McKenna, Benjamin., David L. Dickinson, Henry Orff, and Sean P.A. Drummond (2007) “The Effects of One-Night of Sleep Deprivation on Known-Risk and Ambiguous-Risk Decisions.” **Journal of Sleep Research**, vol. 16, no. 3: pp. 245-52. Published by Wiley-Blackwell. The definitive version is available at www3.interscience.wiley.com (ISSN: 0962-1105) Aug. 17, 2007

The effects of one night of sleep deprivation on known-risk and ambiguous-risk decisions

Benjamin S. Mckenna, David L. Dickinson, Henry J. Orff, Sean P. A. Drummond

ABSTRACT

Sleep deprivation has been shown to alter decision-making abilities. The majority of research has utilized fairly complex tasks with the goal of emulating ’real-life’ scenarios. Here, we use a Lottery Choice Task (LCT) which assesses risk and ambiguity preference for both decisions involving potential gains and those involving potential losses. We hypothesized that one night of sleep deprivation would make subjects more risk seeking in both gains and losses. Both a control group and an experimental group took the LCT on two consecutive days, with an intervening night of either sleep or sleep deprivation. The control group demonstrated that there was no effect of repeated administration of the LCT. For the experimental group, results showed significant interactions of night (normal sleep versus total sleep deprivation, TSD) by frame (gains versus losses), which demonstrate that following as little as 23 h of TSD, the prototypical response to decisions involving risk is altered. Following TSD, subjects were willing to take more risk than they ordinarily would when they were considering a gain, but less risk than they ordinarily would when they were considering a loss. For ambiguity preferences, there seems to be no direct effect of TSD. These findings suggest that, overall, risk preference is moderated by TSD, but whether an individual is willing to take more or less risk than when well-rested depends on whether the decision is framed in terms of gains or losses.

ARTICLE

Total sleep deprivation (TSD) has been shown to cause cognitive performance deficits in a wide range of domains, including alertness, attention, motor responses, inhibition, and many working memory functions (Chee and Choo, 2004; Chuah et al., 2006; Dinges et al., 1997; Pilcher and Huffcutt, 1996). One area not well studied, though, is the effect of TSD on decision making, which involves both convergent and divergent skills (Harrison and Horne, 2000). While early studies assumed that decision making is too complex to be sensitive to the effects of TSD because of the demanding and highly motivating conditions (Corcoran, 1963; Horne and Pettitt, 1985; Wilkinson, 1965, 1992), the few studies that have directly examined this question suggest that TSD does indeed impact decision making.

The majority of research studying the effects of TSD on decision making have utilized fairly complex tasks with the goal of emulating ’real-life’ scenarios (Harrison and Horne, 1999; Linde et al., 1999; Wimmer et al., 1992). For example, Harrison and Horne reported a business simulation game where subjects needed to market a business and earn a profit by reacting to other players and external information provided about the ’market place’. In that study, subjects were less successful running the business while sleep deprived. However, due to the design of the task, that study was unable to identify any particular decisions or particular components of decision making that were specifically impaired by TSD. Other studies have administered tasks aimed at more specific aspects of decision making, such as the Iowa Gambling Task (IGT). The IGT emphasizes the learning of reward and punishment associations to guide ongoing decision making. In the IGT, subjects select cards from among a series of decks and either win or lose money based on the card drawn. There are two decks of cards which carry an overall loss and two decks which carry an overall gain. The cards that carry an overall loss offer immediate high rewards with a concomitant risk of occasional very high loss. The desks with an overall gain, on the other hand, have smaller immediate rewards, but lower risk of a loss. Typically, subjects learn to avoid the former, riskier decks and focus on the latter decks carrying an overall gain (Bechara et al., 1994, 2005). Harrison and Horne found that sleep-deprived subjects are less concerned with negative consequences when faced with high rewards on the ’overall loss’ desk during this task (Harrison and Horne, 1998, 2000). More recently, Killgore et al. (2006) similarly reported that 49.5 h of TSD impairs the ability to weigh immediate short-term benefits against long-term penalties on the IGT. These studies demonstrate that decision-making processes are, in fact, modified during sleep deprivation. The work on the IGT suggests that individuals may be willing to take more risk during TSD than they would when well rested, but the IGT entails a complex assessment of risk taking (Bechara et al., 2005), and therefore only provides an indirect assessment. Additionally, during the IGT subjects are asked to make choices in an environment with missing information (i.e. there are unknown probabilities in the odds of winning or losing) and thus probability assessments are confounded with risk preferences. There are no published studies of which we are aware that utilize a simple measure to directly study risk preferences during TSD. The aim of the present study was to measure potential changes in risk preference, along with the preference for ambiguity in risk decisions, during TSD.

The study of risk in the context of decision making has been an interest in microeconomics for the last century. However, it has only received attention from psychologists in the last few decades (Trepel et al., 2005). The concept of risk varies depending on the context and situation. In economics, risk is commonly associated with the variance of the outcome (pay-off) distribution. For example, one gamble may offer $80 if a coin shows heads and $20 if shows tails while another may offer $60 if a coin shows heads and $40 if shows tails. In both gambles, the expected pay-off is $50, but as the variance is higher in the first gamble, that gamble carries higher risk. Real-world decisions that illustrate these concepts of risk and pay-offs would include investment/savings decisions, surgical alternatives or military operational decisions. Two variables that may influence one’s preference for risk when it is defined in this manner are: (1) whether the gamble involves decisions about gains or about losses; and (2) whether all the relevant odds are known or if some are unknown. When some of the odds are unknown, usually due to missing information, this is said to introduce

’ambiguity’. So, with ambiguity, the level of risk is unclear, as if the coin-flip involved a coin that may or may not have a both heads and tails side (i.e. it is unknown to the decision maker). With investment/savings choices, for example, if companies included in a mutual fund are unknown, then the choice to invest in that mutual fund involves an ambiguous gamble.

Decision-making research has shown that, when the odds are known, individuals are risk seeking for losses but risk avoiding for gains (Kahneman, 2003; Kahneman and Tversky, 1979; Smith et al., 2002). This means that, on average, if faced with two options that can each lead to a loss, individuals choose the more risky option, and if faced with two options that can each lead to a gain, individuals choose the less risky option. So, if someone is trying to minimize a loss, they will take a more risky option if they believe it may mitigate against the size of the loss. If, on the other hand, someone is trying to maximize overall gain, they are likely to take the less risky choice so as to increase the likelihood of gaining at least something. Ambiguity preference is less well studied, with some inconsistent results. However, there is some consensus that individuals are ambiguity avoiding for gains while ambiguity neutral for losses. This means individuals choose a known gamble over an ambiguous one when faced with possible gains, but they chose the option with known odds and the option with ambiguous (i.e. not fully known) odds equally often when faced with losses (Cohen et al., 1987; Curley and Yates, 1985; Hsu et al., 2005; Smith et al., 2002).

To assess the degree to which risk and ambiguity preferences change during sleep deprivation, we used the Lottery Choice Task (LCT) reported by Smith et al. (2002). This task assesses risk and ambiguity preference separately for decisions involving potential gains and those involving potential losses. Based on the general literature on risk preference and on TSD research with the IGT, we hypothesized that: (1) well-rested subjects would be risk seeking for losses and risk avoiding for gains, while ambiguity neutral for losses and ambiguity avoiding for gains; and (2) sleep-deprived subjects would become more risk seeking for both gains and losses.

Methods

Subjects and conditions

A total of 26 young adults performed this task as part of two larger sleep-deprivation studies (eight women; mean age: 23.5 ± 5.3 years; education: 14.7 ± 1.7 years). Additionally, 12 young adults participated in a control group that involved no sleep deprivation (six women; mean age: 24.2 ± 4.3 years; education: 15.2 ± 2.4 years). All subjects in both groups were healthy as established by a physical examination, routine laboratory tests, and interviews covering medical and psychiatric histories. Subjects completed sleep diaries and wore actigraphs for 2 weeks prior to the study to document adherence to regular sleep–wake schedules. Subjects in the experimental group obtained a nightly average of 408 ± 69 min of sleep for the week prior to the study. Subjects in the control group obtained a nightly average of 421.8 ± 71 min of sleep. All subjects were tested twice, on two consecutive days, at approximately the same time of day in the morning. The control group had a normal night of sleep at home in between test administrations. The sleep-deprived experimental group had an average of 22.7 ± .58 h of TSD between test administrations.

Lottery Choice Task

The LCT used in the present study is a shortened version of one used by Smith et al. (2002), which is based on Ellsberg (1961). The LCT examines risk and ambiguity preference by asking subjects to make a series of choices between two gambles with equal expected pay-offs but different risk levels. The LCT was comprised of four conditions, as decisions focused on either risk or ambiguity and involved either gains or losses: Known-risk decisions involving gains (RG), known-risk decisions involving losses (RL), ambiguous-risk decisions involving gains (AG), and ambiguous-risk decisions involving losses (AL). See Fig. 1 for examples of the choices presented to subjects. In the RG and RL conditions (e.g. Fig. 1A), if a subject chooses the lower risk gamble, that decision is classified as being risk averse, and if the higher risk option is taken, that decision is classified as risk seeking. As discussed above, when one of the gamble choices does not clearly define the odds of each outcome, the gamble is said to be ambiguous (e.g. Fig. 1B). To examine whether subjects avoid or seek ambiguity, the LCT includes conditions where one of the gambles in each paired choice is ambiguous (see below for a description of how seek/avoid is determined for ambiguous gambles). Finally, because preferences may differ when gambles involve losses relative to gains, the LCT includes decisions where both options involve losing money and others where both options involve gaining money. This is true for both decisions with known odds and those with ambiguous odds.

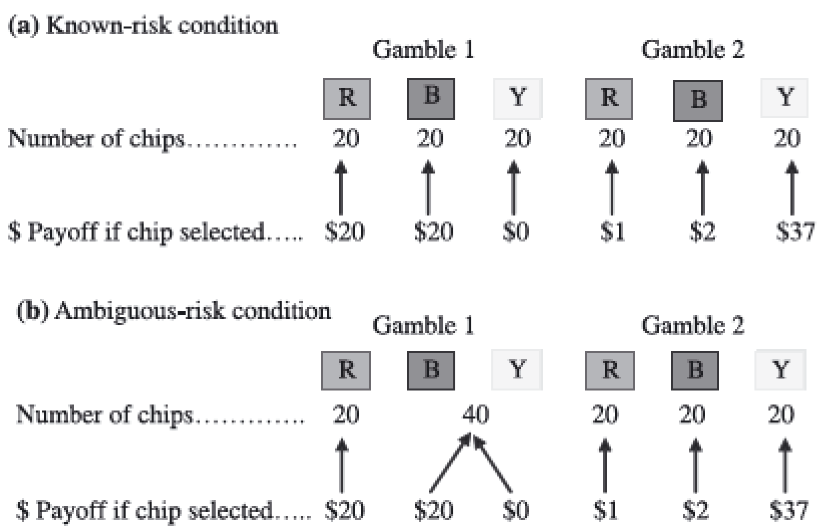

Figure 1. Lottery Choice Task paradigm two examples of the stimuli used to present the gamble choices to subjects. (a) An example from the known-risk decisions involving gains (RG) condition. The gamble on the left has a smaller variance and is considered less risky than the gamble on the right. (b) An example from the ambiguous-risk decisions involving gains (AG) condition. The gamble on the left is ambiguous, while the gamble on the right is identical to the riskier gamble in the RG condition. The three boxes indicate the color of the chip associated with each gamble. Note that only examples from the 'gains' conditions are shown. Loss conditions are identically structured, but have negative dollar amounts associated with the chips. [R] is for red, [B] for blue, and [Y] for yellow. This figure also serves to show an example of a known-risk and an ambiguous-risk decisions that were paired for calculating ambiguity preference (see text for detailed explanation), as each gamble 2 has an identical pay-off variance.

Ten decisions were made on gambles in a known-risk condition (five for gains and five for losses) and 10 decisions were made on gambles in an ambiguous-risk condition (five for gains and five for losses). For all choices, subjects were shown two containers of red, blue, and yellow chips, where the number of each color was defined within the gamble stimuli (see Fig. 1). For known-risk decisions, subjects were asked to decide between two risky options that each had known (but different) odds of either winning (RG) or losing (RL) specific amounts of money, but with identical expected pay-offs (see Fig. 1A). In both choices there are 20 red, 20 blue, and 20 yellow chips in the container, but the monetary value of each color is different in gamble 1 compared with gamble 2. The arrows in Fig. 1A indicate the amount of money that a subject can gain if that color chip is chosen. Gamble 1 is less risky than gamble 2 because the variance of the gains is smaller for gamble 1. Thus, if a subject chooses gamble 1, they are determined to be avoiding risk for that specific decision. If, on the other hand, they choose gamble 2, then they are seeking risk. The known-risk decisions involving losses follow the same format, but the monetary values are negative rather than positive.

Again, following Smith et al., the ambiguous-risk condition decision stimuli are identical to the known-risk condition decision stimuli with the exception that the exact numbers of blue and yellow chips in gamble 1 are unknown (see Fig. 1B). In the ambiguous-risk condition, the arrows from the monetary outcome for both the yellow and blue chips converge on 40. This indicates that there were 40 total blue and yellow chips, but the subject did not know the exact number of each individually (e.g. there could have been eight blue and 32 yellow chips or 19 blue and 21 yellow chips, etc.). As is done in Fig. 1, each set of choices in the ambiguous-risk condition was matched with a similar set of choices from the known-risk condition such that each matched item shared a common gamble 2. Thus, the ambiguous choice was always gamble 1. Assessment of ambiguity preference then required considering both of the matched decisions (risk and ambiguity) and use of the assumption of transitivity (Smith et al., 2002). Transitivity is the preference assumption that states that if A is preferred to B, and B is preferred to C, then A is preferred to C. In the context of this task, if a subject avoids the riskier gamble in the known-risk condition, but chooses the riskier gamble in the matched ambiguous-risk condition, s/he would be determined to be avoiding ambiguity (because to again avoid risk would have required the subject to choose the ambiguous gamble). Alternatively, if a subject chose the riskier gamble in the known-risk condition and then chose the ambiguous gamble in the matched ambiguous-risk condition s/he would be determined to be seeking ambiguity (because to again seek risk would have required them to choose the non-ambiguous gamble – gamble 2 in Fig. 1B). Finally, if the subject chose the riskier gamble in both conditions, or avoided risk in both conditions, then their ambiguity preference was deemed indeterminate. This is because it is unclear, in the first case, whether the subject actively avoided ambiguity or simply again sought risk during the ambiguous-risk condition.

Procedures

Subjects performed two distinct decision-making tasks (one of which was the LCT) in both the first and second testing sessions. For the LCT, the five decisions to be made for each condition were presented on a single piece of paper, and the order of conditions was randomly counterbalanced for each session. Similarly, two different versions of the task were developed and the order of presentation was counterbalanced across subjects. All subjects began the experiment with an endowment of $25. They were told that their decisions would either increase or decrease this amount and that they would be paid their final balance at the end. They were also informed of the method by which their decisions would be played out. Specifically, at the end of the second session, a single decision from the gains conditions (RG and AG) and a single decision from the loss conditions (RL and AL) for each of the two sessions (four total decisions) were randomly selected and the subject’s preferred gamble choice (gamble 1 or gamble 2) was played out to determine final cash pay-off from the LCT. For each of the four decisions selected, the subject blindly drew one chip from the relevant container and either won or lost the amount of money associated with that chip. This payout procedure was only conducted following the second administration of the task. Subjects were not given any feedback between sessions (i.e. there was no determination of winnings or losses) so there would not be an opportunity for knowledge of money won or lost in the first session to alter decisions made in the second session. For ethical reasons, subjects could not owe the experimenters at the end of the study, so any negative payout balance was rounded to $0.

Data Analysis

The raw count data (i.e. the number of risk- or ambiguity-seeking decisions made per condition) were converted into proportional data. However, these data had significantly non-normal distributions on both nights (based on the kurtosis and skewness of the distributions). Therefore, the data were converted into risk preference and ambiguity preference scores. For the known-risk conditions (RG and RL), this was done by taking the proportion of the risk-avoiding responses minus the proportion of risk-seeking responses for each condition. Thus, a score of zero indicates someone who is risk neutral, increasing scores in the positive direction indicate greater risk avoidance, and increasing scores in the negative direction indicate greater risk seeking. The same procedure was followed for the ambiguous-risk conditions (AG and AL) to determine ambiguity preference. Using this ’preference’ metric has two advantages: (1) the distribution of these scores was normal; and (2) this is the same way in which Smith et al. (2002) treated the data in their study.

Group analyses were conducted separately for the known-risk and ambiguous-risk conditions. For both, the initial omnibus analysis was a 2 × 2 × 2 mixed-effects anova (frame by session by group). The effect of interest here was the three-way interaction, as it evaluated whether the two groups showed differential patterns of change across sessions. To follow-up a significant interaction, we examined the frame-by-session two-way interaction separately for each group with repeated measures anova. If that interaction was significant, we then examined the source of the interaction by testing the main effect of session for each level of the variable frame (i.e. gains and losses). This tests whether there is a session effect (e.g. an effect of TSD in the experimental group) for either gains or losses. If the two-way interaction was not significant for a given group, we examined the simple main effects of session and frame. For the control group (where we anticipated a non-significant interaction) the session main effect addresses whether this task shows repeated administration effects (e.g. learning effects), while the frame main effect tests whether our subjects show the same preference differences across gains and losses as typically reported in the literature.

Finally, to confirm that there were no baseline differences between the groups at session 1 that may confound any potential differential session effects observed in the preceding analysis, we conducted a between-groups manova for the session 1 data where the response variables were the preference scores for the four conditions (RG, RL, AG and AL). If this manova was significant, univariate analyses for each condition were conducted.

Results

See Table 1 for the risk and ambiguity preference scores from each group in each session.

Table 1 Group mean ± SE

Group	*RG*	*RL*	*AG*	*AL*
Well-rested experimental group	0.49 ± 0.10	−0.66 ± 0.11	0.18 ± 0.05	−0.08 ± 0.05
Sleep-deprived experimental group	0.18 ± 0.14	−0.49 ± 0.13	0.02 ± 0.09	−0.04 ± 0.07
Session 1 control group	0.47 ± 0.10	−0.63 ± 0.02	0.10 ± 0.06	−0.13 ± 0.12
Session 2 control group	0.40 ± 0.12	−0.80 ± 0.09	0.08 ± 0.06	−0.15 ± 0.08

The conditions are known-risk decisions involving gains (RG), known-risk decisions involving losses (RL), ambiguous-risk decisions involving gains (AG), and ambiguous-risk decisions involving losses (AL) for both the experimental group and the control group.

Known-risk condition (RG and RL)

The omnibus mixed model ANOVA (frame by session by group) showed a significant three-way interaction ($F_{1,36}$ = 5.70, P = 0.022, partial η^2 = 0.137). As stated above, this was followed by analyzing the frame-by-session two-way interaction for each group.

For the control group, the frame-by-session interaction was not significant (P = 0.536, partial η^2 = 0.036; see Fig. 2). The main effects for the control group revealed a significant effect of frame ($F_{1,25}$ = 45.34, P < 0.001, partial η^2 = 0.805), but no significant change across sessions (P = 0.359, partial η^2 = 0.077). The control group showed risk aversion for gains and risk seeking for losses.

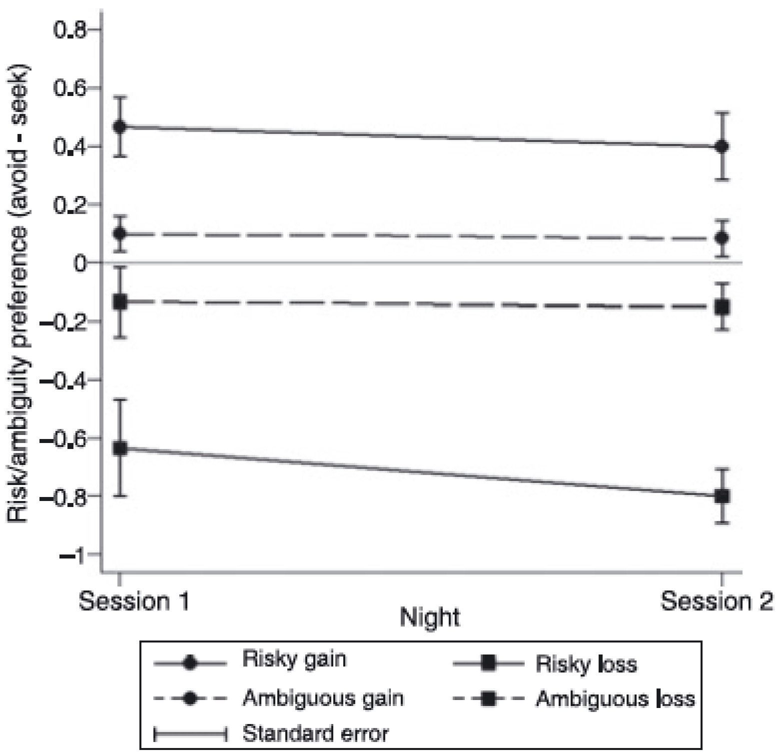

Figure 2. Change in preference following repeated administration to control group. The plotted points indicate the risk and ambiguity preference scores (measured in proportions) for each frame type for both sessions. Positive values indicate avoiding behavior, negative numbers indicate seeking behavior, and zero indicates risk or ambiguity neutrality.

For the experimental group, the frame (RG versus RL)-by-session (well-rested versus TSD) interaction was significant ($F_{1,25}$ = 10.55, P = 0.003, partial η^2 = 0.297; see Fig. 3). Follow-up analyses focusing on the effect of session within frame showed that subjects became significantly less risk avoiding for gains after TSD (t_{25} = 2.30, P = 0.03, η^2 = 0.175). Subjects became less risk seeking for losses after TSD, although this change was not significant (t_{25} = −1.80, P = 0.084, η^2 = 0.115).

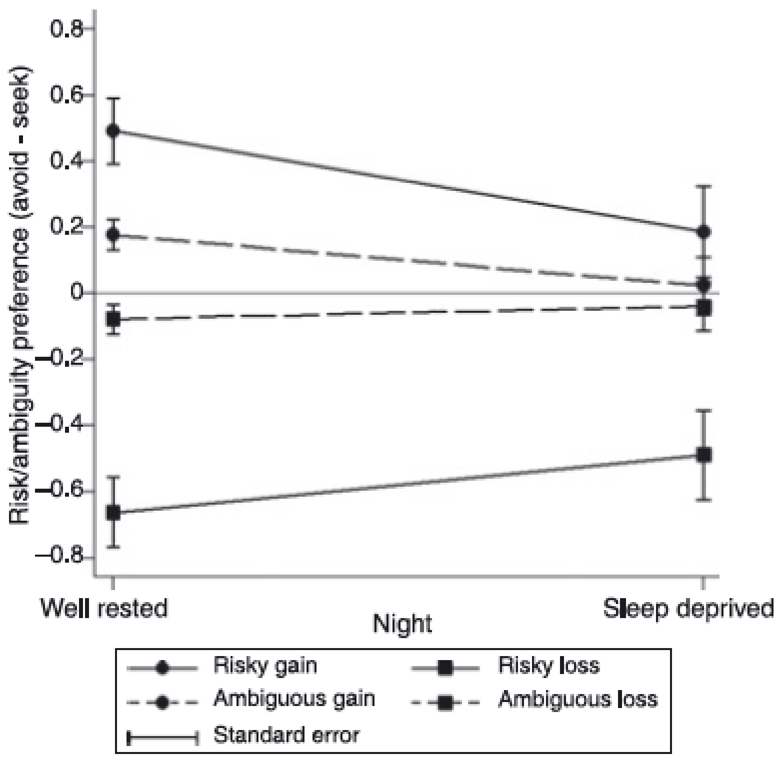

Figure 3. Change in preference following TSD in the experimental group. The plotted points indicate the risk and ambiguity preference scores (measured in proportions) for each frame type when well rested and after TSD. Positive values indicate avoiding behavior, negative numbers indicate seeking behavior, and zero indicates risk or ambiguity neutrality.

In examining baseline group differences at session 1, the MANVOA was not significant (Wilks'λ, P < 0.724; partial η^2 = 0.059), confirming there were no group differences at baseline (Table 1).

Ambiguous risk condition (AG and AL)

The omnibus mixed model ANOVA (frame by session by group) did not show a significant three-way interaction (P = 0.258; partial η^2 = 0.035). The only significant effect in this ANOVA was the main effect of frame ($F_{1,36}$ = 11.50, P = 0.002; partial η^2 = 0.242). Averaged across both groups and both sessions, subjects showed greater ambiguity-avoiding preferences for gains than for losses. To clarify this effect, simple main effects were conducted comparing ambiguity preferences for gains and losses to neutral (i.e. a preference score = 0). These analyses showed that subjects were ambiguity avoiding for gains (t_{37} = 2.38, P = 0.02, η^2 = 0.133) and ambiguity seeking for losses (t_{37} = −2.22, P = 0.03, η^2 = 0.118), although only the former would survive a Bonferroni correction for multiple comparisons, suggesting that subjects are actually ambiguity neutral for losses.

Payout information

The final payout amounts (including the endowment) for the experimental group were (mean ± SD) $26.23 ± 23.4, with a range of $0–67. Final payout amounts for the control group were $21.25 ± 24.4, with a range of $0–55.

Discussion

The LCT used in the present study assessed preference for both risk and ambiguity by having participants make a series of decisions between two gambles to maximize pay-offs. Consistent with the large body of literature on risk preference (Kahneman, 2003; Kahneman and Tversky, 1979; Smith et al., 2002; Tversky and Kahneman, 1992), the results of the control group and the well-rested condition in the experimental group demonstrate that subjects are risk avoiding for gains and risk seeking for losses in the known-risk condition. For the ambiguous-risk condition, well-rested subjects are ambiguity avoiding for gains and ambiguity neutral for losses. Together, these results replicate the study of Smith et al. (2002). The interactions of night (normal sleep versus TSD) by frame (gains versus losses) demonstrate that following as little as 23 h of TSD, the prototypical response to decisions involving risk is altered. Sleep-deprived subjects are less risk avoiding for gains and less risk seeking for losses. In other words, following TSD, subjects were willing to take more risk than they ordinarily would when they were considering a gain, but less risk than they ordinarily would when they were considering a loss. For ambiguity, there seems to be no direct effect of TSD on decisions involving uncertainty.

TSD changes risk preferences

Overall then, it appears that one night of TSD moderates sensitivity to risk. The change in risk preferences following sleep loss may reflect a change in decision-making strategies that varies for gain versus loss. For the known-risk condition, the hypothesized increase in risk-seeking behavior was observed in the RG condition, but not the RL condition. The RG data are also consistent with prior studies of the IGT showing that subjects seem to favor risk during sleep deprivation (Harrison and Horne, 1998; Killgore et al., 2006). One difference between the IGT and the LCT task used here is that the present task allows for the differentiation between decisions involving gains and those involving losses while the IGT does not. Our data suggest the change in risk preference during TSD depends on whether the decision is framed in terms of gains or in terms of losses. As the IGT places an emphasis on gains, that may explain the increased risk seeking on the IGT during sleep deprivation. Thus, our data demonstrate the importance of analyzing the framing of decisions (i.e. gains versus losses) when trying to understand risk preference during sleep loss.

Unlike for the known-risk condition, subjects were essentially always neutral towards ambiguity (statistically, they did show a slight preference to avoid ambiguity for gains). It may be that the missing information of an ambiguous gamble results in no stable strategy. Individuals may not know exactly how to assess risk when faced with ambiguity and thus not respond with any consistent pattern at the group level. The exception to this interpretation in the present study was the fact the subjects were slightly, but significantly, ambiguity avoiding for decision involving gains. The significant difference from neutrality (i.e. an ambiguity preference score of zero) should be interpreted with caution considering that there is no effect of TSD and the effect is very small (Cohen, 1988). When compared with risk, much less research has been conducted on ambiguity, and we are not aware of other studies directly assessing this construct during sleep deprivation.

Potential cognitive mechanisms

The exact cognitive mechanism underlying changes in risk preference with sleep deprivation cannot be ascertained from this study. Nonetheless, one way to approach this question is to consider whether a common mechanism can explain the changes seen here both for risky decisions involving gains and those involving losses, as well as the previous work with the IGT. For example, in all cases, one can interpret the data as showing that individuals become less sensitive to risk following sleep loss. This may be due to an impaired ability to accurately assess risk (e.g. calculation of the odds of various outcomes). If subjects view the same situation as less risky after TSD, even with well-defined gambles, the predicted outcome would be exactly what we report: less risk avoidance for gains and less risk seeking for losses. Alternatively, it may be that risk simply plays a smaller role in the decision-making process during TSD than when individuals are well rested, which would equate to more of a true desensitization process. A third possibility is that subjects may subjectively weigh the value (or utility) of the possible outcomes as more extreme (better for gains and worse for losses) during TSD. This, too, would be expected to lead to more risk taking if the individual felt an outcome would be extremely good (i.e. a gain) and less risk taking when an outcome was valued as extremely bad (i.e. a loss). Finally, it is possible the changes observed here are not related to TSD-induced changes in risk preference, but rather to an increase in random responding or reduced motivation on the task. We do not believe this is the case, though, for at least three reasons. First, in examining the response patterns, there does not appear to be obviously random or effortless responding (e.g. no one selected all the ’left-hand column’ gambles across all choices). Second, we conducted a series of binomial tests to determine if changes in preferences after TSD were random. We found that: (a) whether a preference changed or not, and (b) the direction of that change (towards or away from the riskier option) was not random for both RG and RL conditions (each $P < 0.01$). Third, upon debriefing at the end of the experiment, subjects consistently reported that this was one of the most interesting and engaging aspects of the study, although this was not specifically quantified.

Cognitive mechanisms leading to altered risk preference most likely result from changes in the actual neurophysiology of reward systems in the brain (Gomez-Beldarrain et al., 2004; Knutson and Peterson, 2005; Rolls, 2000; Trepel et al., 2005). One way to test these potential mechanisms might be to examine functional changes during sleep loss in the neural networks important for evaluation of risk and/or the expectancy of outcomes during decision making. Prior work in this area has led to interesting findings that seem to show that activation of specific areas of the brain correlate with factors such as risk assessment (ventral striatum, prefrontal cortex and amygdala), risk preference (dorsolateral prefrontal cortex), decision making (orbital frontal cortex) and reward (ventral striatum, prefrontal cortex, amygdala and hippocampus). Additional studies are needed to help better identify the relationship between these brain regions and objective measures of change in risk preference associated with TSD.

Operational implications

Regardless of the exact mechanism responsible for TSD-related changes in risk preference, these data hold implications for risk management in the operational context. For example, emergency personnel, doctors, and military personnel often must make decisions while sleep-deprived that directly influence lives. Business professionals who are traveling may need to enter negotiations or make strategic decisions while jet-lagged and sleep deprived. Even in a more mundane setting, parents of young babies make many decisions every day in a variety of contexts that could be influenced by a lack of sleep. One important point this study raises is that while, in general, sensitivity to risk seems to be moderated or blunted by sleep deprivation, the exact effect of sleep deprivation on risk-related decisions depends on how those decisions are framed. Whether an individual sees a decision as involving gains or losses influences whether they are more or less willing to take risk. Thus, it may be important to help decision makers frame their decisions in the light required by a given context (e.g. is it better for a surgeon to consider that a risky procedure will prolong life or that it may result in death?). Furthermore, once a mechanism can be identified that underlies changes in risk preferences, it may be possible to develop training regimens to mitigate against those changes.

Limitations

There are some limitations with the present study which should be addressed. First, because the order of the sleep nights (normal sleep versus TSD) was fixed, there may be order effects which influence the reported changes in risk preference. The fixed order was a function of the design of the larger studies from which these data were drawn. To help control for order effects, though, a control group was added to examine any repeated administration effects with the LCT. The results from the control group suggest that there were no systematic changes in risk preference with repeated administration of the test. Thus, changes seen in the experimental group can be more confidently ascribed to TSD effects. Second, determination of ambiguity preferences required using the assumption of transitivity, which results in a number of individual decisions being classified as ’indeterminate’ with respect to ambiguity preference. Therefore, the total number of decisions used in the ambiguous-risk condition was reduced relative to the known-risk condition. The related loss of power may explain why there was no change across nights for the ambiguous condition. However, we do not believe this is likely to be the case, as the well-rested results are consistent with previous work (Smith et al., 2002). Nonetheless, further research could address the limitations in the present design regarding the assessment of ambiguity preferences by increasing the overall number of decisions made (which would result in a greater number of ’usable’ decisions) and/or by using a task that does not require the assumption of transitivity. Third, we administered relatively few trials per condition, raising the issue of whether we obtained a stable measure of preference scores. The lack of significant change in the control group data, though, suggests a reasonable level of stability. Regardless, future studies will likely want to increase the number of trials from which a risk or ambiguity preference score is obtained to increase confidence in the stability of the measures. Fourth, we focused here on very specific aspects of decision making with the goal of better isolating the impact of TSD on components of decision making than pervious studies. However, this also means that the types of decisions made by our subjects do not necessarily perfectly reflect those made outside the laboratory. For example, it is rare that one makes a decision involving risk where there is not the potential for both gains and losses. Future studies will want to systematically alter the types of decisions made in the context of sleep deprivation to bring them closer and closer to those made in everyday life, perhaps eventually incorporating actual simulations of real scenarios. Prior to that, though, research needs to experimentally study all the relevant aspects (or as many as possible) of those 'real-life' decisions so the interpretations of such simulation studies will be more valid and reliable. Fifth, we only used one task to assess the effects of TSD on risk and ambiguity preference in this study. Anytime only a single method is used to measure a given construct, there is concern about finding results that may be specific to that instrument. Future studies will want to use multiple methods for assessing risk preferences and changes in preferences related to sleep deprivation.

In summary, we examined the effects of 23-h TSD on risk and ambiguity preferences during decision making. Results showed that, overall, risk preference is moderated by TSD, but whether an individual is willing to take more or less risk than when well-rested depends on whether the decision is framed in terms of gains or losses. This is the first study to specifically assess risk preference during TSD separately for gains and for losses, and the first to assess TSD effects on risk preferences without confounds of missing information, and our results hold important implications for risk management in operational settings.

Acknowledgements

The authors wish to thank the US National Academy of Sciences and the Japanese Society for the Promotion of Sciences for sponsoring the Japanese-American Beckman Frontiers of Science Symposium, which led to this research collaboration. This study was funded in part by the US Department of the Army award #DAMD17-02-1-0201 and NIH M01 RR00827. The US Army Medical Research Acquisition Activity is the awarding and administering acquisition office. The content herein does not necessarily reflect the position or policy of the Government, and no official endorsement should be inferred.

References

Bechara, A., Damasio, A. R., Damasio, H. and Anderson, S. W. Insensitivity to future consequences following damage to human prefrontal cortex. Cognition, 1994, 50: 7–15.

Bechara, A., Damasio, D., Tranel, D. and Damasio, A. R. The Iowa gambling task and the somatic marker hypothesis: some questions and answers. Trends Cogn. Sci., 2005, 9: 159–162.

Chee, M. W. and Choo, W. C. Functional imaging of working memory after 24 hr of total sleep deprivation. J. Neurosci., 2004, 24: 4560–4567.

Chuah, L. Y. M., Venkatraman, V., Dinges, D. F. and Chee, M. W. The neural basis of interindividual variability in inhibitory efficiency after sleep deprivation. J. Neurosci., 2006, 26: 7156–7162.

Cohen, J. Statistical Power Analysis for the Behavioral Sciences. Lawerence Erlbaum Associates, Hillsdale, NJ, 1988.

Cohen, M., Jaffray, T. and Said, T. Experimental comparisons of individual behavior under risk and under uncertainity for gains and losses. Organ. Behav. Hum. Decis. Process, 1987, 39: 1–22.

Corcoran, D. W. J. Doubling the rate of signal presentation in a vigilance task during sleep deprivation. J. Appl. Psychol., 1963, 47: 412–415.

Curley, S. P. and Yates, J. F. The center and range of the probability interval as factors affecting ambiguity preferences. Organ. Behav. Human Decis. Process, 1985, 36: 273–287.

Dinges, D. F., Pack, F., Williams, K., Gillen, K. A., Powell, J. W., Ott, G. E., Aptowicz, C. and Pack, A. I. Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 hours per night. Sleep, 1997, 20: 267–277.

Ellsberg, D. Risk, ambiguity and the savage axioms. Quart J Econ, 75: 643–669.

Gomez-Beldarrain, M., Harries, C., Garcia-Monco, J. C., Ballus, E. and Grafman, J. Patients with right frontal lesions are unable to assess and use advice to make predictive judgements. J. Cogn. Neurosci., 2004, 16: 74–89.

Harrison, Y. and Horne, J. A. Sleep loss affects risk-taking. J. Sleep Res., 1998, 7 (Suppl. 2): 113.

Harrison, Y. and Horne, J. A. One night of sleep loss impairs innovative thinking and flexible decision making. Organ. Behav. Hum. Decis. Process, 1999, 78: 128–145.

Harrison, Y. and Horne, J. A. The impact of sleep deprivation on decision making: a review. J. Exp. Psychol. Appl., 2000, 6: 236–249.

Horne, J. A. and Pettitt, A. N. High incentive effects on vigilance performance during 72 hours of total sleep deprivation. Acta Psychol., 1985, 58: 123–139.

Hsu, M., Bhatt, M., Adolphs, R., Tranel, D. and Camerer, C. F. Neural systems responding to degrees of uncertainty in human decision-making. Science, 2005, 310: 1680–1683.

Kahneman, D. A perspective on judgment and choice mapping bounded rationality. Am. Psychol., 2003, 58: 697–720.

Kahneman, D. and Tversky, A. Prospect theory – analysis of decision under risk. Econometrica, 1979, 47: 263–291.

Killgore, W. D., Balkin, T. J. and Wesensten, N. J. Impaired decision making following 49 h of sleep deprivation. J. Sleep Res., 2006, 15: 7–13.

Knutson, B. and Peterson, R. Neurally reconstructing expected utility. Games Econ. Behav., 2005, 52: 305–315.

Linde, L., Edland, A. and Bergstrom, M. Auditory attention and multiattribute decision-making during a 33 h sleep-deprivation period: mean performance and between-subject dispersions. Ergonomics, 1999, 42: 696–713.

Pilcher, J. J. and Huffcutt, A. I. Effects of sleep deprivation on performance: a meta-analysis. Sleep, 1996, 19: 318–326.

Rolls, E. T. The orbitofrontal cortex and reward. Cereb. Cortex, 2000, 10: 284–294.

Smith, K., Dickhaut, J., McCabe, K. and Pardo, J. V. Neuronal substrates for choice under ambiguity, risk, gains, and losses. Manage. Sci., 2002, 48: 711–718.

Trepel, C., Fox, C. R. and Poldrack, R. A. Prospect theory on the brain? Toward a cognitive neuroscience of decision under risk. Cogn. Brain Res., 2005, 23: 34–50.

Tversky, A. and Kahneman, D. Advances in prospect theory: cumulative representations of uncertainty. J. Risk Uncertain., 1992, 5: 297–323.

Wilkinson, R. T. Sleep deprivation. In: O. G.Edholm and A. L.Bacharach (Eds) Physiology of Human Survival. Academic Press, London, 1965: 399–430.

Wilkinson, R. T. The measurement of sleepiness. In: R. J.Broughton and R. D.Ogilvie (Eds) Sleep, Arousal and Performance. Birkhauser, Boston, MA, 1992: 254–265.

Wimmer, F., Hoffmann, R. F., Bonato, R. A. and Moffitt, A. R. The effects of sleep deprivation on divergent thinking and attention processes. J. Sleep Res., 1992, 1: 223–230.