Strikeouts	−0.077 ± 0.074	0.8505	6.795 ± 0.013	0.043 ± 0.081	0.297
Stolen bases	0.018 ± 0.025	0.763	0.637 ± 0.004	0.003 ± 0.028	0.544
Caught stealing	0.001 ± 0.014	0.4605	0.285 ± 0.002	−0.028 ± 0.016	0.96
Stolen base attempts	0.019 ± 0.029	0.747	0.922 ± 0.005	−0.025 ± 0.032	0.222
Sacrifice hits	−0.058 ± 0.016	0*	0.340 ± 0.003	−0.015 ± 0.018	0.198
Sacrifice flies	−0.01 ± 0.015	0.235	0.286 ± 0.003	−0.031 ± 0.016	0.029*,†
Grounded into double plays	−0.011 ± 0.023	0.685	0.796 ± 0.004	0.01 ± 0.026	0.352

Away jet lag shows regression coefficients indicating effects on away offensive performance. Regression coefficients are adjusted for team effects. Parameters are expressed on a per game basis with error indicates SE of the estimated effect. *P* values are one tailed, derived from the regression analysis testing whether jet lag adversely impacts performance.

*Metrics where $P < 0.05$.

†Does not pass FDR < 0.2. Average is over all 46,535 games.

offensive parameters. Where aspects of offensive performance were detectably impacted by jet lag, these were nearly universally evident by traveling eastward rather than westward travel (Table 2). Home-team eastward travel, but not westward travel, significantly reduced doubles, triples, and stolen bases, and increased double plays ($P < 0.05$ at a Benjamini–Hochberg false discovery rate <0.2). The only parameter impacted by westward travel was a very minor parameter, stolen base attempts, and this did not quite translate into a statistically significant effect on stolen bases.

In terms of impact on slugging percentage (total bases/at-bats), the effect on doubles largely explains most of the effect. A reduction of 0.146 doubles per game translates into a reduction of 0.292 total bases per game. As the home team averages about 33 at-bats/game, this results in a reduction of 0.008 in slugging percentage, which is most of the observed reduction of 0.010. Thus, doubles can explain much of the aggregate effects of jet lag.

Consistent with the specificity of jet-lag effects on the home-team offense, we did not observe effects of east or west travel on away-team offensive performance on these metrics (Table 3). In fact, the only effects we observed on away-team offensive performance were on relatively minor parameters of sacrifice hits and sacrifice flies, although the latter passed our *P*-value threshold it did not pass our false discovery rate (FDR) threshold. In the case of sacrifice hits, it was dependent on westward travel and in the case of sacrifice flies, eastward travel. Nonetheless, these away- and home-team westward travel effects in single and relatively minor parameters are dwarfed by the multiple parameters impacted after home-team eastward travel. Thus, jet lag selectively impacts the home-team offensive performance, especially on metrics related to aggressive base running.

We then examined the effect of jet lag on major defensive performance metrics (Table 4). Eastward, but not westward, travel also strongly affected defensive performance metrics of slugging percentage allowed (for both home and away teams, $P < 0.05$), fielding-independent pitching (FIP; both home and away) and runs allowed for the away team. FIP attempts to isolate the effects on pitching weighting factors by their impact on earned runs allowed (*Methods*). Runs allowed for the home team were also nearly significant (+0.197, $P = 0.056$). For both home and away teams, these effects were comparable to or exceeded the home-field advantage effect for runs scored/allowed (home vs. away +0.135). Notably, batting average on balls in play (BABIP), an indicator of fielding, was not affected by jet lag, suggesting effects may be pitching-specific. Thus, a jet-lagged team upon return home displays both impaired offensive and defensive

Table 4. Effect of travel direction on the impact of jet lag on home and away aggregate defensive performance

	Home jet lag					Away jet lag				
Defense	West	West *P* value	Average	East	East *P* value	West	West *P* value	Average	East	East *P* value
Runs allowed	−0.083 ± 0.106	0.7825	4.652 ± 0.015	0.197 ± 0.124	0.0555	0.069 ± 0.084	0.2075	4.787 ± 0.015	0.162 ± 0.093	0.041*
Batting average	−0.002 ± 0.003	0.8135	0.254 ± 0.0003	0.003 ± 0.003	0.198	0.002 ± 0.002	0.1525	0.265 ± 0.0004	0.003 ± 0.002	0.095
On-base, %	−0.004 ± 0.003	0.925	0.319 ± 0.0004	0.003 ± 0.003	0.209	0.005 ± 0.002	0.0205*	0.334 ± 0.0004	0.002 ± 0.002	0.17
Slugging, %	−0.002 ± 0.005	0.6765	0.400 ± 0.0007	0.01 ± 0.006	0.046*	0.001 ± 0.004	0.4385	0.420 ± 0.0007	0.009 ± 0.005	0.0285*
FIP	−0.065 ± 0.062	0.86	4.247 ± 0.009	0.204 ± 0.072	0.002*	0.065 ± 0.054	0.1125	4.552 ± 0.009	0.132 ± 0.059	0.013*
BABIP	−0.002 ± 0.003	0.79	0.288 ± 0.0004	−0.002 ± 0.003	0.73	0.002 ± 0.002	0.195	0.296 ± 0.0004	0.002 ± 0.003	0.24

Defensive parameters are shown, where nominally offensive parameters indicate those values allowed by the defensive team. Home and away jet lag show the regression coefficients indicating the effect of jet lag on home- and away-team defensive performance, respectively. Regression coefficients are adjusted for team effects. Parameters are expressed on a per game basis with error indicates SE of the estimated effect. *P* values are one tailed, derived from the regression analysis testing whether jet lag adversely impacts performance.

*Metrics where $P < 0.05$. Average over all 46,535 games.

Table 5. Effect of travel direction on the impact of jet lag on home defensive performance

	Home jet lag				
Defense	West	West *P* value	Average	East	East *P* value
At-bats	0.019 ± 0.143	0.897	35.086 ± 0.020	0.102 ± 0.166	0.54
Singles	−0.111 ± 0.092	0.8875	6.131 ± 0.013	0.041 ± 0.107	0.35
Doubles	0.015 ± 0.047	0.3745	1.802 ± 0.007	−0.018 ± 0.054	0.63
Triples	0.033 ± 0.014	0.0095*	0.179 ± 0.002	−0.01 ± 0.017	0.719
Home runs	−0.023 ± 0.036	0.74	1.029 ± 0.005	0.107 ± 0.041	0.005*
Walks	−0.074 ± 0.07	0.8565	3.303 ± 0.010	0.052 ± 0.081	0.2605
Strikeouts	−0.017 ± 0.091	0.425	6.795 ± 0.013	−0.162 ± 0.105	0.062
Stolen bases	−0.026 ± 0.031	0.802	0.637 ± 0.004	−0.001 ± 0.036	0.5135
Caught stealing	0.025 ± 0.018	0.923	0.285 ± 0.002	0.018 ± 0.02	0.805
Stolen base attempts	−0.001 ± 0.036	0.512	0.922 ± 0.005	0.016 ± 0.042	0.3475
Sacrifice hits	−0.016 ± 0.02	0.7885	0.340 ± 0.003	0.027 ± 0.023	0.1155
Sacrifice flies	−0.031 ± 0.018	0.956	0.286 ± 0.003	0.016 ± 0.021	0.217
Grounded into double plays	0.028 ± 0.029	0.831	0.796 ± 0.004	−0.037 ± 0.033	0.1355
Error	0.019 ± 0.028	0.25	0.672 ± 0.004	−0.067 ± 0.033	0.9785

Home jet lag shows regression coefficients indicating effects on home defensive performance. Regression coefficients are adjusted for team effects. Parameters are expressed on a per-game basis with error indicating SE of the estimated effect. *P* values are one tailed, derived from the regression analysis testing whether jet lag adversely impacts performance.

*Metrics where $P < 0.05$. Average is over all 46,535 games.

performance, whereas a jet-lagged team on the road exhibits impaired defensive performance with relatively minor effects on offensive performance.

To determine what was responsible for the poor defensive performance, we examined specific metrics and found highly significant effects of eastward, but not westward, travel on home runs allowed for both home and away teams (Tables 5 and 6). The finding of the same metric affected in both home and away teams demonstrates independent replicability. In addition, no other specific metrics were detectably affected. To address how important this specific effect is to explaining the aggregate effects, we determined the effects of the change in home runs due to jet lag on slugging percentage and runs allowed. As a home run results in four total bases, an increase of 0.107 and 0.073 home runs per game (for home and away eastward jet lag, respectively) would result in an increase of 0.428 and 0.292 total bases per game or an increase of 0.012 and 0.009 in slugging percentage that approximates the 0.010 and 0.009 that we observed. Thus, essentially all of the effect on slugging percentage can be explained by the change in home runs. Given the average number of runners on base when a home run is hit, a home run results in about 1.594 runs on average for the period 1992–2011. Therefore, an increase of 0.107 and 0.073 home runs per game would result in an increase of 0.171 and 0.116 runs per game that are the majority (87% and 72%, respectively) of the 0.197 and 0.162 runs per game effects that we observed. Not only are the effects of jet lag on pitching comparable to the effect of home-field advantage, those effects are largely explained by a single measure: home runs allowed.

Although eastward travel was generally more detrimental to the defense, one prominent metric that was disrupted by westward, but not eastward, travel was walks allowed by the away team (+0.128 for westward travel, $P < 0.05$ vs. +0.017 for eastward travel, $P = 0.393$; Table 6). This effect only affected the away team but not the home team (−0.074, $P = 0.858$; Table 5). A westward-specific effect on on-base percentage allowed by the visitor, to which walks contribute, was also observed (+0.002,

Table 6. Effect of travel direction on the impact of jet lag on away aggregate defensive performance

	Away jet lag				
Defense	West	West *P* value	Average	East	East *P* value
At-bats	−0.097 ± 0.112	0.388	33.497 ± 0.019	0.005 ± 0.124	0.968
Singles	0.098 ± 0.072	0.086	6.017 ± 0.012	0.044 ± 0.079	0.2885
Doubles	−0.053 ± 0.037	0.9255	1.769 ± 0.006	0.004 ± 0.041	0.464
Triples	−0.002 ± 0.012	0.5535	0.205 ± 0.002	−0.014 ± 0.014	0.8415
Home runs	−0.004 ± 0.028	0.5585	1.033 ± 0.005	0.073 ± 0.031	0.0095*
Walks	0.129 ± 0.058	0.013*	3.435 ± 0.010	0.017 ± 0.064	0.3925
Strikeouts	−0.074 ± 0.072	0.1545	6.202 ± 0.013	−0.019 ± 0.08	0.4075
Stolen bases	0.027 ± 0.025	0.1365	0.634 ± 0.004	0.013 ± 0.028	0.3205
Caught stealing	0.016 ± 0.014	0.8815	0.262 ± 0.002	−0.006 ± 0.015	0.3345
Stolen base attempts	0.044 ± 0.029	0.066	0.896 ± 0.005	0.006 ± 0.032	0.4205
Sacrifice hits	0.023 ± 0.016	0.075	0.348 ± 0.003	−0.01 ± 0.018	0.7075
Sacrifice flies	0.019 ± 0.015	0.0985	0.295 ± 0.003	−0.005 ± 0.016	0.61
Grounded into double plays	0.007 ± 0.023	0.622	0.762 ± 0.004	0.028 ± 0.025	0.871
Error	−0.008 ± 0.023	0.6285	0.675 ± 0.004	0.027 ± 0.025	0.144

Away jet lag shows regression coefficients indicating effects on away defensive performance. Regression coefficients are adjusted for team effects. Parameters are expressed on a per game basis with error indicates SE of the estimated effect. *P* values are one tailed, derived from the regression analysis testing whether jet lag adversely impacts performance.

*Metrics where $P < 0.05$. Average is over all 46,535 games.

P = 0.021) The only defensive metric affected by westward home-team travel was triples allowed (+0.033, $P < 0.01$). Unlike effects observed after eastward travel of the home or away team, neither of these westward travel effects was sufficiently large to impact FIP or runs allowed. Thus, there appear to be unique effects of westward travel relative to eastward travel on performance separate from the larger effects of eastward travel.

Discussion

Here we examined MLB data spanning 20 y and including over 40,000 games. Multivariate regression analysis was applied to account for team/park effects and home-field advantage, as well as travel direction, to isolate the effect of jet lag on performance metrics. Moreover, we examined whether jet lag impaired metrics of both broad and specific aspects of performance. Our data were able to recapitulate prior findings demonstrating jet-lag effects on winning percentage and runs scored were generally stronger after eastward travel (4, 6). Due to our comprehensive analysis, we uncovered effects of jet lag. For example, we observed effects of home-team jet lag on home offensive performance. These specific effects of home-team jet lag on offensive performance were not observed in a prior study (4) as a much smaller number of jet-lag games was measured and only winning percentage and runs scored were examined. We did not detect an important effect of away-team jet lag on major parameters of away-team offensive performance, which had not been assessed by any of the prior studies, thus demonstrating specific jet-lag effects. In particular, among the away-team offensive metrics, only sacrifice hits, generally the result of a managerial decision, were shown to be affected by jet lag, after controlling for the FDR. We found that home and away jet lag singularly affected home runs allowed, explaining the far majority of the effects on runs allowed due to jet lag. This observation in two independent populations (home and away) further substantiates the conclusion.

Our finding that most major jet-lag effects are evident after eastward but not westward travel supports the hypothesis that observed effects are due to a failure of the circadian clock to synchronize to the environmental light–dark cycles and not due to general travel effects. Nonetheless, we did observe some isolated effects of westward travel, although they had limited effects on major offensive or defensive parameters. Previous studies have attributed effects of westward travel not to circadian synchronization effects, but to performing at a nonoptimal time of day (7, 10, 11). Less than 10% of all jet-lag games were played during the day and thus, a more systematic analysis of interactions between jet lag and time-of-day was not feasible.

We can speculate on why we detected a more robust effect of jet lag on the home team than on the away-team offense, revealing an interaction between jet lag, that is, when traveling east, and home or away status. One possibility is that the away team has a more structured daily schedule when away from home than does the home team when returning home. This home/away dichotomy may not be evident on defense as pitchers, especially starting pitchers who play every fifth day, have a more structured schedule leading up to their start irrespective of whether they are home or away. Another possibility is that the away team may already be sufficiently impaired that the additional jet-lag effects are difficult to detect. It is worth reiterating that the failure to detect a jet-lag effect in the away team is evident in the context of a larger number of away jet-lag games than home jet-lag games.

We did observe a striking effect of jet lag on home runs allowed on both the home and away teams. Pitching location and velocity appear to be important for determining the probability of giving up a home run relative to a swinging strike [swinging at and missing a pitch in the strike zone (18)]. Thus, we hypothesize that jet lag, particularly in the eastward direction, may adversely affect these aspects of pitching which in turn impact home runs allowed. Detailed data on the velocity and trajectory of pitches, collected by the Pitchf/x system, are available for recent seasons; similar data on the velocity and location of batted balls are expected to be widely available in the near future. As such data for future seasons become available, it will be possible to expand upon the analysis provided here to include a wider range of variables and to give a more complete picture of the effects of jet lag on baseball performance.

The results on the effect of jet lag on home runs allowed suggest that teams may want to change their travel protocol to mitigate this effect. For instance, a starting pitcher scheduled for a game in which the team is jet lagged might travel to the game location a few days ahead of the team, to adjust to the new time zone. Taken together, these quantitative high-resolution data reveal a surprising specificity in the effect of circadian misalignment on athletic performance.

Methods

Data Collection. All MLB games from 1992–2011 were included in this study. Individual game information was collected from MLB through retrosheet.org. To ensure accuracy, we sampled games from the dataset and compared the data to those from MLB.com and baseball-reference.com. The resulting game log contained information on winning/losing team, home/away status, and offensive/defensive statistics for each game. During this time period, a total of 46,535 games was played. For suspended games that were not completed, we have followed the convention used by MLB: We have not counted such games in computing winning percentages, but we have used the statistics from those games.

Assessment of Jet Lag. Because of difficulties in acquiring exact travel schedules aside from a date-by-date schedule, we assumed that as soon as the game before the trip was over, the team traveled to adapt to a new time zone. The resulting jet lag (circadian time) was quantified based on the convention that 24 h are needed to adapt to every new time zone crossed. After spending 24 h within a time zone, a team's assigned jet lag would move 1 h closer to 0, which represents full adaptation. Off days, cancelled games, and the midseason All-Star break were all treated as teams moving closer to a jet lag of 0. For example, if the Chicago White Sox traveled to Boston (Eastern Standard Time) from Chicago (Central Standard Time), the first day of the series is +1 jet lag, and the second 0. The third day is 0 again because the White Sox had fully adapted to the Eastern Time Zone the day before. If the White Sox traveled from Boston to Los Angeles (Pacific Standard Time) the next day, the first day of the series is now −3 because the White Sox traveled three time zones. A database of the jet-lag games is summarized in Table S2.

Multivariate Regression Analysis to Assess Jet-Lag Effects. To determine whether the team's performance was influenced by the circadian disruption of its own or that of the opposing team, we defined jet lag for each team as those with a circadian time of 2 h or more, and no jet lag as a circadian time of 1 h or less. We then used a multivariable regression analysis to obtain the ordinary least-square estimates. The following model was used for each statistic:

$$
\begin{aligned}
Y_i = {} & \delta_1 X_{HomeWest} + \delta_2 X_{HomeEast} + \delta_3 X_{AwayWest} + \delta_4 X_{AwayEast} + \delta_5 X_{HomeANA} \\
& + \delta_6 X_{HomeARI} + \delta_7 X_{HomeATL} + \delta_8 X_{HomeBAL} + \delta_9 X_{HomeBOS} + \delta_{10} X_{HomeCWS} \\
& + \delta_{11} X_{HomeCIN} + \delta_{12} X_{HomeCLE} + \delta_{13} X_{HomeCOL} + \delta_{14} X_{HomeDET} + \delta_{15} X_{HomeFLO} \\
& + \delta_{16} X_{HomeHOU} + \delta_{17} X_{HomeKCR} + \delta_{18} X_{HomeLAD} + \delta_{19} X_{HomeMIL} + \delta_{20} X_{HomeMIN} \\
& + \delta_{21} X_{HomeNYY} + \delta_{22} X_{HomeNYM} + \delta_{23} X_{HomeOAK} + \delta_{24} X_{HomePHI} + \delta_{25} X_{HomePIT} \\
& + \delta_{26} X_{HomeSDP} + \delta_{27} X_{HomeSEA} + \delta_{28} X_{HomeSFG} + \delta_{29} X_{HomeSTL} + \delta_{30} X_{HomeTBR} \\
& + \delta_{31} X_{HomeTEX} + \delta_{32} X_{HomeTOR} + \delta_{33} X_{HomeWAS} + \delta_{34} X_{AwayANA} + \delta_{35} X_{AwayARI} \\
& + \delta_{36} X_{AwayATL} + \delta_{37} X_{AwayBAL} + \delta_{38} X_{AwayBOS} + \delta_{39} X_{AwayCWS} + \delta_{40} X_{AwayCIN} \\
& + \delta_{41} X_{AwayCLE} + \delta_{42} X_{AwayCOL} + \delta_{43} X_{AwayDET} + \delta_{44} X_{AwayFLO} + \delta_{45} X_{AwayHOU} \\
& + \delta_{46} X_{AwayKCR} + \delta_{47} X_{AwayLAD} + \delta_{48} X_{AwayMIL} + \delta_{49} X_{AwayMIN} + \delta_{50} X_{AwayNYY} \\
& + \delta_{51} X_{AwayNYM} + \delta_{52} X_{AwayOAK} + \delta_{53} X_{AwayPHI} + \delta_{54} X_{AwayPIT} + \delta_{55} X_{AwaySDP} \\
& + \delta_{56} X_{AwaySEA} + \delta_{57} X_{AwaySFG} + \delta_{58} X_{AwaySTL} + \delta_{59} X_{AwayTBR} + \delta_{60} X_{AwayTEX} \\
& + \delta_{61} X_{AwayTOR} + \delta_{62} X_{AwayWAS}.
\end{aligned}
$$

The variable Y_i represents the performance of interest. δ_1 and δ_2 are the indicator variables for jet lag for the home team, east and west travel direction, respectively. δ_3 and δ_4 are the indicator variables for jet lag for the away team, east and west travel direction, respectively. A value of 0 was assigned if the team had no jet lag (1 h or less), and 1 if the team had jet lag (2 h or more). To account for team effects, we assigned indicator variables for each home and away team. The model was adjusted so that both home- and

NEUROSCIENCE

away-team coefficients were with respect to the Chicago Cubs, although this arbitrary assignment does not affect any of the jet-lag coefficients. The resulting model's jet-lag variables reported P values were adjusted after the team effect was taken into account.

All statistical analyses were performed using STATA. We used a one-tailed t test with a statistical significance level of $P < 0.05$ for parameters that may be adversely impacted by jet lag. We used a two-tailed t test for parameters that are neutral with respect to jet lag, for example, at-bats. The parameters, unless indicated otherwise, were averages on a per-game basis. We used an FDR threshold of 0.2 calculated using the Benjamini–Hochberg procedure (19).

Definition of Terms. Runs Scored/Allowed: number of times that a player reaches home base.

Batting Average: hits divided by at-bats.

On-Base Percentage: hits plus walks plus hit-by-pitch divided by at-bats plus walks plus hit-by-pitch plus sacrifices.

Slugging Percentage: total bases by hits divided by at-bats.

At-Bats: plate appearances subtracting sacrifices, hit-by-pitch, and walks.

Single/Double/Triple/Home Run: a hit resulting in the batter reaching first base/second base/third base without an error.

Home Runs: a hit resulting in batter passing all bases and reaching home without an error.

Walks: reaching first base after not swinging at four pitches out of the strike zone.

Strikeouts: three strikes, either pitches in the strike zone or swung on and missed.

Stolen Bases: advancing a base while the defense is in possession of the ball.

Sacrifice Hits: a hit on the ground that advances a runner but sacrifices the hitter as out (usually a bunt).

Sacrifice Flies: a hit in the air to the outfield that advances a runner but sacrifices the hitter as out.

Grounded into Double Plays: ground balls that result in two outs.

Error: failure of a fielder to make a routine play, allowing a player to advance or reach base.

FIP: measures pitcher performance in preventing runs independent of defensive performance, that is, experiencing league average results on balls in play. FIP constant for each year was obtained from FanGraph, and was added to each game to get the final FIP.

$$FIP = \frac{13 * Home\ \ Runs + 3 * (walks + hit\text{-}by\text{-}pitch) - 2 * strikeouts}{innings} + FIP\ constant.$$

BABIP: measures percentage of balls in play are hits, excluding home runs, and is considered a rough measure of pitching-independent defensive performance.

$$BABIP = \frac{Hits - Home\ \ Runs}{At\text{-}Bats - Home\ \ Runs - Strikeouts + Sacrifice\ Flies}.$$

ACKNOWLEDGMENTS. We thank V. Kilman, F. Turek, P. Zee, G. Allada, and M. Rosbash for comments. This work was supported, in part, by Defense Advanced Research Projects Agency (DARPA) Grant D12AP00023. This effort was, in part, sponsored by DARPA. The content of the information does not necessarily reflect the position or policy of the government, and no official endorsement should be inferred.

1. Mohawk JA, Green CB, Takahashi JS (2012) Central and peripheral circadian clocks in mammals. *Annu Rev Neurosci* 35:445–462.
2. Sack RL (2010) Clinical practice. Jet lag. *N Engl J Med* 362(5):440–447.
3. Waterhouse J, Reilly T, Atkinson G, Edwards B (2007) Jet lag: Trends and coping strategies. *Lancet* 369(9567):1117–1129.
4. Recht LD, Lew RA, Schwartz WJ (1995) Baseball teams beaten by jet lag. *Nature* 377(6550):583.
5. Leatherwood WE, Dragoo JL (2013) Effect of airline travel on performance: A review of the literature. *Br J Sports Med* 47(9):561–567.
6. Winter WC, Hammond WR, Green NH, Zhang Z, Bliwise DL (2009) Measuring circadian advantage in Major League Baseball: A 10-year retrospective study. *Int J Sports Physiol Perform* 4(3):394–401.
7. Jehue R, Street D, Huizenga R (1993) Effect of time zone and game time changes on team performance: National Football League. *Med Sci Sports Exerc* 25(1):127–131.
8. Reilly T, Waterhouse J (2009) Sports performance: Is there evidence that the body clock plays a role? *Eur J Appl Physiol* 106(3):321–332.
9. Smith RS, Efron B, Mah CD, Malhotra A (2013) The impact of circadian misalignment on athletic performance in professional football players. *Sleep* 36(12):1999–2001.
10. Smith RS, Guilleminault C, Efron B (1997) Circadian rhythms and enhanced athletic performance in the National Football League. *Sleep* 20(5):362–365.
11. Steenland K, Deddens JA (1997) Effect of travel and rest on performance of professional basketball players. *Sleep* 20(5):366–369.
12. Aschoff J, Hoffmann K, Pohl H, Wever R (1975) Re-entrainment of circadian rhythms after phase-shifts of the Zeitgeber. *Chronobiologia* 2(1):23–78.
13. Takahashi T, et al. (1999) Re-entrainment of circadian rhythm of plasma melatonin on an 8-h eastward flight. *Psychiatry Clin Neurosci* 53(2):257–260.
14. Medicine AAoS (2005) Circadian rhythm sleep disorder, jet lag type (jet lag disorder). *The International Classification of Sleep Disorders: Diagnostic and Coding Manual* (American Academy of Sleep Medicine, Westchester, IL), 2nd Ed, pp 129–130.
15. Czeisler CA, et al. (1999) Stability, precision, and near-24-hour period of the human circadian pacemaker. *Science* 284(5423):2177–2181.
16. Aschoff J, Wever R (1962) *Naturwissenschaften* 49:337.
17. Monk TH, Buysse DJ, Carrier J, Kupfer DJ (2000) Inducing jet-lag in older people: Directional asymmetry. *J Sleep Res* 9(2):101–116.
18. Karakolis T (2012) What is More Important for a Fastball: Velocity, Location, or Movement. Available at www.fangraphs.com/community/what-is-more-important-for-a-fastball-velocity-location-or-movement-2/. Accessed July 30, 2014.
19. Benjamini Y, Hochberg Y (1995) Controlling the false discovery rate: A practical and powerful approach to multiple testing. *J R Stat Soc B* 57(1):289–300.