Moderate Sleep Restriction and time-of-day impacts on simple social interactions

David L Dickinson[1,2,3], Todd McElroy[4]

Abstract: Simple bargaining games are the foundation of more complex social interactions, and neuroscience research has shown that deliberative brain processes are necessary for social-decision making. We study how commonly-experienced adverse sleep states, which can harm deliberative processes, impact outcomes in classic simple bargaining games. We experimentally manipulated and objectively measured sleep in 184 young-adult subjects: each was prescribed one week of sleep restriction and one week of well-rested sleep levels. The optimality of the time-of-day for decisions (early morning or late evening) was also randomly assigned across subjects. Increased sleepiness is estimated to significantly reduce altruism, trust, and trustworthiness. We conclude that commonly experienced adverse sleep states, in particular sleep restriction, reduce prosocial behaviors, and can limit benefits from short-term social interactions.

[1]Department of Economics & the CERPA (Center for Economic Research and Policy Analysis), Appalachian State University, Boone, NC, USA.
[2]IZA (Institute for the Study of Labor), Bonn, Germany
[3]ESI (Economic Science Institute), Chapman University, Orange, CA, USA
[4]Department of Psychology, Florida Gulf Coast University, Ft. Myers, FL, USA.

Prosocial preferences help encourage positive interactions and promote economic institutions that require trust/trustworthiness. We explore how commonly experienced adverse sleep states impact well-established outcomes in ultimatum, dictator, and trust games. The literature is virtually silent on the impact of sleep loss on social decision making, and the rare exceptions utilize total sleep loss protocols (*1,2*). A main contribution of our work is to experimentally manipulate sleep in ecologically valid ways that are highly applicable to real world decision makers. We consider a dual-process framework where automatic thinking (System 1) and deliberate thinking (System 2) processes both contribute towards decision outcomes. Increased sleepiness is hypothesized to decrease the relative input of System 2, which we predict will negatively impact prosocial behavior (*1-5*). The implications are significant given the prevalence of adverse sleep states in modern society, and these results identify a key determinant of inefficiencies in certain social exchanges.

Critical to our hypothesis is the argument that prosocial behavior requires deliberative thinking and active suppression of myopic self-interest (*3,6,7*). Interestingly, recent evidence suggests that reduced deliberation promotes altruism and cooperation in certain contexts (*8-10*), though some found no such relationship (*11-13*). Nevertheless, none of these studies manipulated sleep. The literature showing that deliberative (prefrontal) brain regions are necessary for prosocial decisions (*3,4,6*) is more relevant, because sleep deprivation is known to disproportionately harm prefrontal cortex functions (*14-16*). Existing research also links adverse sleep states with less deliberative decisions (*14,17-19*), and findings of lower levels of altruism and trust in younger versus older children (*20-22*) may also imply that prefrontal development promotes pro-social choice. Together, existing literature supports our hypothesis that sleepy subjects, who will deliberate less, will be less prosocial.

To examine our research question, we recruited 184 young adult subjects (30 control: 154 treatment: 18-39 years old, mean 21.66 ± 4.43 years old) to participate in a 3-week study. Treatment subjects were validated morning-type or evening-type subjects (*23*) who were randomly assigned to early morning (7:30am-9:00am) or late evening (10:00pm-11:30pm) decision sessions (Table S1). In this way, we randomly matched or mismatched subjects to more preferred circadian timing of the decisions. Research grade actigraphy devices objectively monitored subject sleep levels for 3 weeks. Treatment subjects were prescribed one week of 5-6 hrs/night attempted sleep (Sleep Restricted=SR) and one week of 8-9 hrs/night attempting to sleep (Well-Rested=WR)—control subjects were prescribed two WR weeks. Week 2 of the 3-week protocol was an ad lib sleep week used to wash out the effects of the week #1 condition prior to starting week #3. This design is a mix of between (circadian match/mismatch) and within (SR/WR) components. Subjects were compensated a fixed payoff ($80) for schedule compliance and providing sleep data, and they earned additional cash in the decision experiments. In total, 149 (30 control: 119 treatment) subjects provided complete sleep data and were deemed compliant based on objective actigraphy measured sleep levels. Compliant treatment subjects slept approximately 1.5 hours more per night during the SR week than the WR week (see Fig. S1 and (*24*) for details on compliance scoring).

At the end of the SR and WR weeks (counterbalanced across subjects), subjects were administered the classic ultimatum, dictator, and trust games (see Supp. Mat.: *Methods and Materials*). In the ultimatum game, responders may reject the proposed division of a $10 pie, in which case both parties receive $0, whereas the dictator game allows the dictator to unilaterally divide the pie without possibility of rejection. Hence, while the ultimatum game is well-known, the dictator game provides a more clean measure of altruism. In the trust game, the amount of the $10 pie the first mover passes along, or "trusts" to the second mover, is tripled by the experimenters and the second mover then decides how much, if any, to pass back.

Subjects were asked to self-report sleepiness during the decision sessions using the Karolinska Sleepiness scale (*25,26*). To test treatment manipulations we regress self-report sleepiness on treatment, demographics, and sleep control variables. Both SR and circadian mismatch manipulations significantly increase sleepiness ($p<.01$). Though domain-specific nonlinear interaction effects between sleep and circadian misalignment may exist (*27,28*), we do not include an interaction term in our analysis given the lack of ex ante hypothesis regarding its form or how it might vary across decision tasks we administer.

Figures 1-4 plot the predicted dependent variable from each game as a function of *Personal Sleep Deprivation Level* (or "*Personal SD*"), which is the difference between a subject's self-reported optimal nightly sleep and the actigraphy measured nightly sleep over the prior week. All Figures plot the key variable results holding demographics, session identifier, and other sleep related control variables constant. Random effects estimations account for the two observations per subject. Except for the case of ultimatum game outcomes in Fig. 1, key results are robust to alternative specifications and alternative coding options of the key sleep level variable (see Tables S2-S6). The estimated direct effect of circadian mismatch on outcomes is insignificant in each case, and so Figs 1-4 show only the outcome prediction as a function of sleep restriction.

Figs 1 and 2 show the estimated increased greed by first movers in both the ultimatum and dictator games as a result of sleep restriction. The ultimatum result is less robust and a smaller effect size (see Tables S2, S3), which is perhaps not surprising given the confound of self-interest and fear of rejection. A null result not shown is that second-mover ultimatum decisions—minimum acceptable offers—are not significantly affected by sleep restriction (Tables S2, S3). Second-mover minimum acceptable offers also reflect a conflict between greed (or "altruism") and aversion to a zero payoff. Ultimatum results are shown given the ubiquitous nature of the game, but the dictator result (Fig 2) more clearly depicts how SR reduces altruism.

Figs. 3 and 4 show predicted lower levels of trust and trustworthiness as a result of sleep restriction. Fig. 3 also shows the estimated null impact on trust decisions when a "risk" version of the trust game was played—here, the 2nd-mover decision is automated and drawn from a distribution. As seen in Fig. 3, SR only impacts first-mover choices when the risk of passing money is embedded in an actual 2-person exchange. The trust result is quite robust (see Tables S5, S7) and highlights an important inefficiency that results from mild but chronic sleep restriction: lower levels of trust imply reduced cooperation and unrealized gains in simple social interactions.

Trustworthiness is also negatively impacted by SR, as shown in Fig. 4, and we also estimated trustworthiness to be even more negatively impacted when larger initial amounts are trusted (Table S6, see also note below Table S2). This indicates that SR may have a particularly damaging effect on future interactions when more significant and clear trust signals are sent. Given the SR effect on trustworthiness, one might argue that reduced trust results from an accurate anticipation of reduced trustworthiness. Our data cannot directly test whether this is the case, but we reject this interpretation for two reasons: First, this reasoning is not consistent with the ultimatum results—SR weakly increases greed even though MAOs are unchanged. Second, this interpretation implies that sleepy subjects retain anticipation skills requiring theory-of-mind brain region activation, which is a region harmed by sleep loss (*29,30*).

Because our treatment manipulations were intended to increase sleepiness, we also evaluated whether sleepiness is the primary mediator of these results (Table S7). For the two-step estimation we first regressed the Karolinska sleepiness scores on demographics and sleep variables. As noted earlier, both SR and circadian mismatch are statistically significant ($p<.01$) predictors of higher sleepiness scores. This first stage estimation identifies the extent that variation in sleepiness is due to subject-specific and experimental manipulations in our design (*31*).

Step two used the predicted values of sleepiness scores as a covariate (instrument) in the main outcome variable models. The instrument for sleepiness predicts higher Ultimatum proposals and lower Dictator altruism, lower trust, and lower trustworthiness (see Table S7). These results indicate that our experimental conditions alter behavior via their impact on subject sleepiness. They also highlight that, while circadian mismatch is not estimated to directly impact behavioral outcomes in these games, circadian mismatch does indirectly affect social decisions via its impact on sleepiness.

We examined the impact of chronic but mild sleep restriction and suboptimal circadian timing on decisions in simple social interactions. These games form the building blocks of many more complex interactive environments where social preferences loom large. Because we examined subjects in an ecologically valid setting, and compensatory strategies to combat the sleepiness were allowed, our results can be viewed as a conservative estimate of the impact of common sleep states in these simple games. The robust result is that sleepiness reduces altruism, trust, and trustworthiness. At least for short-term social interactions, our results imply that common adverse sleep states reduce pro-social outcomes and lead to unrealized gains (i.e., inefficiencies) in simple exchanges requiring trust. Future research should seek to evaluate whether these effects are also robust to repeated, longer-term, or less anonymous interactions.

REFERENCES AND NOTES

1. C. Anderson, D.L. Dickinson, Bargaining and Trust: The Effects of 36hr Sleep Deprivation on Socially Interactive Decisions. *J. Sleep Res.* **19**, 54-63 (2010).
2. M. Ferrara, A. Bottasso, D. Tempesta, M. Carrieri, L. De Gennaro, G. Ponti, Gender differences in sleep deprivation effects on risk and inequality aversion: Evidence from an economic experiment. *PLoS ONE* **10**, e0120029 (2015).
3. J. K. Rilling, A. G. Sanfey, The neuroscience of social decision-making. *Annu. Rev. Psychol.* **62**, 23-48 (2011).
4. I. Krajbich, R, Adolphs, D. Tranel, N. L. Denburg, C. F. Camerer, Economic games quantify diminished sense of guilt in patients with damage to the prefrontal cortex. *J. Neurosci.* **29**, 2188-2192 (2009).
5. M. W. Chee, L. Y. Chuah, Functional neuroimaging insights into how sleep and sleep deprivation affect memory and cognition. *Curr. Opin. Neurol.* **21,** 417-423 (2008).
6. E. Fehr, C. F. Camerer, Social neuroeconomics: the neural circuitry of social preferences. *Trends Cogn. Sci.* **11**, 419-427 (2007).
7. A. Achtziger, C. Alós-Ferrer, A. K. Wagner, The impact of self-control depletion on social preferences in the ultimatum game. *J. Econ. Psychol.* **53**, 1-16 (2016).
8. D. G. Rand, J. D. Greene, M. A. Nowak, Spontaneous giving and calculated greed. *Nature.* **489**, 427-430 (2012).
9. D. G. Rand, A. Peysakhovich, G. T. Kraft-Todd, G. E. Newman, O. Wurzbacher, M. A. Nowak, J. D. Greene, Social heuristics shape intuitive cooperation. *Nat. Comm*. **5,** (2014).
10. D. G. Rand, V. L. Brescoll, J. A. C. Everett, V. Capraro, H. Barcelo, Social heuristics and social roles: Intuition favors altruism for women but not for men. *J. Exp. Psychol. Gen.* forthcoming.
11. P. P. J. L. Verkoeijen, S. Bouwmeester, Does intuition cause cooperation? *PLOS ONE.* **9**, e96654 (2014).
12. G. Tinghög, D. Andersson, C. Bonn, H. Böttiger, C. Josephson, *et al*, Intuition and cooperation reconsidered. *Nature.* **498**, E1-E2 (2013).
13. I. Krajbich, B. Björn, T. Hare, E. Fehr, Rethinking fast and slow based on a critique of reaction-time reverse inference. *Nat. Commun.* **6,** 7455 (2015).
14. J. A. Horn, Human sleep, sleep loss and behavior. Implications for the prefrontal cortex and psychiatric behavior. *Brit. J. Psychiat.* **162**, 413-419 (1993).
15. A. Muzur, E. F. Pace-Schott, J. A. Hobson, The prefrontal cortex in sleep. *Trends Cogn. Sci*. **6**, 475-481 (2002).
16. M. W. Chee, L. Y. Chuah, Functional neuroimaging insights into how sleep and sleep deprivation affect memory and cognition*. Curr. Opin. Neurol.* **21**, 417-423 (2008).
17. S.-S. Yoo, N. Guhar, P. Hu, F. A. Jolesz, M. P. Walker, The human emotional brain without sleep—a prefrontal amygdale disconnect. *Curr. Biol.* **17,** 877-878 (2007).

18. T. McElroy, D. L. Dickinson, Thoughtful days and valenced nights: How much will you think about the problem? *Judg. Decision Making.* **5**, 516-523 (2010).
19. D. L. Dickinson, T. McElroy, Rationality Around the Clock: Sleep and Time-of-Day Effects on Guessing Game Responses. *Econ. Lett.* **108**, 245-248 (2010).
20. J. F. Benenson, J. Pascoe, N. Radmore, Children's altruistic behave in the dictator game. *Evol. Hum. Behav.* **28**, 168-175 (2007).
21. E. Fehr, H. Bernhard, B. Rockenbach, Egalitarianism in young children. *Nature*, **454**, 1079-1083 (2008).
22. E. Fehr, D. Glätzle-Rützler, M. Sutter, The development of egalitarianism, altruism, spite and parochialism in childhood and adolescence. *Eur. Econ. Rev.* **64**, 369-383 (2013).
23. A. Adan, H. Admiral, Horne and Ostberg morningness-eveningness questionnaire: A reduced scale. *Pers. Indiv. Dif.* **12**: 241-253 (1991).
24. D. L. Dickinson, S. P. A. Drummond, T. McElroy, 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. *Working paper* (2016).
25. T. Åkerstedt, M. Gillberg, Subjective and objective sleepiness in the active individual. *Int. J. Neurosci.* **52**, 29-37 (1990).
26. K. Kaida, M. Takahashi, T. Åkerstedt, A. Nakata, Y. Otsuka, T. Haratani, K. Fukasawa, Validation of the Karolinska sleepiness scale against performance and EEG variables. *Clin. Neurophysiol*. **117**, 1574-1581 (2006).
27. H. P. A. Van Dongen, D. F. Dinges, Investigating the interaction between the homeostatic and circadian processes of sleep-wake regulation for the prediction of waking neurobehavioural performance. *J. Sleep Res.* **12**, 181-187 (2003).
28. T. M. Burke, F. A. J. L. Scheer, J. M. Ronda, C. A. Czeisler, K. P. Wright, Sleep inertia, sleep homeostatic and circadian influences on higher-order cognitive functions. *J. Sleep Res.* **24**, 364-371 (2015).
29. G. Coricelli, R. Nagel, Neural correlates of depth of strategic reasoning in medial prefrontal cortex. *Proc. Natl. Acad. Sci. U.S.A.*, **106**, 9163-9168 (2009).
30. D. L. Dickinson, T. McElroy, Circadian effects on strategic reasoning. *Exp. Econ.* **15**, 444-459 (2012).
31. We note that the impact of gender is implicit in these results. First stage estimates show that female subjects are significantly sleepier, controlling for other demographics and sleep variables.
32. S. E. Goldman, K. L. Stone, S. Ancoli-Israel, T. Blackwell, S. K. Ewing, R. Boudreau, … A. B. Newman, Poor sleep is associated with poorer physical performance and greater functional limitations in older women. *Sleep*, **30**, 1317–1324 (2007).
33. J. A. Horne, O. Östberg, A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int. J. Chronobiol.* **4**, 97-110 (1976).
34. I. Chelminski, T. V. Petros, J. J. Plaud, F. R. Ferraro, Psychometric properties of the reduced Horne and Östberg questionnaire. *Pers. Indiv. Dif.* **29,** 469-78 (2000).
35. W. Güth, R. Schmittberger, B. Schwarze, An experimental analysis of ultimatum bargaining. *J. Econ. Behav. Organ.* **3,** 367-388 (1982).
36. R. Forsythe, J.L. Horowitz, N.E. Savin, M Sefton, Fairness in simple bargaining games, *Game. Econ. Behav*. **6,** 347-369 (1994).

37. J.E. Berg, J.W. Dickhaut, K.A. McCabe, Trust, reciprocity, and social history, *Game. Econ. Behav.* **10,** 122-142 (1995).
38. K. Kroenke, R. L. Spitzer, J. B. Williams, The Patient Health Questionnaire-2: validity of a two-item depression screener. *Med. Care.* ***41***, 1284–92 (2003).
39. R. L. Spitzer, K. Kroenke, J. B. Williams, B. Löwe, A brief measure for assessing generalized anxiety disorder: the GAD-7. *Arch. Int. Med.* **166**, 1092-1097 (2006).
40. D. Watson, L. A. Clark, A. Tellegen, Development and validation of brief measure of positive and negative affect: The PANAS scales. *J. Pers. Soc. Psychol.* **54**, 1063 (1988).
41. R. M. Shiffrin, W. Schneider, Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychol. Rev.* ***84,*** 127-190 (1977).
42. S. A. Sloman, The empirical case for two systems of reasoning. *Psychol. Bull.* **199,** 3–22 (1996).
43. **Acknowledgements:** This work was supported by National Science Foundation grant BCS-1229067. We thank S.P.A. Drummond for assistance designing the sleep protocol, T. Perry, A. Beckett, L. Morris, R. McClelland, and E. Wilson for help with sessions, and N. Stroh and S. Rule for assistance with decision tasks and sleep data preparation and scoring. Comments from seminar participants at numerous universities is gratefully acknowledged. Data is available from Dickinson on request.

Supplementary Materials
Materials and Methods
Tables S1-S7
Fig S1-S2
References (*32-42*)

Figure 1: Forecast derived from Table S5 with levels of all statistically insignificant variables set to zero. Fig. shows range of values of *Personal SD* observed in sample of compliant treatment subjects. Results show that when ultimatum proposers are more chronically sleep restricted, they offer less. Note: ultimatum second movers were not estimated to change their minimum acceptable offers as a function of sleep restriction.

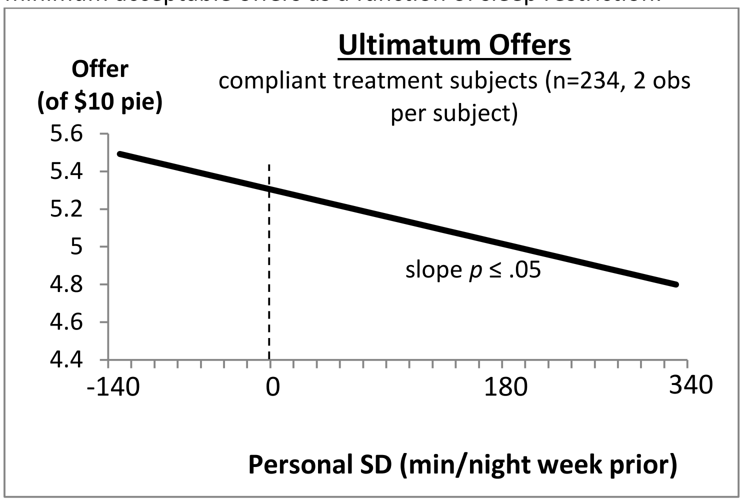


Figure 2: Forecast derived from Table S6 with levels of all statistically insignificant variables set to zero. Fig. shows range of values of *Personal SD* observed in sample of compliant treatment subjects. Results show that when dictators are more chronically sleep restricted, they are less altruistic.

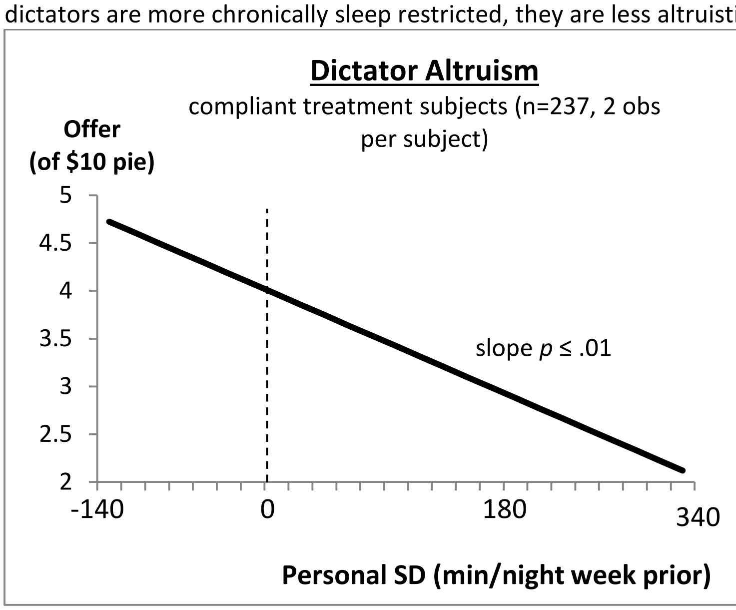


Figure 3: Forecast derived from Table S7 with levels of all statistically insignificant variables set to zero. Fig. shows range of values of *Personal SD* observed in sample of compliant treatment subjects. Results show that when subjects are more chronically sleep restricted, they trust less of the $10 pie. Non-human trust line shows predicted trust when 2nd-mover is known to be an automatic pass-back algorithm as opposed to another subject. Trusted amounts in non-human trust are not significantly affected by *Personal SD*.

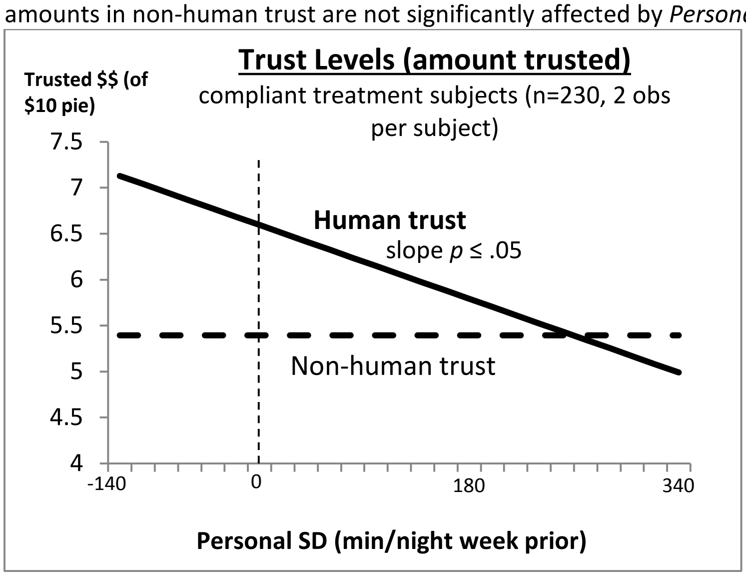
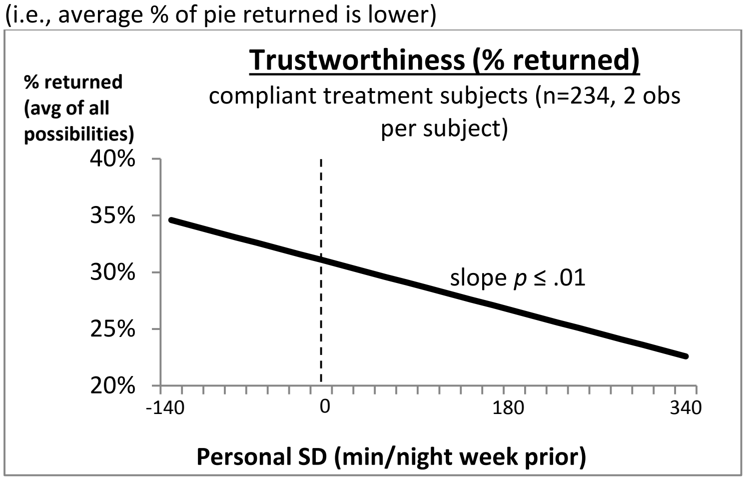


Figure 4: Forecast derived from Table S8 with levels of all statistically Insignificant variables set to zero. Fig. shows range of values of *Personal SD* observed in sample of compliant treatment subjects. Results show that when subjects are more chronically sleep restricted, they are less trustworthy. (i.e., average % of pie returned is lower)



SUPPLEMENTARY MATERIALS (APPENDIX)
Materials and Methods
Tables S1-S7
Fig S1-S2

MATERIALS AND METHODS

1. Experimental Design

Sleep Data Acquisition

Actigraphy data acquisition (Actiwatch Spectrum Plus devices; Philips Respironics) was at 30-second time epochs. Each epoch is initially scored as "sleep" or "wake" with manufacturer's software. Rest period start/end times are then adjusted manually, if necessary, using subject-entered actigraph event markers and with the input of complementary sleep diaries. All manual scoring is conducted using validated scoring protocols (*32*).

The devices use an MEMS type accelerometer and sample data at 32 Hz. Devices are waterproof at 1m for 30 minutes and so subjects were instructed to wear them 24 hr a day during the 3-week protocol, except for the exceptional removal to avoid device damage (e.g., contact sports, working with chemicals, etc). Battery life at 30-second data sampling epochs is over 30 days and so subjects had no concerns with battery life or device recharge.

Circadian Match/Mismatch Protocol: Details

We first administered a large-scale online survey meant to provide information on subject sleep habits. Over several waves of the online survey we generated several thousand responses to our survey (mostly student responses). The first page of the survey was a consent page requiring consent to continue. In addition to asking for basic demographic information, the survey administered a set of validated screener questions for anxiety and depression. Subjects at risk of major depressive or anxiety disorder were not recruited for our study, given the correlation between these conditions and sleep disturbance. Importantly, within the online survey we also included a validated measure of their diurnal preference, which is assessed in the survey using the short form of the morningness-eveningness questionnaire, henceforth rMEQ (*23*). The rMEQ classifies individuals on a scale of 4-25, with morning-types having rMEQ score from 18-25 and evening-types having rMEQ score from 4-11. While this diurnal preference measure is based on self-reports of the subjects, it has been validated against physiological data on oral temperatures (*33*) and is a standard tool in circadian research.

From our database, we recruit morning-types and evening-types, who we had randomly assigned, ex ante, to participate in either a morning (7:30 a.m.) or an evening (10:00 p.m.) experiment session. This resulted in approximately half of our sample being circadian matched (mismatched) for the risky choice experiment.[1] Table S1 shows how the circadian manipulation distributed subjects across our experimental design cells.

---

[1] Due to the rarity of true morning-type subjects—less than 10% in young adult populations are morning-types (*34*)—we extend our rMEQ cutoff to include rMEQ scores of 16 and 17. To compensate, we only recruit the more extreme (and still abundant) evening-type subjects with rMEQ scores from 4-9. In this way, our sample is still drawn from the tails of the rMEQ distribution and eliminates the same amount of support from the non-tail portion of the rMEQ distribution compared to if we had used the traditional morning-type cutoff (rMEQ=18) but included non-extreme evening types (rMEQ=10-11) in our sample.

Simple Bargaining: Ultimatum (*35*), Dictator games (*36*), and Trust (*37*) games.
We administer the classic versions of these games using a $10 starting sum. Note that for the Trust game we do not endow the responder with any money (and so, a subject attempting to equalize first-mover/second-mover earnings will send back a different amount than if the same endowed both first and second-mover with $10).

The games are administered via the strategy method whereby all subjects made decisions in the role of both first-mover and second-mover prior to knowing to which role he/she was randomly assigned. Only after all decisions were made do we make random role assignments (first- or second-mover), randomly assign subjects to an anonymous counterpart in the same session, and then randomly select one of the games to count for payoff during that decision session. Outcomes in this game were only revealed at the end of the decision session, when payoff for these and other decision tasks were given out in cash.

Table S1
Sample Size Per Design Cell (treatment subjects)

	Morning Session	**Evening Session**
Morning-type	34 (30)	38 (28)
Evening-type	39 (30)	38 (31)
	Sample size = 149 subjects Matched obs = 76, Mismatched obs = 73 (compliant & sleep data intact shown in parenthesis)	

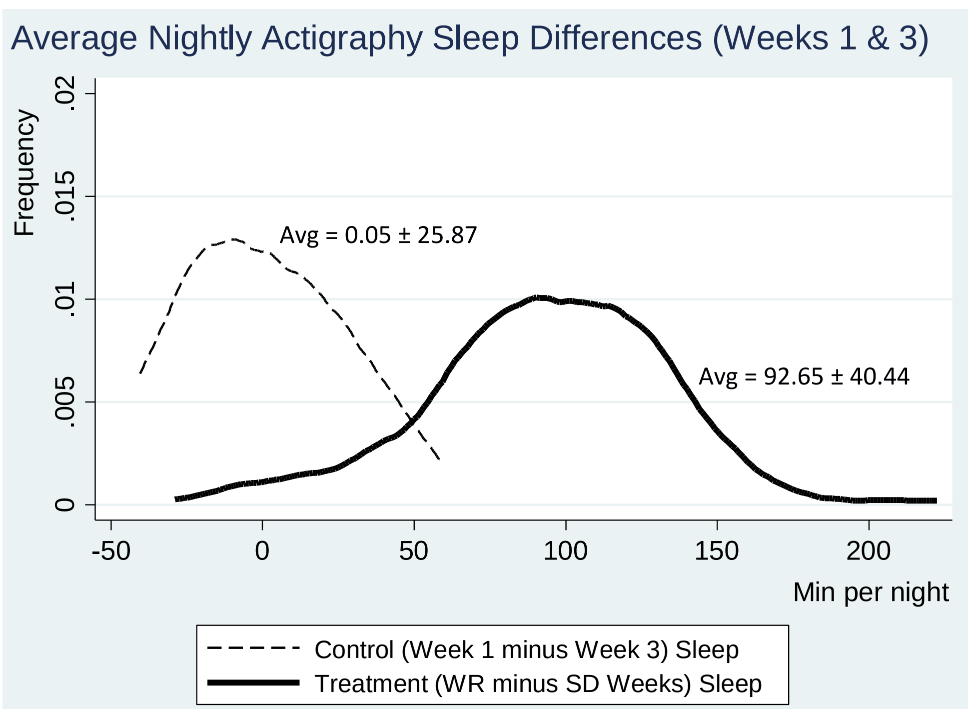
Notes: Circadian mismatches cells shaded
Table reproduced from Dickinson *et al* (2016) (*24*)

2. Sample Information
A comprehensive analysis of attrition, compliance, and validation of the protocol in generating significant differences in sleepiness can be found in Dickinson *et al* (2016). A total of 256 subjects were recruited for the study. Of these, 35 (14%) failed to show up for Session 1, and of the remaining 221 subjects, 184 completed the protocol (n=30 control subjects, n=154 treatment subjects). Higher depression risk scores on the primary care PHQ-2 screening questionnaire (*35*) predict a lower likelihood of showing up for the first study session (after recruitment signup), and they additionally predict a lower likelihood of completing the protocol conditional on showing up for the first session. Higher scores on the anxiety disorder risk screener GAD-7 (*36*) predict an increased likelihood of completing the protocol, conditional on starting the protocol (i.e., showing up for the first study session). It should be noted that scores on these two primary care screening questionnaires have some predictive power regarding selection and attrition in our sample, even though subjects surpassing the standard primary care cutoff for risk of depressive or anxiety disorder were *not* recruited at all. In other words, the variation in the screener score results within the “safe zone” (i.e., below the cutoff that typically generates follow-up screening for these disorders) explains some of the final sample qualities. For this result, these screener scores are included in the main statistical analysis as a way to account for their potential effect on behavioral outcomes via their impact on predicting protocol completion. The only other demographic

or session control variable predicting study completion was *Morning Session*, where we find that subjects randomly assigned to a morning session group were more likely to finish the protocol conditional on starting the protocol.

Of the 184 subjects completing the study, actigraphy malfunction caused the loss of data on a few subjects, such that we have 179 subjects (n=30 control subjects, n=149 treatment subjects) of complete actigraphy data. Using our standard for compliance for treatment subjects, which requires a subject to have at least a ≥ 60 minutes difference between nightly sleep during the well-rested compared to sleep-restricted weeks, we have 119 compliant treatment subjects—a compliance rate of about 80% (n=30 control subjects were 100% compliant). Figure S1 shows the distribution of differences (WR-SR) of nightly sleep amounts for the treatment versus control subjects. As can be seen from Fig. S1, a compliance standard of a treatment week difference of at least 60 min/night sleep is statistically sound. That is, a subject drawn at random from our study who has at least this 60 min difference between nightly sleep amounts in the two treatment weeks is unlikely to have been drawn from the control subject sample (see distribution overlap points).

Figure S1: Sleep difference distributions (control vs. treatment subjects)



Finally, we report significant increases in subjective sleepiness reports from subjects as a result of both the sleep restriction and circadian mismatch manipulations (*25*). There is some evidence that the overall effectiveness of the manipulation is stronger regarding the sleep restriction manipulation, compared to the circadian mismatch manipulation. This claim is substantiated from data on a subset of n=80 of our subject for whom we administered the PANAS instrument to measure positive and negative affective states (*37*). Sleep restriction is found to significantly increase subject self-reported irritability and decrease self-reported alertness. The same is not true of the circadian mismatch manipulation as there is no estimated difference in these mood states resulting from the mismatch manipulation.

3. Statistical Analysis

Full Estimations of Key Outcome Models

In general, the only robustly significant session variable predicting behavioral outcomes is the *Session #3* indicator variable. The estimated coefficient on this variable indicates increased greed, reduced trust, and reduced trustworthiness in the final (2^{nd}) administration of the tasks relative to the first. This is consistent with the hypothesis that deliberative thought produces more pro-social decisions in two ways. First, end-period effects in these economic games generally lead to an increase in self-interested outcomes as any possible benefit from pro-social behavior (in terms of possible reciprocation in future interaction, even though our subject pairings were anonymous and randomized each session) is eliminated when subjects know they will never interact again. Secondly, the final session implies that the tasks are no longer novel to our subjects, and a significant literature in psychology concludes that subjects are more likely to use automatic thought for non-novel tasks (*38,39*). This would also imply that we should observe decreases in pro-social outcomes in line with our hypothesis regarding the connection between deliberative thought and pro-social choice.

Table S2: Key Outcome Estimations with categorical variables only for experimental manipulation (along with controls for morningness/eveningness preference, session time-of-day, and session number)

Random effects GLS regressions
Standard errors clustered on subject (2 observations per subject)

Variable	Ultimatum $$ Offer	Ultimatum $$ MAO	Dictator $$ Offer	Trust person $$ Offer	Trust Distribution $$ Offer	Trust-worthiness^ % passback
SR (=1)	-.084 (.088)	-.019 (.131)	-.491 (.199)**	-.476 (.248)*	-.076 (.249)	-.017 (.013)
MM (=1)	.077 (.170)	.234 (.300)	-.217 (.333)	-.119 (.363)	.521 (.396)	-.001 (.024)
Morning Session (=1)	.079 (.169)	.362 (.300)	.284 (.333)	.273 (.363)	-.288 (.396)	.003 (.024)
MEQ score (higher=MT)	.0007 (.015)	-.012 (.027)	-.016 (.030)	-.053 (.033)	-.024 (.036)	-.001 (.002)
Session #3 (=1)	-.175 (.088)**	-.590 (.131)***	-.704 (.199)***	-.622 (.248)**	-.014 (.249)	-.037 (.013)***
Constant Term	4.503 (.245)***	2.044 (.429)***	3.994 (.488)***	6.102 (.537)***	4.818 (.583)***	.303 (.035)***
N	234	236	237	230	236	234
Wald X^2	5.05	22.60***	18.40***	11.91**	2.84	9.36*

Notes: *,**, *** indicate significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test.
^ Estimation of the Trustworthiness model using the alternative dependent variable of returned amounts when 50% or more of pie is trusted shows that the sleep restriction treatment reduced trustworthiness when high levels of trust are at stake (β = -.024, p <.05).

Table S3: Ultimatum Decisions
Random effects GLS regression (for full sample)
Dependent Variable= *Portion of $10 pie offered to 2nd-mover*

	Ultimatum Offers (n=234 obs)		***Minimum Acceptable Offer*** (n=236 obs)	
	(1)	**(2)**	**(3)**	**(4)**
Variable	**Coef (st. error)**	**Coef (st. error)**	**Coef (st. error)**	**Coef (st. error)**
Constant	4.70 (.60)***	5.29 (.54)***	4.71 (1.01)***	4.70 (.94)***
Female (=1)	-.29 (.18)	-.27 (.18)	-.61 (.31)**	-.62 (.31)**
Age	-.02 (.02)	-.02 (.02)	-.08 (.04)**	-.08 (.04)**
Depression score	.10 (.12)	.11 (.12)	.02 (.21)	.02 (.21)
Anxiety score	-.02 (.04)	-.02 (.04)	.06 (.07)	.06 (.07)
Epworth score	-.01 (.03)	-.01 (.03)	-.03 (.04)	-.03 (.04)
Session #3	-.18 (.09)**	-.18 (.09)**	-.59 (.13)***	-.59 (.13)***
Morning Session (=1)	.10 (.17)	.10 (.17)	.47 (.30)	.47 (.30)
Morningness Score	.01 (.02)	.01 (.02)	.02 (.03)	.02 (.03)
Circadian Mismatched (=1)	.02 (.17)	-.004 (.17)	.11 (.30)	.11 (.30)
Nightly Sleep week prior (min)	.001 (.001)	---	-.00003 (.001)	---
Personal SD (min/night)	---	-.0014 (.0007)**	---	.00001 (.001)
Wald chi-squared test (10)	9.43	12.32	31.68***	31.75***

Notes: *,**, *** indicate significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test

Table S4: Dictator Decisions
Random effects GLS regression (for full sample)
Dependent Variable= *Portion of $10 pie offered to 2nd-mover*

	Dictator Offers (n=237 obs)	
	(1)	**(2)**
Variable	**Coef (st. error)**	**Coef (st. error)**
Constant	1.39 (1.22)***	3.96 (1.05)***
Female (=1)	-.03 (.36)	.06 (.35)
Age	-.01 (.04)	-.02 (.04)
Depression score	-.23 (.23)	-.18 (.23)
Anxiety score	.11 (.08)	.10 (.08)
Epworth score	.06 (.05)	.06 (.05)
Session #3	-.71 (.20)***	-.72 (.20)***
Morning Session (=1)	.29 (.34)	.31 (.33)
Morningness Score	-.01 (.03)	-.02 (.03)
Circadian Mismatched (=1)	-.22 (.34)	-.32 (.33)
Nightly Sleep week prior (min)	.004 (.002)**	---
Personal SD (min/night)	---	-.005 (.002)***
Wald chi-squared test (10)	23.02***	29.36***

Notes: *,**, *** indicate significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test

Table S5: Trust Decisions
Random effects GLS regression (for full sample)
Dependent Variable= *Portion of $10 pie trusted to 2nd-mover*

	Trust person (Social) (n=230 obs)		***Trust algorithm (Asocial)*** (n=236 obs)	
	(1)	**(2)**	**(3)**	**(4)**
Variable	**Coef (st. error)**	**Coef (st. error)**	**Coef (st. error)**	**Coef (st. error)**
Constant	3.91 (1.39)***	6.51 (1.18)***	4.48 (1.48)***	5.40 (1.28)***
Female (=1)	-.33 (.40)	-.24 (.39)	-.47 (.43)	-.45 (.42)
Age	-.01 (.04)	-.01 (.04)	.01 (.05)	.01 (.05)
Depression score	-.27 (.26)	-.23 (.26)	-.39 (.28)	-.36 (.28)
Anxiety score	.10 (.09)	.09 (.09)	.10 (.09)	.09 (.09)
Epworth score	.01 (.06)	.01 (.06)	-.03 (.06)	-.03 (.06)
Session #3	-.64 (.25)***	-.63 (.25)**	-.02 (.25)	-.04 (.25)
Morning Session (=1)	.26 (.38)	.27 (.38)	-.32 (.41)	-.31 (.40)
Morningness Score	-.06 (.04)	-.06 (.04)	-.02 (.04)	-.03 (.04)
Circadian Mismatched (=1)	-.13 (.37)	-.21 (.37)	.52 (.40)	.47 (.40)
Nightly Sleep week prior (min)	.005 (.002)**	---	.001 (.002)	---
Personal SD (min/night)	---	-.004 (.002)**	---	-.003 (.002)
Wald chi-squared test (10)	15.44	16.07*	6.91	8.58

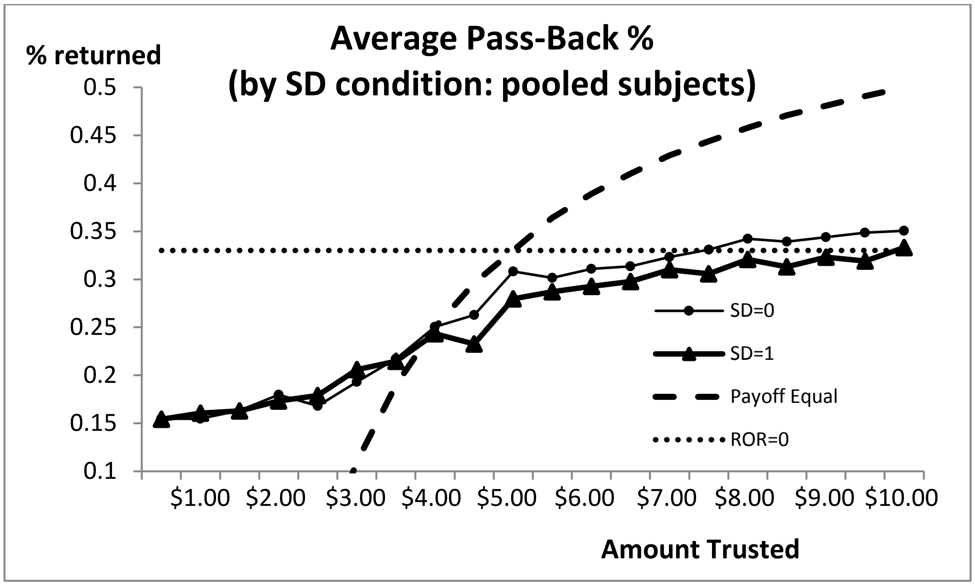
Notes: *,**, *** indicate significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test

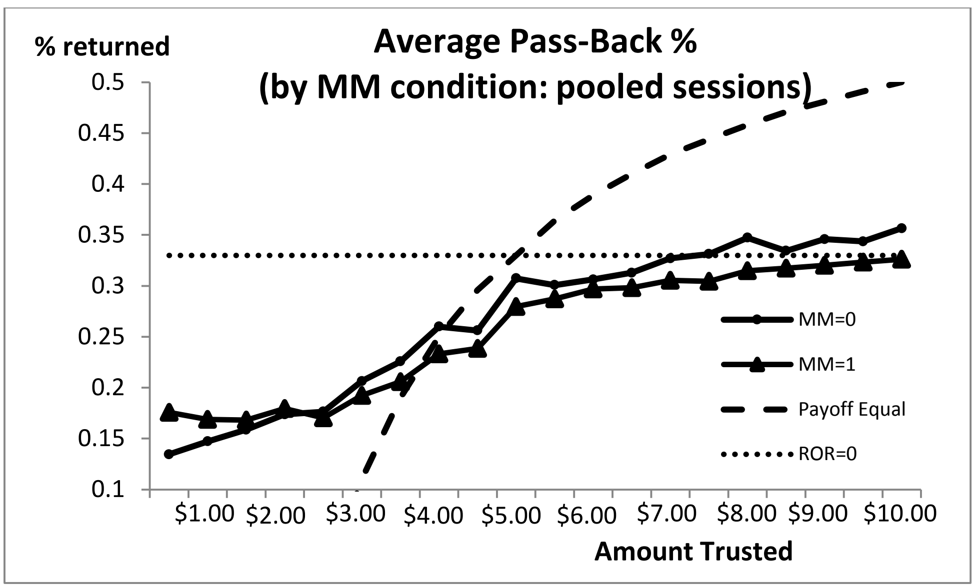
Table S6: Trustworthiness Decisions
Random effects GLS regression (for full sample)
Dependent Variable= *average % returned (from strategy choice set)*

(n=234 obs)	DV = Avg Trustworthiness over all amounts trusted	DV = Avg Trustworthiness over all amounts trusted	DV = Avg Trustworthiness **for amounts ≥ $5** trusted
	(1)	**(2)**	**(3)**
Variable	**Coef (st. error)**	**Coef (st. error)**	**Coef (st. error)**
Constant	.19 (.09)**	.31 (.08)***	.41 (.08)***
Female (=1)	-.01 (.03)	-.003 (.03)	-.02 (.03)
Age	.001 (.003)	.0001 (.003)	-.001 (.003)
Depression score	-.02 (.02)	-.02 (.02)	-.02 (.02)
Anxiety score	.005 (.006)	.005 (.006)	.008 (.006)
Epworth score	.001 (.004)	.001 (.004)	.001 (.004)
Session #3	-.04 (.01)***	-.04 (.01)***	-.03 (.01)***
Morning Session (=1)	.001 (.03)	.002 (.02)	.01 (.03)
Morningness Score	-.001 (.002)	-.002 (.002)	-.002 (.003)
Circadian Mismatched (=1)	.0004 (.02)	-.004 (.02)	-.02 (.03)
Nightly Sleep week prior (min)	.0002 (.0001)*	---	---
Personal SD (min/night)	---	-.0002 (.0001)**	-.0003 (.0001)***
Wald chi-squared test (10)	12.84	15.60	18.24**

Notes: *,**, *** indicate significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test
Model 3 shows that Personal SD more strongly impacts trustworthiness when a strong initial trust signal is received.

Figure S2: Trustworthiness Distributions (by sleep condition)





Notes: This Fig. S2 does not control for other variables or take into account the repeat-administration nature of the data and is for illustrative purposes only. ROR is the rate-of-return on the first-mover's investment or amount trusted. Because the experimenter triples whatever amount is initially trusted, a one-third trustworthiness level will return back the invested capital to the first-mover. The Payoff Equal amount takes into account that only the first-mover is endowed with the initial $10 to trust or not. For example, if all $10 is trusted, then the second-mover possesses $30 (and the first mover possesses zero). The second-mover will have to send back 50% to guarantee equal payoffs of $15 for each.

Table S2-S6 Note: Results in Tables S2-S6 are also robust to the exclusion of extreme sleeper subjects who were personally sleep deprived > 2.5 hours (SR condition) or < ½ hour (WR condition). Standard errors increase slightly, though key results are still statistically significant at $p < .10$ or better. The magnitude of the estimated effects from removing the more extreme sleepers, not surprisingly, is slightly reduced.

Table S7: Instrumental Variables Estimation to examine sleepiness mediating effects.

Instrumental Variables 2SLS Regression of Behavioral Outcomes
(Karolinska sleepiness scores, or KSleepy, is instrumented)

First Stage Regression: KSleepy instrumented in first stage regression with *Session#3*(-), *Female*(+), *Age*(+), *Anxiety, Depression*(-), *PersonalSD*(+), *Epworth Score*(+), *Morning Session*(-), *MEQ score, Mismatch*(+).
(parentheses highlight significant predictors (p≤.10) and the direction of their effect on sleepiness in the first stage regression).

Standard errors clustered on subject (2 observations per subject)

Variable	**Ultimatum $$ Offer**	**Ultimatum $$ MAO**	**Dictator $$ Offer**	**Trust person $$ Offer**	**Trust algorithm $$ Offer**	**Trust-worthiness % passback**
***KSleepy*(instr)**	-.17 (.08)**	-.04 (13)	-.46 (.16)***	-.35 (.16)**	-.17 (.17)	-.02 (.01)**
Session #3	-.25 (.10)**	-.60 (.14)***	-.88 (.22)***	-.79 (.27)***	-.10 (.25)	-.04 (.02)***
Female	-.13 (.15)	-.59 (.31)*	.42 (.37)	-.002 (.04)	-.41 (.45)	.01 (.03)
age	-.01 (.02)	-.06 (.04)	-.02 (.04)	-.02 (.04)	-.005 (.04)	.0001 (.002)
Depression score	.06 (.09)	.002 (.19)	-.30 (.22)	-.27 (.27)	-.34 (.28)	-.02 (.02)
Anxiety score	-.03 (.03)	.05 (.07)	.12 (.07)	.10 (.07)	.09 (.07)	.005 (.005)
Constant	5.91 (.71)***	4.83 (1.19)***	5.93 (1.31)***	7.44 (1.22)**	5.75 (1.27)***	.38 (.09)***
N	234	236	237	230	236	234
Wald X^2	10.42	30.97***	25.45***	12.19*	5.89	11.91*

Notes: *,**, *** indicate significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test.
Ksleepy scores are the average of the pre- and post-decision Karolinska self-report sleepiness ratings for each subject.
The same 2SLS model run using the alternative Trustworthiness variable (i.e., average percentage passed back on all possible first-mover trusted amounts of at least half the pie), shows similar results to the Trustworthiness model above, except that the magnitude of the instrumented KSleepy variable is a bit larger in magnitude (-.023 vs -.019) and estimated a bit more precisely (p=.03 vs p=.038). This is consistent with what is reported in the main text that the impact of sleep restriction (via the mediating variable, self-reported sleepiness) to reduce trustworthiness is somewhat magnified for those decisions involving a more sizeable and clear signal of trust by the first-mover.

References (*32-42*)