Sleep restriction increases coordination failure

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This manuscript was compiled on September 6, 2017

This paper examines how commonly experienced sleep restriction (SR) may impact coordination failure in a well-known coordination game. The ability to coordinate choices is an important determinant of group efficiency because coordination failure is costly. We study mild but chronic SR because current evidence from industrialized countries shows that some 25%-50% of working adults sleep less than 7 hrs/day, which has been estimated to cost an economy anywhere from 1%-3% of its annual GDP (1). While existing research has focused on how SR impacts basic cognition and certain components of decision making, there is a gap in our understanding of how SR impacts group decision making. Using an ecologically valid at-home protocol, we analyze data from 100 subjects randomly assigned to 7 evenings of prescribed SR (5-6 hrs/night) or well-rested sleep levels (8-9 hrs/night) (n=47 SR, n=53 WR). After the treatment week, we administer the minimum effort coordination game to anonymous groups of n=3 subjects. We report that SR significantly increases the likelihood of group coordination failure and its associated inefficiency costs. Specifically, the inclusion of just one SR subject can be sufficient to eliminate the beneficial coordination effects of playing repeatedly with the same group members. In operational settings, coordination failure would imply costly effort waste, and so our research is the first to identify an inefficiency cost that may compound previously recognized performance and behavioral impacts of SR. These results likely have implications for our understanding of the importance of deliberative decision processes, in general, on successful coordination.

sleep-restriction | coordination | group decision making | experiments

1. Introduction

Coordination games have widespread applications of interest across disciplines, and how individuals solve coordination problems (or factors that predict coordination failure) are a natural focal point for behavioral research. This paper seeks to extend our understanding of the importance of deliberation and high-level cognition in successful coordination by randomly inducing a commonly occurring cognitive state prior to decision making. Specifically, we experimentally manipulate sleep levels in subjects over the course of one week to generate an ecologically valid set of well-rested (assigned 8-9 hrs nightly sleep) and sleep restricted (5-6 hrs nightly sleep) subjects. These treatments approximate the difference between recommended nightly sleep levels and those experienced by a significant portion of the adult population in many countries.

Coordination problems are, in general, of significant interest to game theorists as a standard paradigm to study cooperative dilemmas. Because coordination games present a multiplicity of Pareto-ranked Nash equilibria, they stand in contrast to other well-known cooperative dilemmas in game theory like the Prisoner's Dilemma or common pool resource problem. And, some research suggests that individuals may coordinate on the most inefficient possible Nash outcome in such games (2–5), which makes the identification of factors that lead to coordination failure of importance. Our behavioral focus on sleep restriction as one such potential factor is intended as a highly real-world relevant way to manipulate the likelihood that subjects are making coordination game choices as a product of more deliberative versus more automatic decision processes.*

This paper is aimed at contributing to both coordination game and sleep literatures. We manipulate sleep levels to those found commonplace in modern society—nearly 30% of U.S. adults operate daily at levels of sleep restriction (SR) we examine (7).† Yet, little is known about how commonly experienced SR impacts group interactions. Because SR can be thought of as an ecologically valid way to alter the cognitive mechanism used to make decisions, our results will have implications for our understanding of the general underpinnings of decision making. And, the controlled decision environment we examine allows us to quantify the costs of coordination failure in a way that is difficult in naturally occurring field settings.

2. Background Literature

Coordination games. Experimental research has well-established results showing coordination failure (2–4, 8). Nevertheless, some factors may facilitate coordination, such as repeated interaction with the same group members (see (9), for a review of different factors that may facilitate coordination). Suffice it to say that coordination success is possible, if not challenging to achieve, and our paper hopes to add to our understanding of how the cognitive approach to

Significance Statement

Thirty percent of US adults experience insufficient sleep and reports calculate its associated economic losses in billions of dollars annually. We find that insufficient sleep has significant spillover effects in group settings due to increased miscoordination. These coordination failure costs would be in addition to other costs, such as reduced performance due to sleepiness. Using a well-established game theory paradigm, a minimum-effort coordination game, we find that the ability of groups to coordinate effort choices declines as more members are sleep restricted. Coordination failure is therefore analogous to costly wasted effort in this group setting. We find that the sleep restriction effect is large and can erase the coordination improvements experienced from repeated interactions with the same group members.

Please provide details of author contributions here.

The authors declare no conflict of interest.

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* Kilgore et al. (6) highlights how decisions relying on critical components of the prefrontal cortex—those necessary for deliberation and executive function—are particularly vulnerable to the impact of sleep deprivation.

† The U.S. Centers for Disease Control and Prevention has labeled the levels of chronic partial sleep deprivation we study as a public health epidemic.

decisions—as dictated by a sleep level manipulation—may impact the likelihood of coordination failure.[‡]

Effects of sleep in social games. The literature on sleep and social interactions is somewhat limited in sleep research. We know of no studies that explicitly examine coordination games and sleep restriction, notwithstanding the large literature on sleep and decision making. A few studies have looked at the impact of sleep restriction or deprivation on simple social interactions, which may yield some clues to help guide our hypotheses. A single night of total sleep deprivation (TSD) reduces trust (11), which is consistent with TSD increasing aversion to exploitation risk in a social interaction. TSD has also been shown to reduce risk taking and dictator giving selectively for female subjects (12). In a larger sample of chronic but partially sleep restricted (SR) subjects more similar to levels found in naturally occurring data, SR reduced prosocial behaviors (including trust) (13). Such results are consistent with related research showing that deliberative thinking, which is less likely with SR, is important for prosocial decision (see also (14–17)).

Coordination games, of course, contain elements of both trust and risk. TSD increases risky choice over monetary gambles in the gains domain (18). Relatedly, a more mild manipulation of sleepiness has been shown to increase preference for risk taking among sleepier subjects (19).[§] So, the literature suggests SR likely reduces trust but increases willingness to take monetary risk. If successful coordination requires trust and/or willingness to take risk, then it is unclear what impact SR may have on coordination success/failure. Our study will provide first evidence on which SR effect likely dominates in a coordination setting that is more complex than simple 2-person trust.

An equilibrium refinement suggested recently in the literature is that one can uniquely predict outcomes in coordination using a reference outcome based choice (20). Here, Schneider and Leland (20) develop the Reference-Dependent Maximin (RDM) criterion, based on the premise that subjects first anchor on the maximin strategy and then deviate only if advantageous. In our parameterization, this RDM criterion predicts outcomes at the worst Nash equilibrium (minimum effort). Thus, we can identify an equilibrium selection criterion that yields a unique prediction in our parameterization. The RDM criterion (20) is described as a "heuristic", but we do not claim that such a heuristic results from "automatic thought" processes. Thus, our hypotheses in this game regarding the impact of SR remains an open empirical question. We only state that this somewhat sophisticated RDM criterion makes a unique prediction of minimum effort in our particular minimum effort task. One would also predict convergence to low effort levels using game-theoretic selection criteria that consider the maximization of a potential function (21).

3. Experimental Design

At Home Sleep Protocol. A preliminary online survey was administered initially to generate a database of several hundred potential subjects on which we had necessary demographic and sleep data for recruitment to the main one-week study. The preliminary survey administered a validated short form of the morningingness-eveningness questionnaire (22) and screening questions for depressive and anxiety disorder, among other self-report sleep measures. We did not recruit subjects scoring at risk for major depressive or anxiety disorder or those who self-reported a sleep disorder. Strong morning- and evening-type individuals were excluded so that we did not introduce the confounding factor of circadian timing of the decision.[¶]

Once excluded subjects were removed from the database, remaining subjects were randomly assigned, ex ante, to the well-rested (WR) or sleep-restricted (SR) treatment condition. At that point, recruitment emails invited individuals to participate in a one-week experiment that would involve a prescribed nightly sleep level for 7 nights (the recruitment email included the specific sleep prescription randomly assigned to the subject).[‖] Subjects were also informed they would be required to wear an actigraphy device to objectively yet passively measure sleep levels, keep a basic sleep diary provided by the experimenters, and participate in a 1.5 hour decision session at the end of the week.[**] This one-week experiment protocol therefore required two lab visits by the subject. Session 1 included informed consent procedures, survey instruments to collect data on a 6-item cognitive reflection task (24) and short-version of the Big Five personality measures (25), assignment of the actigraphy device and sleep diary, and subject questions were answered regarding the prescribed sleep treatments without revealing any individual subject's treatment assignment. In other words, groups of typically 15-18 subjects were recruited at a time, and these groups were a mix of SR and WR subjects so that the coordination games would contain some sleep level heterogeneity in the group compositions.

Upon leaving Session 1, subject contact with experimenters was limited to daily text or emails each subjects would send to report bed/wake times. This was in addition to similar information reported in each subject's sleep diary, but the emails allowed the experimenter to have some daily monitoring of attempted sleep levels. Nevertheless, these emails are self-report and only serve as complementary and subservient to the objective sleep data in the final sleep data scoring. The experimenters also emailed subjects every 1-2 days during the treatment week to remind subjects of the prescribed sleep levels, caution the subjects regarding risk of certain activities when sleepy (which was a likely byproduct of the SR treatment, of course), and to remind subjects of the approaching decision Session 2. Session 2 occurred one week after session 1 (at the same time of day as Session 1) and included a short survey and self-report on sleepiness, decision task administration, and then the removal of actigraphy devices and cash payments for the decision experiments. In addition to variable payoffs for outcomes in the decision experiments, subjects also received a fixed payment of $25 for adherence to the conditions of

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[‡] Others have recognized the potential impact of sleep on successful work team outcomes from an organizational standpoint(10). Our experimental approach is intended to examine an environment where coordination success or failure can be clearly quantified.

[§] Specifically, their protocol randomly assigned validated morning-type and evening-type subjects to take part in the risky (individual) asset bundle choice experiment at either an early morning (7:30 am) or later evening (10:00 pm) experiment session time.

[¶] Also important to remove circadian timing effects was the fact that all sessions for the main experiment were held at non-extreme times-of-day (between 10am-4pm) and sessions were only held Tuesday-Thursday (to minimize weekend effects).

[‖] Subjects were not allowed to opt out of one treatment in order to select the other. Thus, subjects either participated in their randomly assigned sleep condition, or they could not participate in the experiment.

[**] The actigraphy device is a wrist-worn accelerometer intended to be worn all day every day with few exceptions. Importantly, we use devices common to sleep research that have several advantages over lower cost commercial devices. The validity of the particular devices we used has been established in the literature and actigraphy is well-accepted as a way to generate objective and valid data on sleep levels in non-disordered individuals (23).

the sleep treatment week. Subjects were made aware that the fixed payment would be received several days later by Amazon.com gift code or check (their choice) after sleep data were downloaded and the experimenters could verify good faith efforts at compliance.[††]

Minimum effort coordination game. During the decision session, subjects were administered the minimum effort coordination game through the Veconlab online platform.[‡‡] The game was played with groups of 3 subjects and the session administered both a 10-round treatment using a partner matching protocol and a 10-round treatment using a stranger matching protocol (order of treatments varied across groups).[§§] Table A1 (in the SI) describes payoffs as a function of one's effort choice and the minimum effort choice of the other two players in one's group. Effort choice, e, has marginal cost of effort for each subject at $c = \$.64$. Given this parameterization and our range of effort choice $e \in [1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7]$, each marginal increase of .1 effort units cost a subject \$.064.

Predictions can be made based on several theories of equilibrium refinement, and in all cases, the prediction given parameterization is coordination on minimal effort. This is true if assuming risk dominance, or if examining the potential games in our framework (21). As noted above, our parameters are such that the RDM criterion (20) predicts minimum effort choices for all $c > \$.50$ (see (26)), for a useful example of how effort choice varies with the cost of effort in this minimum effort choice environment). Based on existing literature on coordination games (see survey in (9)), there may be behavioral foundations to predict increased coordination (i.e., non-minimal effort choices) in the Partner matching treatment.

4. Results

Attrition, compliance, and manipulation check. We recruited n=127 treatment subjects into the main study, although not all subjects finished the protocol. Of those recruited, n=11 subjects failed to show up for Session 1 (i.e., no-shows: n=8 female), of which n=3 had been assigned to the SR condition. Of the 116 subjects who started the protocol, 14 (n=12 female) subjects withdrew at some point during the treatment week. Subjects who withdrew were all assigned to the SR condition.[¶¶] We therefore had a total of 102 treatment condition subjects who completed the main one-week sleep and decision study. Sleep watch data were corrupted for two subjects, leaving 100 subjects worth of complete sleep data (n=62 females. n=47 SR, n=53 WR subjects).

Sleep data were scored using standard procedures and the objective nightly average sleep levels of subjects in the SR and WR treatment conditions are shown in Figure 1 (kernel density estimates). The main analysis utilizes the full set of 102 subjects who completed the protocol, and therefore considered the SR or WR condition as an "intent to treat" variable. Alternatively, we also conducted robustness analysis using the subsample of data on subjects deemed compliant with the sleep prescription condition (SI Tables A2-A6). Our standard for treatment condition compliance required SR subjects to have 375 minutes objectively measured nightly sleep and WR subjects 405 minutes nightly sleep.[***] The highlighted region of noncompliance between 6.25 and 6.75 nightly hours of sleep (see Figure 1) is close to average nightly sleep levels in adults from recent survey evidence.[†††] Robustness analysis that removes subjects with nightly sleep near average levels can be thought of as a way to remove subjects difficult to clearly classify as SR or WR.[‡‡‡]

Validity of the protocol at manipulating sleep levels and/or sleepiness can be shown by comparing several distinct measures across the treatment groups. In addition to the objective sleep level data, during Session 2 the subjects self-report sleepiness (on a 1-9 scale: 9= most sleepy) and the extent to which the protocol altered one's typical sleep level ("self-report sleep gain/loss" range was [-4, +4] where 0 would imply "no effect" on typical sleep levels). A fourth measure was constructed, Personal SD, to describe the personal sleep deprivation for a subject. This measure was constructed by subtracting the subject's objective nightly sleep quantity from that subject's self reported nightly sleep need for optimal performance, expressed in hours/night. This subjective measure of optimal sleep, however, was collected during the preliminary sleep survey at an earlier point in time and is not endogenous with respect to the experimental treatment assignment. To the extent that a subject has an accurate assessment of whether he/she is a higher or lower sleep-need individual, the Personal SD measure is a more individually accurate measure of one's level of SR (or WR) in our study (SI Tables A2-A8 include analysis using this constructed measure as the sleep descriptor). For all measures consider, we report a highly statistically significant difference between the SR and WR group, whether including all subjects or the subset of compliant subjects ($p < .01$ in all instances; see lower section of Figure 1, which reports results of Mann-Whitney nonparametric tests for differences in mean values of each measure across treatment groups).

Experimental results. We analyze the following outcome measure from our data: effort choices, earnings, the likelihood of group coordination, and total effort waste costs. Table 1 reports results from models estimating individual Effort (column (1)) and Earnings (column (2)) as a function of the treatment (Partner vs Stranger matching protocol), treatment order (dummy variable for Partner condition in 2nd 10-round treatment), the Round ($= 1 - 20$), a dummy variable for

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[††] It is important to note that our standard for "compliance" with respect to paying subjects the \$25 payment was not as stringent as our standard for compliance regarding our data analysis later in this paper. In general, we wished to err on the side of paying subjects the \$25 in most instances and gave partial payment to the few subjects who withdrew partway through the sleep treatment week.

[‡‡] See http://veconlab.econ.virginia.edu/cg/cg.php for the Veconlab experiment page describing the coordination game.

[§§] Because this design required a group size divisible by 3, we recruited a small number of subjects for Session 2 as backup participants so that we would be able to fully use the data on the more costly sleep treatment subjects. Backups recruited for only the decision session were administered a separate informed consent document because of the fact that they did not participate in the sleep treatment week.

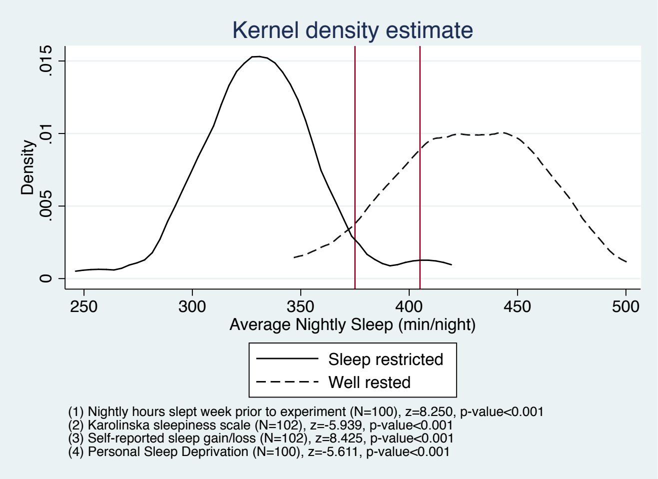
[¶¶] The fact that all those lost due to mid-week attrition were SR subjects is likely due to SR compliance being more difficult than anticipated. That said, of those who finished the protocol, most who were deemed noncompliant with the sleep prescription were WR subjects. Thus, rather than withdraw from the study, the WR subject was more likely to simply finish the protocol, only later to be identified as noncompliant.

[***] Using a within-subjects protocol, (27) also used a compliance standard that was subjective but somewhat data driven and based on the desire to minimize the likelihood that a treatment subject was statistically indistinguishable from a control subject not assigned to SR.

[†††] See National Sleep Foundation. 2005. 2005 Sleep in America Poll. [Online] Available: http://www.sleepfoundation.org/sites/default/files/2005_summary_of_findings.pdf [accessed March 31, 2017]. More recent Gallup poll results highlight that average sleep levels of younger adults, as compared to all adults, are lower and so average sleep levels of young adults the age of our college student sample are likely within our noncompliance range of sleep (see http://www.gallup.com/poll/166553/less-recommended-amount-sleep.aspx [accessed March 31, 2017])

[‡‡‡] Note that this compliance standard identifies more WR noncompliant subjects (n=14) than SR noncompliant subjects (n=2). In total, we have n=84 subjects deemed compliant by this standard.

Fig. 1. Treatment validation



(1) Nightly hours slept week prior to experiment (N=100), z=8.250, p-value<0.001
(2) Karolinska sleepiness scale (N=102), z=-5.939, p-value<0.001
(3) Self-reported sleep gain/loss (N=102), z=8.425, p-value<0.001
(4) Personal Sleep Deprivation (N=100), z=-5.611, p-value<0.001

Table 1. Individual behavior

VARIABLES	(1) Effort	(2) Earnings
Partner cond. in last 10 rounds	0.115***	0.013
	[0.032]	[0.013]
Partner condition	0.030*	0.045***
	[0.018]	[0.011]
Round	-0.010***	0.005***
	[0.002]	[0.001]
Sleep restricted	-0.040	0.029
	[0.041]	[0.020]
Sleep restricted × Partner cond.	0.046*	-0.006
	[0.026]	[0.017]
Sleep restricted × Partner cond. last	-0.059	-0.007
	[0.045]	[0.018]
Sleep restricted × Round	0.006**	-0.002*
	[0.002]	[0.001]
Constant	1.347***	0.276***
	[0.027]	[0.016]
Observations	2,040	2,040
R-squared	0.110	0.060

Robust s.e. in brackets, errors clustered at the individual level
*** $p<0.01$, ** $p<0.05$, * $p<0.10$

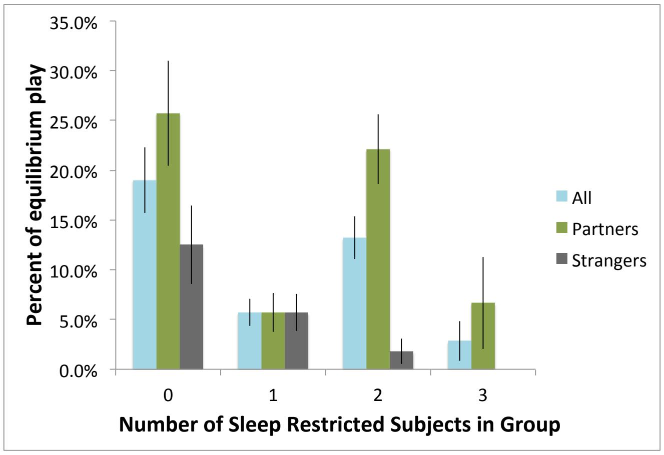
assignment to the SR condition, and interactions between SR, Round, Partner matching, and Partner treatment order. Similar models to those estimated in Table 1 were estimated using continuous measures of sleep level, models using only the subset of compliant subject data, and models using intent-to-treat to predict objective sleep levels in a 2-stage instrumental variables approach. Our results are robust to these alternative estimation approaches (SI Tables A3, A4).

Table 1 results in column (1) indicate that subject effort converges across rounds towards predicted minimal effort, but the Partners condition predicts significantly higher effort levels (more so when Partners occurs after the Strangers treatment). This is consistent with previous results in the literature that report higher average effort levels with Partner matching (9). Regarding the impact of SR on effort choice, our estimates indicate that SR subjects contribute significantly more than WR subjects with Partner matching in general, and the convergence to lower minimal effort across rounds occurs at a slower rate for SR subjects (SI Fig A1). This estimated impact of SR on effort levels is robust across the various specifications (SI Table A3).

Column (2) of Table 1 shows results from a estimating similar specifications with subject Earnings as the dependent variable (see also SI Table A4). Here, we see that Partners matching increases earnings, and earnings also increase with each round. Given the column (1) results in Table 1 showing convergence towards lower effort levels, this Earnings result is likely due to a decrease in wasteful (uncoordinated) effort choices. Regarding earnings, there is no significant interaction between SR and the Partners matching (as was found with effort levels). However, SR has a robust effect of decreasing earnings across rounds (likely due to the slower convergence to lower efforts compared to WR group members).

The results on Effort and Earnings can be reconciled by evaluating the impact of SR on effort choice disparity or "gap" in a group (SI Table A7) as well as the distinct minimum and maximum effort levels in a group (SI Table A8). These highlight how differential impacts on group minimum and maximum effort levels are responsible for coordination failure costs. More succinctly, Figure 2 shows the percentage of groups coordinating on equilibrium play as a function of the number of SR subjects in the group (separated by Partners or Strangers condition). In general, groups populated with all SR subjects fail to coordinate significantly more often than groups populated with all WR subjects. In Partners groups coordination failure is not monotonic with respect to the number of total SR members in the group. However, the results in Strangers groups are striking: there is a monotonically decreasing frequency of coordinated effort choices as the number of SR subjects in the group rises. In fact, our data show no instance of a group with three SR subjects successfully coordinating on any effort choice in even a single round of play.

Fig. 2. Equilibrium play by group composition



More formally, Table 2 shows estimation results where the likelihood of coordination on any equilibrium outcome (no matter which of the multiple equilibria it is) is regressed on the number of SR subjects in the 3-person group. Consistent with Figure 2 we find that, even controlling for Round of play, additional SR group members significantly decrease the

Table 2. Likelihood of equilibrium play (i.e., identical effort choices)

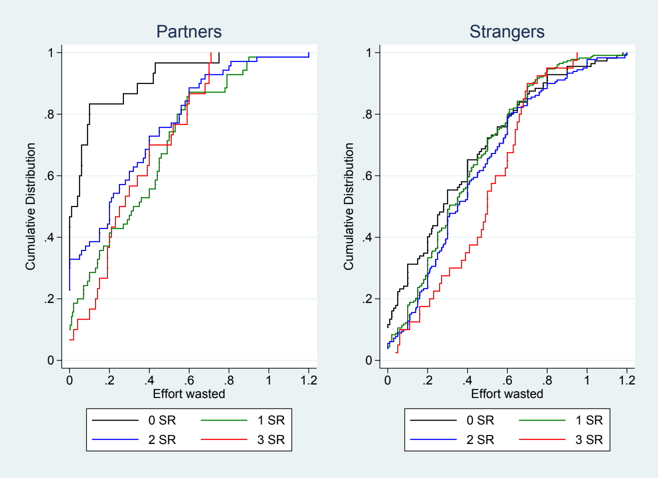
VARIABLES	(1) All	(2) Strangers	(3) Partners
Partner condition	0.069***		
	[0.021]		
Round	0.011***	0.007***	0.020***
	[0.002]	[0.002]	[0.005]
One SR subject in group	-0.080***	-0.038**	-0.166**
	[0.025]	[0.018]	[0.067]
Two SR subjects in group	-0.032	-0.048**	-0.035
	[0.027]	[0.022]	[0.068]
Three SR subjects in group$^+$	-0.061***	-	-0.106**
	[0.020]	-	[0.041]
χ^2 test on SR dummies	15.91	6.259	12.80
d.f.	3	2	3
p-value	0.001	0.044	0.005
1 SR $=$ 2 SR	4.66	0.80	6.32
d.f.	1	1	1
p-value	0.0308	0.3721	0.0119
2 SR $=$ 3 SR	0.80	-	6.75
d.f.	1	-	1
p-value	0.3721	-	0.0094
Number of clusters	401	365	38
Observations	760	340	380

Probit models (marginal effects). Robust s.e. in brackets, clustered at group level. $^+$ Dummy for 3 SR subjects perfectly predicts failure of equilibrium play in Strangers (see also Figure 2)
*** p<0.01, ** p<0.05, * p<0.10

likelihood of effort coordination [§§§] Table 2 also confirms the established result in the literature that Partners matching significantly increases the likelihood of successful coordination(9) (in addition to increasing the level of effort to a more payoff-preferred equilibrium, as was noted in Table 1). Notably, the coefficient estimates on the SR dummy variables in Table 2 indicate that the increased miscoordination due to sleep restricted group members can be sufficiently high so as to negate the coordination-improving effect of Partner interactions.

Finally, we note that coordination failure, per se, may not be very costly if miscoordination is minor. We define effort waste costs as the sum of group effort that is in excess of the minimum effort in the group, which represents costly effort that does not increase the group outcome. The previous analysis of equilibrium play likelihood does not consider that miscoordination (i.e., disequilibrium play) can vary in its severity. Figure 3 plots the cumulative distribution function of the total effort waste amount in each coordination game. Here, we see that cumulative group effort costs generally increase when a group contains SR members. Most stark is the low effort waste in Partner groups that contain zero SR subjects, where we see that the introduction of just one SR member is sufficient to significantly increase effort waste costs. The Kolgomorov-Smirnov test of differences in distribution of waste between groups with no SR subjects and groups with all SR subjects is significant (p-value<.001) and robust to potential correlation between rounds of play.[¶¶¶] Our key result, therefore, is that we document first evidence on how SR increases coordination failure and miscoordination waste, which are costs of sleep restriction in group interactions that have gone previously unidentified.

Fig. 3. Effort waste costs



5. Discussion

This investigation was aimed at understanding how commonly experienced levels of sleep restriction impact choices and coordination in group interactions. Our results are consistent with the hypothesis that equilibrium play (i.e., successful coordination of choices) decreases when more group members are sleep restricted. This finding highlights that coordination failure and its associated inefficiency costs are important, though previously unidentified, costs of sleep restriction. Because our sleep restriction protocol is highly externally valid, these results have great relevance for real world decision makers in operational settings. Coordination failure in team production may, for example, be more likely if workers have poor sleep habits. The inefficiency costs resulting from wasted effort in such groups would be difficult to identify in field settings. Our study combined elements of both field and laboratory methods so that the sleepiness we induce is realistic, and the coordination game setting is controlled and generates quantifiable data.

A common concern in many developed countries is the increasing prevalence of insufficient sleep within its population. The impacts of insufficient sleep are somewhat well-known in terms of its likely impacts on worker productivity, absenteesm, and adverse health effects. Such impacts of insufficient sleep have been found to cost the economies of several developed countries 1%-3% of their respective annual GDP (1). Such effects, however, do not consider behavioral effects that may represent another dimension to the cost of insufficient sleep. And, while research has made significant recent advances in our understanding of how sleep restriction impacts decision making, almost none of this research has focused on social or

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[§§§] Only in comparing 2-SR versus 1-SR subject groups in the Partners treatment do we find that an additional SR subject increases the likelihood of coordination, although 2-SR subject groups in Partners do not coordinate significantly more than 3-WR subject groups (and significantly less than 3-SR subject groups).

[¶¶¶] In 10,000 bootstrap draws accounting for serial correlation in Partner sessions, we find that the Kolmogorov-Smirnov test is significant at the 5% level 93% percent of the time.

interactive group decision environments, which is the focus of our study.

Unlike other group or socially-interactive decision environments, coordination problems are unique in their ability to evaluate choices when multiple Pareto-ranked equilibria are present. When groups converge to any payoff-inferior equilibrium, there are unrealized gains that imply an opportunity cost of suboptimal effort coordination. Our results focus more on the efficiency costs of wasted effort choices that exist when coordination is not realized, no matter how high or low the average effort choice within a group. Mild but chronic sleep restriction is found to significantly increase coordination failure and total effort wasted. These miscoordination costs have implications for what countermeasured may be most helpful. Wellness programs that focus on sleep health may be advisable, or there may be an increased need for hierarchy in an organizational setting as a way to improve coordination through supervisory control. However, such workplace strategies to help limit coordination failure are themselves costly to implement. While future research will no doubt shed additional light on this important topic, it is clear that insufficient sleep is costly in ways not previously appreciated.

6. Materials and Methods

Human Subjects Protections. This study was reviewed and approved by the Office of Research Protections Institutional Review Board at Appalachian State University. The online preliminary survey was approved under IRB 09-0252, and the main study (sleep manipulation and decision making) was approved under IRB 16-0067. Consent for the online survey was obtained on p. 1 of the survey (necessary for subjects to continue through the survey), and consent for the main study was obtained from participants at the beginning of Session 1.

Actigraphy Sleep Data Acquisition. Subjects were assigned wrist-worn actigraphy devices commonly used in sleep research and validated against polysomnographic measures of total sleep time (23). Unlike commercial sleep trackers, these devices provide subjects no sleep data feedback during the treatment week (this is only made known upon downloading the sleep data upon study completion) and the device batteries are sufficient to collect data the entire study week without recharge. Subjects were also issued sleep diaries to complete daily and turn in at the end of the treatment week, and subjects sent daily emails to the experimenter to report wake/bed times. The emails and sleep diaries were complementary to assist the actigraphy data scoring following procedures common to sleep studies (28). The experimenter emailed subjects about every 2 days to maintain contact, provide details and reminders of study parameters, caution subjects regarding behaviors that might put them at risk if experiencing drowsiness as a result of participation in the experiment, and to remind subjects of the upcoming Session 2 that finalized the study.

Procedures. The experiments were conducted in the APPEEL laboratory for experimental economics at Appalachian State University. Nine cohorts of subjects were recruited, each containing a mix of subjects randomly assigned the SR or WR sleep level in the study invitation email. Sleep treatment assignments were kept private for subjects in the laboratory session, and interactions in the coordination game were anonymous. Decision sessions included three tasks in total, one of which was the coordination game. Subjects received a fixed \$25 compensation for compliance with the prescribed sleep levels (verified by actigraphy), and providing completed sleep diaries. Fixed compensation (by check or Amazon gift code) was paid several days after completion of Session 2, which was known to subjects, so that researchers could first download the sleep data and verify compliance efforts. Subjects also received variable cash payoffs for outcomes in the decision experiments, including coordination game. The coordination game task was computerized and administered through the Veconlab platform for experiments—the coordination game option used is at http://veconlab.econ.virginia.edu/cg/cg.php.

Acknowledgements. DLD received support from Appalachian State University and the National Science Foundation under grant BCS-1229067. The authors thank seminar participants in the sleep research group at Monash University for useful comments.

1. Hafner M, Stepanek M, Taylor J, Troxel WM, van Stolk C (2016) Why sleep matters–the economic costs of insufficient sleep. *Rand Europe* research reports(1791).
2. NoortVanvan Huyck JB, Battalio RC, Beil RO (1990) Tacit coordination games, strategic uncertainty, and coordination failure. *Amer Econ Rev* 80(1):234–248.
3. NoortVanvan Huyck JB, Battalio RC, Beil RO (1991) Strategic uncertainty, equilibrium selection, and coordination failure in average opinion games. *Q J Econ* 106(3):885–910.
4. Cooper RW, DeJong DV, Forsythe R, Ross TW (1992) Communication in coordination games. *Q J Econ* 107(2):739–771.
5. Ochs J (1995) Coordination problems. *Handb Exp Econ* pp. 195–252.
6. Killgore WDS, Grugle NL, Balkin TJ (2012) Gambling when sleep deprived: don't bet on stimulants. *Chronobiol Int* 29(1):43–54.
7. Schoenborn C, Adams P (2010) Health behaviors of adults: United states, 2005-2007. *Vital and Health Statistics. Series 10, Data from the National Health Survey* (245):1–132.
8. Cooper RW, DeJong DV, Forsythe R, Ross TW (1990) Selection criteria in coordination games - some experimental results. *Amer Econ Rev* 80(1):218–233.
9. Devetag G, Ortmann A (2007) When and why? a critical survey on coordination failure in the laboratory. *Exp Econ* 10(3):331–344.
10. Barnes CM, Hollenbeck JR (2009) Sleep deprivation and decision-making teams: Burning the midnight oil or playing with fire? *Acad Manag Rev* 34(1):56–66.
11. Anderson C, Dickinson DL (2010) Bargaining and trust: the effects of 36-h total sleep deprivation on socially interactive decisions. *J Sleep Res* 19(1, 1):54–63.
12. Ferrara M, et al. (2015) Gender differences in sleep deprivation effects on risk and inequality aversion: evidence from an economic experiment. *PLOS ONE* 10(3).
13. Dickinson DL, McElroy T (2017) Sleep restriction and circadian effects on social decisions. *Eur Econ Rev* 97(Aug):57–71.
14. Rilling JK, Sanfey AG (2011) The neuroscience of social decision-making. *Annu Rev Psychol* 62:23–48.
15. Krajbich I, Bartling B, Hare T, Fehr E (2015) Rethinking fast and slow based on a critique of reaction-time reverse inference. *Nat Commun* 6.
16. McCabe K, Houser D, Ryan L, Smith V, Trouard T (2001) A functional imaging study of cooperation in two-person reciprocal exchange. *P NATL ACAD SCI USA* 98(20):11832–11835.
17. Chee MWL, Chuah LYM (2008) Functional neuroimaging insights into how sleep and sleep deprivation affect memory and cognition. *Curr Opin Neurol* 21(4):417–423.
18. McKenna BS, Dickinson DL, Orff HJ, Drummond SPA (2007) The effects of one night of sleep deprivation on known-risk and ambiguous-risk decisions. *J Sleep Res* 16(3):245–252.
19. Castillo M, Dickinson DL, Petrie R (2017) Sleepiness, choice consistency, and risk preferences. *Theor Decis* 82(1):41–73.
20. Schneider M, Leland JW (2015) Reference dependence, cooperation, and coordination in games. *Judgm Decis Mak* 10(2):123–129.
21. Monderer D, Shapley L (1996) Potential games. *Game Econ Behav* 14(1):124–143.
22. Adan A, Almirall H (1991) Horne and Ostberg morningness eveningness questionnaire - a reduced scale. *Pers Indiv Differ* 12(3):241–253.
23. Sadeh A (2011) The role and validity of actigraphy in sleep medicine: an update. *Sleep Med Rev* 15(4):259–267.
24. Primi C, Morsanyi K, Chiesi F, Donati MA, Hamilton J (2015) The development and testing of a new version of the cognitive reflection test applying item response theory (IRT). *J Behav Decis Making* June 1.
25. Gosling SD, Rentfrow PJ, Swann WB (2003) A very brief measure of the big-five personality domains. *J Res Pers* 37(6):504–528.
26. Goeree JK, Holt CA (2005) An experimental study of costly coordination. *Game Econ Behav* 51(2):349–364.
27. Dickinson DL, Drummond SP, McElroy T (2017) The viability of an ecologically valid chronic sleep restriction and circadian timing protocol: An examination of sample attrition, compliance, and effectiveness at impacting sleepiness and mood. *PLOS ONE* 12(3):e0174367.
28. Goldman SE, et al. (2007) Poor sleep is associated with poorer physical performance and greater functional limitations in older women. *Sleep* 30(10):1317–1324.

A. Supporting Information

Table A1. Payoff matrix of coordination game

		Minimum of Other Members' Effort Choices						
		1.1	1.2	1.3	1.4	1.5	1.6	1.7
My effort choice	1.1	.396	.396	.396	.396	.396	.396	.396
	1.2	.332	.432	.432	.432	.432	.432	.432
	1.3	.268	.368	.368	.368	.368	.368	.368
	1.4	.204	.304	.404	.504	.504	.504	.504
	1.5	.140	.240	.340	.440	.540	.540	.540
	1.6	.076	.176	.276	.376	.476	.576	.576
	1.7	.012	.112	.212	.312	.412	.512	.612

Note: Light-shaded payoff cells reflect costly effort choice waste of other group members that do not directly impact one's own payoff.

Table A2. Protocol validation

Intent-to-treat	
Nightly hours slept week prior to experiment ($N = 100$)	$z = 8.250$, p-value< 0.001
Karolinska sleepiness scale ($N = 102$)	$z = -5.939$, p-value< 0.001
Self-reported sleep gain/loss ($N = 102$)	$z = 8.425$, p-value< 0.001
Personal Sleep Deprivation ($N = 100$)	$z = -5.611$, p-value< 0.001
Compliant subjects	
Nightly hours slept week prior to experiment ($N = 84$)	$z = 7.870$, p-value< 0.001
Karolinska sleepiness scale ($N = 84$)	$z = -5.336$, p-value< 0.001
Self-reported sleep gain/loss ($N = 84$)	$z = 7.748$, p-value< 0.001
Personal Sleep Deprivation ($N = 84$)	$z = -6.157$, p-value< 0.001

Note: Mann-Whitney tests. The number of observations for Intent-to-treat reflect two lost observations of sleep data from the actigraphy device measurements. Those two subjects were still able to provide the self report measures of Ksleepy or sleep gain/loss

Table A3. Effort

	(1)	(2)	(3)	(4)	(5)	(6)
	Model 1		Model 2			
			OLS		IV	
VARIABLES	All	Compliant	All	Compliant	All	Compliant
Partner cond. in last 10 rounds	0.115***	0.124***	0.108***	0.136***	0.159**	0.158**
	[0.032]	[0.040]	[0.040]	[0.049]	[0.068]	[0.067]
Partner condition	0.030*	0.018	0.002	0.002	-0.016	-0.020
	[0.018]	[0.019]	[0.019]	[0.020]	[0.042]	[0.034]
Round	-0.010***	-0.009***	-0.010***	-0.009***	-0.018***	-0.015***
	[0.002]	[0.002]	[0.002]	[0.002]	[0.004]	[0.004]
Sleep restricted	-0.040	-0.034				
	[0.041]	[0.043]				
Sleep restricted × Partner cond.	0.046*	0.065**				
	[0.026]	[0.028]				
Sleep restricted × Partner cond. last	-0.059	-0.056				
	[0.045]	[0.053]				
Sleep restricted × Round	0.006**	0.005**				
	[0.002]	[0.002]				
Personal sleep deprivation			-0.015	-0.012	-0.047	-0.031
			[0.016]	[0.018]	[0.036]	[0.031]
Per. sleep depriv. × Partner cond.			0.030***	0.029***	0.037*	0.038**
			[0.009]	[0.009]	[0.022]	[0.018]
Per. sleep depriv. × Partner cond. last			-0.011	-0.022	-0.040	-0.037
			[0.019]	[0.022]	[0.036]	[0.033]
Per. sleep depriv. × Round			0.001	0.001	0.006**	0.005**
			[0.001]	[0.001]	[0.002]	[0.002]
Constant	1.347***	1.332***	1.354***	1.336***	1.415***	1.376***
	[0.027]	[0.028]	[0.031]	[0.034]	[0.067]	[0.057]
Observations	2,040	1,680	2,000	1,680	2,000	1,680
R-squared	0.110	0.116	0.112	0.111	0.083	0.092

Robust standard errors in brackets
*** p<0.01, ** p<0.05, * p<0.10

Table A4. Earnings

	(1)	(2)	(3)	(4)	(5)	(6)
	Model 1		Model 2			
			OLS		IV	
VARIABLES	All	Compliant	All	Compliant	All	Compliant
Partner cond. in last 10 rounds	0.013	0.011	-0.011	-0.006	0.020	0.013
	[0.013]	[0.015]	[0.016]	[0.019]	[0.029]	[0.025]
Partner condition	0.045***	0.053***	0.055***	0.063***	0.054**	0.062***
	[0.011]	[0.014]	[0.014]	[0.017]	[0.024]	[0.022]
Round	0.005***	0.005***	0.006***	0.007***	0.010***	0.010***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.003]	[0.003]
Sleep restricted	0.029	0.037				
	[0.020]	[0.024]				
Sleep restricted × Partner cond.	-0.006	-0.013				
	[0.017]	[0.020]				
Sleep restricted × Partner cond. last	-0.007	-0.003				
	[0.018]	[0.020]				
Sleep restricted × Round	-0.002*	-0.003*				
	[0.001]	[0.002]				
Personal sleep deprivation			0.021**	0.025**	0.041**	0.039**
			[0.009]	[0.011]	[0.018]	[0.016]
Per. sleep depriv. × Partner cond.			-0.007	-0.009	-0.004	-0.007
			[0.007]	[0.008]	[0.013]	[0.012]
Per. sleep depriv. × Partner cond. last			0.010	0.007	-0.006	-0.002
			[0.007]	[0.008]	[0.015]	[0.012]
Per. sleep depriv. × Round			-0.001**	-0.002**	-0.004**	-0.004**
			[0.001]	[0.001]	[0.002]	[0.001]
Constant	0.276***	0.269***	0.253***	0.243***	0.216***	0.215***
	[0.016]	[0.019]	[0.019]	[0.023]	[0.034]	[0.033]
Observations	2,040	1,680	2,000	1,680	2,000	1,680
R-squared	0.060	0.066	0.072	0.076	0.043	0.058

Robust standard errors in brackets

*** $p<0.01$, ** $p<0.05$, * $p<0.10$

Table A5. Distance to group minimum effort

	(1)	(2)	(3)	(4)	(5)	(6)
	Model 1		Model 2			
			OLS		IV	
VARIABLES	All	Compliant	All	Compliant	All	Compliant
Partner cond. in last 10 rounds	0.028*	0.033*	0.049**	0.053**	0.036	0.043
	[0.015]	[0.017]	[0.022]	[0.025]	[0.034]	[0.030]
Partner condition	-0.035***	-0.047***	-0.054***	-0.062***	-0.060**	-0.070***
	[0.012]	[0.015]	[0.015]	[0.018]	[0.028]	[0.025]
Round	-0.009***	-0.009***	-0.010***	-0.010***	-0.016***	-0.015***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.003]	[0.003]
Sleep restricted	-0.044*	-0.050*				
	[0.024]	[0.027]				
Sleep restricted × Partner cond.	0.022	0.037*				
	[0.019]	[0.022]				
Sleep restricted × Partner cond. last	-0.013	-0.017				
	[0.025]	[0.027]				
Sleep restricted × Round	0.004***	0.005***				
	[0.002]	[0.002]				
Personal sleep deprivation			-0.027**	-0.030**	-0.058***	-0.051***
			[0.010]	[0.012]	[0.020]	[0.018]
Per. sleep depriv. × Partner cond.			0.017**	0.019**	0.018	0.020
			[0.007]	[0.008]	[0.016]	[0.014]
Per. sleep depriv. × Partner cond. last			-0.014	-0.015	-0.008	-0.011
			[0.010]	[0.011]	[0.019]	[0.017]
Per. sleep depriv. × Round			0.002***	0.002***	0.006***	0.005***
			[0.001]	[0.001]	[0.002]	[0.002]
Constant	0.210***	0.212***	0.235***	0.239***	0.294***	0.281***
	[0.018]	[0.021]	[0.021]	[0.024]	[0.039]	[0.036]
Observations	2,040	1,680	2,000	1,680	2,000	1,680
R-squared	0.063	0.065	0.071	0.070	0.041	0.047

Robust standard errors in brackets

*** $p<0.01$, ** $p<0.05$, * $p<0.10$

Table A6. Distance to group median effort

	(1)	(2)	(3)	(4)	(5)	(6)
	Model 1		Model 2			
			OLS		IV	
VARIABLES	All	Compliant	All	Compliant	All	Compliant
Partner cond. in last 10 rounds	0.002	0.006	0.009	0.004	-0.015	-0.002
	[0.011]	[0.012]	[0.015]	[0.017]	[0.025]	[0.021]
Partner condition	-0.016**	-0.031***	-0.019*	-0.025**	-0.014	-0.038**
	[0.007]	[0.007]	[0.009]	[0.011]	[0.019]	[0.016]
Round	-0.005***	-0.005***	-0.005***	-0.005***	-0.009***	-0.009***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.002]	[0.002]
Sleep restricted	-0.017	-0.024				
	[0.016]	[0.018]				
Sleep restricted × Partner cond.	-0.007	0.011				
	[0.013]	[0.013]				
Sleep restricted × Partner cond. last	0.017	0.014				
	[0.016]	[0.017]				
Sleep restricted × Round	0.002**	0.002**				
	[0.001]	[0.001]				
Personal sleep deprivation			-0.005	-0.006	-0.028*	-0.028*
			[0.008]	[0.009]	[0.015]	[0.014]
Per. sleep depriv. × Partner cond.			0.001	0.001	-0.004	0.005
			[0.005]	[0.006]	[0.011]	[0.009]
Per. sleep depriv. × Partner cond. last			0.001	0.006	0.014	0.008
			[0.007]	[0.008]	[0.013]	[0.011]
Per. sleep depriv. × Round			0.000	0.000	0.003**	0.003**
			[0.000]	[0.000]	[0.001]	[0.001]
Constant	0.144***	0.148***	0.144***	0.145***	0.186***	0.187***
	[0.011]	[0.013]	[0.015]	[0.018]	[0.028]	[0.029]
Observations	2,040	1,680	2,000	1,680	2,000	1,680
R-squared	0.047	0.049	0.041	0.045	0.012	0.024

Robust standard errors in brackets

*** p<0.01, ** p<0.05, * p<0.10

Table A7. Gap at the group level

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	OLS	OLS	OLS	IV	OLS	IV
Partner condition	-0.051***	-0.053***	-0.050***	-0.053***	-0.052***	-0.057***
	[0.018]	[0.018]	[0.018]	[0.020]	[0.018]	[0.022]
Round	-0.012***	-0.014***	-0.012***	-0.012***	-0.015***	-0.020
	[0.001]	[0.003]	[0.001]	[0.002]	[0.003]	[0.012]
No. of sleep restricted subjects in group	0.023**	0.010				
	[0.010]	[0.017]				
No. of SR subjects in group × Round		0.001				
		[0.002]				
Mean Personal Sleep Deprivation of subjects in group			0.010	0.090**	-0.006	0.045
			[0.011]	[0.044]	[0.019]	[0.078]
Mean Pers. SD of subjects in group × Round					0.002	0.004
					[0.002]	[0.007]
Constant	0.381***	0.399***	0.394***	0.255***	0.423***	0.335**
	[0.021]	[0.031]	[0.026]	[0.079]	[0.037]	[0.144]
Observations	760	760	760	760	760	760
R-squared	0.167	0.168	0.158	0.051	0.159	0.051

Robust s.e. in brackets, errors clustered at the group level

*** p<0.01, ** p<0.05, * p<0.10

Table A8. Group Dynamics

	OLS						IV		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
VARIABLES	Min	Max	Gap	Min	Max	Gap	Min	Max	Gap
Partner condition	0.077***	0.026	-0.051***	0.076***	0.025	-0.050***	0.076***	0.024	-0.053***
	[0.023]	[0.025]	[0.018]	[0.022]	[0.023]	[0.018]	[0.023]	[0.024]	[0.020]
Round	-0.002	-0.014***	-0.012***	-0.002	-0.014***	-0.012***	-0.002	-0.014***	-0.012***
	[0.002]	[0.002]	[0.001]	[0.002]	[0.002]	[0.001]	[0.002]	[0.002]	[0.002]
No. of SR subjects in group	0.007	0.029**	0.023**						
	[0.015]	[0.014]	[0.010]						
Mean Personal SD				0.045***	0.055***	0.010	0.026	0.114**	0.089**
				[0.013]	[0.013]	[0.011]	[0.056]	[0.051]	[0.044]
Constant	1.171***	1.552***	0.381***	1.100***	1.495***	0.394***	1.135***	1.391***	0.257***
	[0.027]	[0.029]	[0.021]	[0.029]	[0.033]	[0.026]	[0.095]	[0.092]	[0.079]
Observations	760	760	760	760	760	760	760	760	760
R-squared	0.064	0.161	0.167	0.113	0.188	0.158	0.104	0.139	0.054

Robust s.e. in brackets, errors clustered at the group level

*** $p<0.01$, ** $p<0.05$, * $p<0.10$

Table A9. Equilibrium play

	All				
	SR subjects in group				
	0	1	2	3	Total
Off equilibrium	115	281	217	68	681
Percent	0.81	0.94	0.87	0.97	0.90
In equilibrium	27	17	33	2	79
Percent	0.19	0.06	0.13	0.03	0.10

Fisher's exact test p-value < 0.001

	Partners				
	SR subjects in group				
	0	1	2	3	Total
Off equilibrium	52	132	109	28	321
Percent	0.74	0.94	0.78	0.93	0.84
In equilibrium	18	8	31	2	59
Percent	0.26	0.06	0.22	0.07	0.16

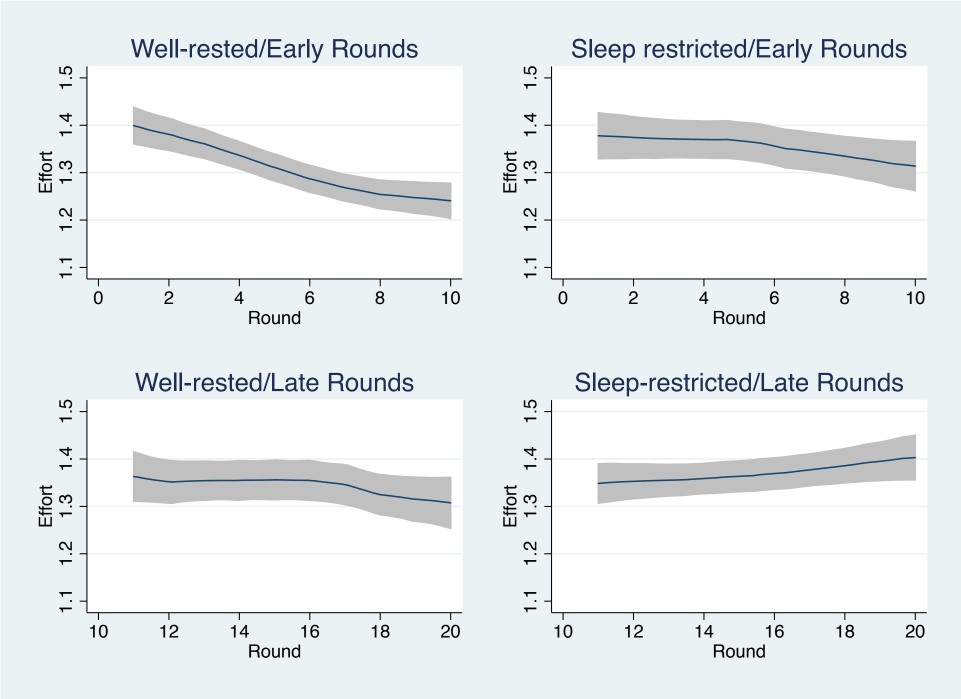
Fisher's exact test p-value < 0.001

	Strangers				
	SR subjects in group				
	0	1	2	3	Total
Off equilibrium	63	149	108	40	360
Percent	0.88	0.94	0.98	1.00	0.95
In equilibrium	9	9	2	0	20
Percent	0.12	0.06	0.02	0.00	0.05

Fisher's exact test p-value = 0.009

Fig. A1. Effort by round and experimental condition

Partners



Strangers