THE INFLUENCE OF RESPIRATORY SINUS ARRHYTHMIA AND TIME OF DAY ON DECISION MAKING AND RISK TAKING

by

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TABLE OF CONTENTS

TABLE OF CONTENTS – *Continued*

TABLE OF CONTENTS – *Continued*

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES – *Continued*

ABSTRACT

Humans make a wide variety of decisions every day – from which route to take to the store to which job offer to accept. It has recently been proposed that two different systems, one affective and intuitive (System 1), the other logical and deliberative (System 2) interact to guide decision making. Neuroimaging research has supported this hypothesis, but other physiological indices of emotion regulation have been largely unexplored in the context of decision making. Respiratory Sinus Arrhythmia (RSA) is an index of cardiac vagal control, and has been shown to mediate emotion regulation, and vary under stress. Both impaired sleep and the phase of the sleep/wake circadian schedule also influence the expression and regulation of emotion. Sleep deprivation has been shown to lead to poor decision-making, but the relationship between sleep/wake circadian rhythms and decision making has been largely unexplored. Physiological indicators of emotion regulation (such as RSA) are likely to interact with sleep/wake circadian rhythms to influence the strategies used in decision making. The present study found that while time of day did not have an independent influence on decision making or risk taking, these functions appear to fluctuate with body temperature, a physiological index of circadian phase, with optimal performance occurring at higher body temperatures. Furthermore, while RSA appears to be unrelated to decision making and risk taking, circadian phase may influence physiological responses to stress (as measured by RSA) at different times of the day. In particular, morning-types may be more reactive to stress in the evening than during the day. Further research is needed to validate and clarify these findings.

BACKGROUND AND RATIONALE

Humans make a wide variety of decisions every day – from which route to take to the store to which job offer to accept. It has recently been proposed that two different systems, one affective and intuitive (System 1), the other logical and deliberative (System 2; (Stanovich & West, 2000) interact to guide decision making. Neuroimaging research has supported this hypothesis (e.g., (McClure, Laibson, Loewenstein, & Cohen, 2005), but other physiological indices of emotion regulation have been largely unexplored in the context of decision making. Respiratory Sinus Arrhythmia (RSA) is an index of cardiac vagal control, and has been shown to mediate emotion regulation (Porges, 1991, 1997), and vary under stress (Berntson et al., 1994; Berntson, Cacioppo, & Fieldstone, 1996). Both impaired sleep and the phase of the sleep/wake circadian schedule are also likely to influence the expression and regulation of emotion (Watson, 2000). There is evidence to suggest that sleep deprivation leads to poor decision-making (Killgore, Balkin, & Wesensten, 2006), but the relationship between sleep/wake circadian rhythms and decision making has been largely unexplored. Physiological indicators of emotion regulation (such as RSA) are likely to interact with sleep/wake circadian rhythms to influence the strategies used in decision making. The possibility that decision-making and cognitive processing may be influenced by circadian processes has enormous practical significance. In a society that values 24-hour operations, it is critical that we determine the conditions that are optimal and suboptimal for decision making. There are also important clinical implications of this research. Individuals with insomnia often worry and ruminate at night and are unable to turn off their “racing minds”. Insomnia may be a

direct consequence of the inability to solve problems when cognitive resources are less available.

Diurnal Rhythms of Cognitive Function

Two systems influence the time at which humans go to sleep at night and arise in the morning: a circadian system and a homeostatic system. Daily or circadian endogenous rhythms have been observed in all forms of life from bacteria and single-celled organisms to humans. In humans these rhythms exist for a wide variety of physiological, biochemical, and behavioral processes, including sleep, body temperature, and cognitive performance (Czeisler & Khalsa, 2000). The circadian rhythm of body temperature is closely tied to the sleep/wake rhythm in that our temperature is higher when we are awake and lower when we are asleep (Czeisler & Khalsa, 2000). Several studies investigating circadian variations in cognitive performance have found that performance varies with body temperature, such that when body temperature is at its lowest, performance is most impaired (Colquhoun, 1971; Kleitman, 1963). These initial studies found that participants' performance rose throughout the morning, peaked around mid-day, and declined in the evening and night hours. Tasks in these studies consisted mainly of motor and reaction time tasks. More recent studies show that other important areas of cognitive functioning such as vigilance, memory, mathematics processing, cognitive speed, and spatial orientation show similar effects (Monk et al., 1997).

Recently, Monk and colleagues (Monk et al., 1997) studied the relationship between cognitive performance and endogenous circadian rhythms (e.g. body

temperature, melatonin) in seventeen healthy adults. Participants were studies under controlled conditions, including constant wakeful bed rest, temporal isolation, and homogenized meals, for 36 hours. During this time, rectal temperature was measured every minute, and performance was assessed every hour. On even-numbered hours, a visual vigilance task was performed, and on odd-numbered hours, performance on serial search, verbal reasoning, and manual dexterity was assessed. Results indicated that performance on most measures was positively correlated with body temperature, with better performance occurring when body temperature was highest, and declines in performance as body temperature dropped. Furthermore, subjective measures of alertness did not account for the relationship between body temperature and performance, suggesting that variations in performance were not simply due to rhythmic variations in subjective alertness.

Cognitive function and self-reported circadian phase. In addition to changes in cognitive function observed across physiologically measured circadian phase, self-reported circadian phase has been shown to impact variations in cognitive function over the course of the day. This self-reported circadian phase is typically measured by the Horne-Östberg Morningness-Eveningness Questionnaire (MEQ; (Horne & Ostberg, 1976), which allows for individuals to be classified as “morning types”, “evening types”, or “neither types” based on the time of day that they believe is optimal for their performance of various activities (see Methods section for a full description of the MEQ).

Horne, Brass, and Pettitt (Horne, Brass, & Pettitt, 1980) first studied this relationship using a simulated production-line inspection task. The task was given to a

group of ten “morning types” and a group of ten “evening types” at fifteen time points (three times per day over five days) across different times of the waking day (between 8:00am and 10:00pm). The investigators also measured oral temperature each time the task was given. The task employed for the study consisted of participants “sitting at a conveyor belt and rejecting faulty items” (p. 30). The main outcome variables of this task were the number of correctly rejected faulty items and the number of incorrectly rejected perfect items. Results indicated that there were no differences between groups or across time points in the amount of incorrectly rejected perfect items; a finding likely due to the low incidence of this type of error. When the investigators examined the number of items that were correctly rejected during the task, a different pattern emerged for morning types versus evening types. In morning types, performance declined over the course of the day (i.e., was at its best in the morning and got worse as the day progressed), whereas in evening types, performance improved (i.e., was at its worst in the morning and got better as the day progressed). Furthermore, performance was positively correlated with body temperature in evening types (i.e., performance was better at higher temperatures), consistent with the literature described above. In morning types, body temperature and performance were negatively correlated (i.e., performance was worse at higher temperatures). These results suggest that morning and evening types have optimal performance at the peak of their self-reported circadian phase, independence of their body temperature. Results also suggest that morning and evening types may exhibit opposite relationship between body temperature and performance.

Bennett, Petros, Johnson, and Ferraro (Bennett, Petros, Johnson, & Ferraro, 2008) investigated the relationships between self-reported circadian phase, time of day, and executive functioning in 77 healthy control participants. Participants were grouped into morning-type (*n*=37) and evening-type (*n*=40) categories based on scores on the MEQ. They were subsequently administered a series of measures of executive functioning, including the Weschler Adult Intelligence Scale (WAIS-III), the Digit Span subtest of the WAIS-III, the Conners Continuous Performance Test (CPT), the Controlled Oral Word Association Test (COWAT), and the Wisconsin Card Sorting Task (WCST) either in the morning (8:00-10:00am) or in the afternoon (3:00-5:00pm). Tympanic temperature was also measured during the testing session. There were no significant main effects or interactions of time of day or self-reported circadian phase on performance on the CPT, the Digit Span subtest of the WAIS-III, or the COWAT. Investigators found significant interactions between time of day and self-reported circadian phase on both "cognitive efficiency" and "cognitive flexibility" outcomes of the WCST, suggesting that morning types performed better than evening types during the morning session, whereas evening types performed better than morning types during the afternoon session. Results also revealed a significant interaction between time of day and self-reported circadian phase on body temperature such that morning types had a lower body temperature in the morning than in the afternoon, while the body temperature of evening types did not differ between time points. These results suggest that self-reported circadian phase not have the same impact on performance on all types of tasks. Furthermore, these findings reiterate the finding above indicating that body temperature rhythms and their effects on

performance may differ based on self-reported circadian phase. Taken together, these studies indicate that self-reported circadian phase may play an important role in diurnal variations in cognitive functioning, and may moderate the relationship between body temperature rhythms and cognitive functioning.

The role of homeostatic sleep drive in cognitive function. The homeostatic system for sleep is based on the idea that the longer we are awake, the more we need to sleep. In other words, there is a "sleep drive" that accumulates over the course of a day. Immediately upon awakening, most people will experience a phenomenon known as "sleep inertia" (Ferrara & De Gennaro, 2000); it takes some time to really wake up and be ready for the day. Once past this sleep inertia phase there is not much drive or desire to go back to sleep. As wakefulness is maintained throughout the day, however, this drive for sleep increases, so that by nighttime, we are ready to sleep again. If we are prevented from sleeping, this drive continues to build up. Several studies show that if a person is completely deprived of sleep, their performance will suffer. However, even under conditions of total sleep deprivation, performance tends to improve at what would normally be wake time, or morning (Weinger & Ancoli-Israel, 2002). These data suggest that both the circadian and homeostatic systems of the sleep-wake cycle contribute to variations in cognitive functioning.

In order to conduct research on the specific influences of circadian rhythms on performance, as in the studies described above, the homeostatic system must be controlled for. This is accomplished using a methodology known as the "constant routine." In this protocol (originally described by Czeisler, Allan, and

Kronauer,(Czeisler, Allan, & Kronauer, 1990)), subjects are submitted to constant conditions for a specified period of time. These conditions typically consist of a constant ambient temperature, humidity, and light level, a consistent body position (usually semi-recumbent), and a snack and drink at a constant interval (usually every 2 hours). In many experiments, sleep is permitted during constant routines, but the procedures and timing of sleep are highly dependent upon the research question. Because the constant routine is vastly different from the ways in which people live on a daily basis, results obtained using this procedure are limited in their generalizability. While it is often useful to know the specific influence of circadian rhythms on many aspects of human functioning, in many cases it may be more valuable to study functioning under more externally valid conditions. Accordingly, several such studies have been conducted investigating variations in cognitive functioning over the course of a day.

Wertz and colleagues (Wertz, Ronda, Czeisler, & Wright, 2006) investigated patterns of cognitive performance in nine healthy volunteers over the course of six days. Each subject was allowed eight hours of sleep per night, and performance was assessed using a standardized addition test at 1, 21, 41, 61, and 120 minutes after awakening, and every two hours thereafter. Results demonstrated an effect of sleep inertia on performance, with severe impairments seen within the first three minutes of wakefulness, and deficits in performance seen up to two hours after awakening. Following this two-hour period, performance peaked and remained stable until about 10 hours after awakening, when participants showed a decline in performance, known as the “mid-afternoon dip.” This decline lasted for about two hours, and functioning returned to peak

until participants reached about 16 hours of wakefulness. At this time (when participants were nearing their bedtime) performance again declined.

Wright et al. (Wright, Hull, Hughes, Ronda, & Czeisler, 2006) investigated the interaction of the homeostatic and circadian systems of sleep-wake regulation by asking participants to complete a number of cognitive performance tasks (e.g., mathematics, cognitive speed, vigilance, and alertness) every two hours daily for 34 days. Results from this study support the findings of Wertz et al. (Wertz et al., 2006), in that performance was optimal once participants had been awake for about two hours, and remained at this optimal level until about 10 hours of wakefulness. Participants also experienced a "mid-afternoon dip," which lasted about two hours. Following this dip, performance returned to optimal levels. In combination, these findings suggest that once an individual has been awake for two hours, their cognitive performance will be relatively stable throughout the remainder of the day, with the exception of a small decline after about 10 hours of wakefulness. Cognitive performance declines as the brain "winds down" for the night, and this decline begins after about 16 hours of wakefulness.

Variations in brain activity across the day. Neuroimaging studies of sleep states have indicated that, in general, brain activity decreases as an individual moves from waking to sleep (Nofzinger, 2005). The prefrontal cortex are the first areas of the brain to go "off-line" as an individual falls asleep, stay off-line throughout the sleep period, and are the last to come back "on-line" upon awakening (Braun et al., 1997; Maquet et al., 1992; Maquet et al., 1990; Wright, Badia, & Wauquier, 1995). These regions are also the

most compromised by fatigue and sleepiness (Perlis, Jungquist, Smith, & Posner, 2005), and are necessary for optimal cognitive functioning.

Maquet et al. (Maquet et al., 1990) investigated brain activation using positron emission tomography (PET) as a measure of regional glucose metabolism in the brain during wakefulness and sleep. Eleven healthy participants were studied during three states: relaxed wakefulness, slow wave sleep (SWS) and rapid eye movement (REM) sleep. Results indicated that glucose metabolism was reduced during SWS as compared to wakefulness throughout the brain and that it was similar to wakefulness during REM sleep. This group conducted a subsequent study examining glucose metabolism with PET during stage 2 sleep in 12 participants (Maquet et al., 1992). Results of this study showed that glucose metabolism was reduced in stage 2 sleep relative to wakefulness, but this difference was not statistically significant in most brain regions. Significant reductions in glucose metabolism from wakefulness to stage 2 sleep were, however observed in the frontal cortex. Taken together, these studies suggest that brain activity decreases as an individual makes the transition from wakefulness into sleep, and that the frontal cortex is likely one of the first areas to show this decline.

Wright and colleagues (Wright et al., 1995) examined changes on electroencephalographic (EEG) spectral power during the transition from wakefulness into sleep. Twelve participants attempted to take a 20-minute nap while their EEG was recorded. Participants were instructed simply to go to sleep; sleep was defined as the first minute of stage 2 sleep, and subjects were awoken one minute after the first sleep spindle or K-complex (both indicators of stage 2 sleep). Results indicated that changes in spectral

power associated with sleep onset vary across scalp location. Specifically, alpha power declines in more frontal regions first, while declines in posterior regions are not observed until later. Furthermore, posterior brain regions continue to show changes in spectral power (i.e. decreased alpha, increased theta) after frontal regions have completed the transition to a sleep state. These findings suggest that the brain "shuts off" from front to back. Frontal regions are likely to be less available as an individual approaches sleep, whereas posterior structures remain active for a longer time period.

Braun and colleagues (Braun et al., 1997) measured regional blood flow using PET in 37 healthy volunteers during pre-sleep wakefulness, SWS, and REM sleep. While decreases in blood flow in SWS compared to pre-sleep wakefulness were observed in association cortices (e.g., frontal and parietal lobes), activity in sensory cortices was largely unchanged. Furthermore, activity similar to wakefulness was observed in REM sleep in all brain regions except those associated with higher-order association and neural integration.

Taken together, these neuroimaging results suggest that brain activity decreases as an individual makes the transition from wakefulness to sleep. Specifically, areas associated with higher-order processes (e.g., cognitive function), such as those in the frontal lobe, show greater decreases in activity earlier in the transition period. This implies that behaviors that rely on these brain regions to maintain optimal performance will suffer as an individual moves from a state of wake to a state of sleep.

Sleep and decision making. While much research supports the finding that cognitive function varies over the course of the day, the relationship between decision

making and circadian rhythms has yet to be studied. A few studies have investigated the influence of sleep deprivation on decision making (Killgore, 2007; Killgore et al., 2006; McKenna, Dicjinson, Orff, & Drummond, 2007). Killgore and colleagues (Killgore et al., 2006) examined the effect of 49 hours of sleep deprivation on performance in the Iowa Gambling Task (IGT; (Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Tranel, & Damasio, 2000) in 34 healthy volunteers. The IGT asks participants to select from one of four decks of cards; each card contains either a gain or loss of money. Two of the decks ("good" decks) contain cards with high rewards and moderate losses, such that repeated sampling from these decks will result in a net profit. The other two decks ("bad" decks) also contain cards with high rewards, but the losses in these decks are much greater, such that repeated sampling will result in a net loss. Healthy participants in IGT experiments typically learn that two decks are bad, and choose from the "good" decks more frequently. Patients with prefrontal cortex lesions, however, are more likely to choose from the more risky "bad" decks (Bechara et al., 2000). Killgore et al. (2006) found that following sleep deprivation, participants choose cards from the risky decks more frequently than at baseline. These findings suggest that behaviors mediated by the prefrontal cortex, such as decision making, may be particularly sensitive to sleep loss.

McKenna and colleagues (McKenna et al., 2007) studies the effects of 23 hours of sleep deprivation on risk seeking behavior related to gains and losses in 26 healthy participants. Previous studies report that in general, individuals are risk-seeking for losses and risk-averse for gains (Kahneman, 2003). McKenna et al. found that following sleep deprivation, participants were more likely to take risks to achieve gains and less likely to

take risks to avoid losses as compared to baseline. These findings suggest that sleep deprivation moderates risk preference, and that these effects depend upon whether the decision is framed in terms of gains or losses.

Decision Making and Emotion

Researchers in the field of decision-making have developed a number of behavioral tasks to test people's abilities to make decisions (Stanovich & West, 2000). It has been proposed that two different systems interact to guide decision making. System 1 relies on affect and intuition, while System 2 is more logical and deliberative. A well-studied task, known as the "Ultimatum Game" (Guth, Scmittberger, & Schwarz, 1982), can be used to distinguish which of these systems, emotional or rational, is taking precedence in an individual's decision-making process. In this task, two players (a proposer and a responder) are asked to split a sum of money (typically $10). The proposer makes an offer of how the money is to be split, and the responder can either accept or reject that offer. If the offer is accepted, the money is split as proposed. If the offer is rejected, neither player receives any money. Economic models of decision making predict that any non-zero offer should be accepted by the responder, on the basis that any gain (even a few cents out of $10) is better than no gain. However, research on the Ultimatum Game has shown that about half of all unfair offers (defined as an offer of less than 30% of the original pot) are rejected. This task is uniquely suited to tap into the way that the process of decision-making changes over the course of the sleep/wake cycle. People may be more likely to rely on emotional reactions to guide their decisions as the

evening progresses and the brain regions involved in cognitive processing become less active. This reliance on emotional reactions could result in the rejection of unfair offers, despite the fact that this will prevent any gain in income.

The Balloon Analogue Risk Task (Lejuez et al., 2002) is a computer-based behavioral measure of risk taking. In this task, a balloon is displayed on the computer screen, and the participant can choose to either pump up the balloon or collect the money reward in the "bank." With each pump of the balloon, a certain amount of money is added to the bank, such that the more the balloon is pumped up, the greater the potential reward. The caveat to this is that at some point, the balloon will explode. If the balloon does explode, no money is rewarded to the participant, and the next trial commences. Performance on the BART has been shown to be highly correlated with measures of sensation seeking, impulsivity, and deficiencies in behavioral constraint. Furthermore BART performance is associated with self-report of addictive, safety, and health risk behaviors, indicating good external validity. The BART has also been shown to differentiate between smokers and non-smokers (Lejuez, Aklin, Jones et al., 2003) and predict risk-taking behaviors in adolescents (Lejuez, Aklin, Zvolensky, & Pedulla, 2003). The risk-taking tendencies measured by the BART may be mediated by the interaction of System 1 and System 2: System 1 is likely to account for impulsive and risky behavior, whereas System 2 may serve to regulate excessive engagement in these behaviors.

Neuroimaging in decision making. Recent work by McClure and colleagues (McClure et al., 2005) has supported through neuroimaging the hypothesis that two independent brain systems are involved in decision-making: one that relies more on

emotional reactions, and one that relies more on a rational evaluation of the decision. The brain regions involved in the emotional processes correspond to regions of the brain that were found to be relatively active during sleep (Nofzinger et al., 2002). McClure et al. (McClure et al., 2005) examined the brain regions associated with decision making in a delayed versus immediate reward task in healthy volunteers. While participants underwent a functional magnetic resonance imaging (fMRI) scan, they were asked to make choices between smaller rewards that would be granted immediately and larger rewards that would be granted after a variable delay. The results showed that areas including the ventral striatum and medial prefrontal cortex were more activated during choices involving an immediate reward versus choices between two delayed rewards. These regions are thought to be associated with reward expectation and impulsive behavior. Furthermore, areas such as the lateral prefrontal and parietal cortices showed a positive relationship with decision difficulty on all trials (i.e. greater activation was related to more difficult decisions). These regions are thought to be associated with higher-order processes such as deliberative reasoning. These findings suggest that decision making in humans is regulated by competition between lower-level, more automatic processes and higher-level reasoning and processing.

Sanfey et al. (Sanfey, Rilling, Aronson, Nystrom, & Cohen, 2003) investigated the brain regions involved in decision making in the Ultimatum Game. In this study, participants were asked to engage in an UG task, responding to fair and unfair offers, while in the fMRI scanner. Areas associated with emotion, such as the anterior insula, and areas associated with higher reasoning, such as the dorsolateral prefrontal cortex

(dlPFC) were activated in response to unfair offers. The relative activation of these two areas was predictive of whether the offer was accepted or rejected. When unfair offers were rejected, activation in the anterior insula was higher than activation in the dlPFC. When unfair offers were accepted, activation in the dlPFC was higher than activation in the anterior insula. These results suggest that the higher-order "rational" processing provided by the dlPFC is necessary to overcome the emotional, or "gut," reaction to reject unfair offers.

RSA and Emotion Regulation

Heart rate has been shown to vary systematically with respiration, slowing during periods of expiration and increasing during inspiration. This phenomenon is known as respiratory sinus arrhythmia, or RSA (Daly, 1985). The heart is innervated both by the vagus nerve, which is part of the parasympathetic nervous system and originates in the brainstem, and by sympathetic nerves originating in the thoracolumbar system in the spinal cord. These two sources work together to moderate heart rate. While variations in nerve activity with respiration are evident in both sympathetic and parasympathetic systems, the sinoatrial synapses in the heart act as a low-pass filter to eliminate the fluctuations in the sympathetic system. Therefore, RSA is thought to index parasympathetic (more specifically vagal) control of the heart (Berntson, Cacioppo, & Quigley, 1993; Berntson, Quigley, & Lozano, 2007). As a part of the parasympathetic nervous system, the vagus nerve not only exerts its own influence on the heart, but also helps to maintain homeostasis by way of negative feedback in response to sympathetic

excitation (Porges, 1991). Studies of the influence of emotion on galvanic skin response suggest that emotion is regulated by the sympathetic nervous system. Porges (Porges, 1991, 1997) proposed that because negative feedback from the vagus regulates sympathetic arousal, an index of vagal tone, such as RSA, may be a physiological marker of emotion regulation.

Variability of RSA. In order to elucidate the relative contributions of circadian rhythm and sleep-wake state to fluctuations in RSA, Burgess et al. (Burgess, Trinder, Kim, & Luke, 1997) studied 12 participants during two 26-hour constant routines, one of which allowed sleep while the other did not. The measures evaluated in this study included EEG monitoring of sleep-wake state, respiratory activity, core body temperature, and EKG from which RSA was derived. RSA demonstrated a consistent 24-hour rhythm across both study periods, independent of sleep-wake state. These findings suggest that RSA follows a circadian pattern that is not influenced by the sleep-wake system. Additional research by this group supports the finding that changes in RSA are not related to sleep onset per se, but to circadian factors (Burgess, Kleiman, & Trinder, 1999; Burgess, Trinder, & Kim, 1999).

Bernston et al. (Berntson et al., 1994) examined the effects of stress on parasympathetic activity using pharmacological blockades in 10 healthy participants. Participants' heart rate was measured during the completion of three stress tasks on three separate occasions. On one occasion (control), participants were administered saline prior to task completion. On another occasion, participants were administered metoprolol prior to task completion, in order to block sympathetic activation. On the third occasion,

participants were administered atropine prior to task completion in order to block parasympathetic activity. RSA was subsequently derived from these heart rate data. Results of this study show that parasympathetic activity decreases during speech stress, mental arithmetic, and a reaction time task, as indicated by reduced RSA during these conditions. In a subsequent study, the same group (Berntson et al., 1996) further supported the finding that vagal activity decreases with stress (specifically during mental arithmetic tasks).

Combining stress manipulations and circadian timing, van Eekelen and colleagues (van Eekelen, Houtveen, & Kerkhof, 2004) examined 29 subjects during a 24-hour constant routine on dual task performance and cold pressor tests. These tasks were completed by subjects every three hours, and heart rate activity was monitored throughout the study period. The results indicate that RSA reactivity is influenced by circadian time, such that reactivity was increased in the morning and decreased in the evening.

The Present Study

Today's society functions on a 24-hour clock, with many businesses and occupations requiring staffing at all hours of the day and night. This schedule necessitates that individuals be awake to perform needed duties at times when they would otherwise be sleeping. One can imagine that working when you should be sleeping could lead to poorer performance and accidents on the job. In fact, studies show that the majority of job-related errors and motor vehicle accidents occur in the middle of the night.

Furthermore, most major news-worthy catastrophes, such as the Three Mile Island disaster, the Exxon-Valdez spill, and the Space Shuttle Challenger explosion occurred as a result of errors made during the early morning hours (Mitler et al., 1988). While previous research suggests that many areas cognitive functioning are impaired during such periods, no studies to date have investigated the specific impact of time of day on decision making. Such research could be crucial in preventing errors in judgment that could potentially put many people at risk.

The present study aimed to examine the relationships between time of day and decision making. Specifically, the present study tested the hypothesis that the time of day at which decisions are made influences the relative contribution of System 1 and System 2 to decision making and risk taking. Influences of time of day on decision making have yet to be studied, but the literature described above supports the hypothesis that individuals will be less likely to make "irrational" decisions, and less likely to take risks when tested at the peak of their circadian rhythm, and that this will be due to the deliberative processes of System 2 compensating for the intuitive judgments made by System 1. The study also aimed to examine potential mediators and moderators of the relationship between time of day and decision making, including circadian phase preference and respiratory sinus arrhythmia.

METHODS

Participants

Two hundred participants were recruited using flyers posted around the University of Arizona Campus, on the website craigslist.com, and through the University of Arizona Psychology Department's experiment website. On average participants were of 18.9 years old (range = 18-23 years), and had a mean education of 13.5 years (range = 13-16 years). Participants were excluded if their age was outside the range of 18-25 years, or if they had a history of untreated medical, psychiatric, or sleep disorders. Participants were also excluded if they were experiencing significant symptoms of depression (defined by a score greater than 14 on the Beck Depression Inventory – 2nd Edition) or anxiety (defined by a score greater than 8 on the Beck Anxiety Inventory) at the time of their baseline assessment.

Study Design

The study consisted of three sessions, all of which were conducted in a private room at the University of Arizona Sleep Research Laboratory. During the first session, the informed consent form was reviewed, and participants completed a series of screening questionnaires, including a demographic questionnaire, a medical information questionnaire, the Beck Depression Inventory – 2nd Edition, and the Beck Anxiety Inventory. During this session, participants who qualified for participation also completed

the Horne-Östberg Morningness-Eveningness Questionnaire (MEQ) and the Penn State Worry Questionnaire, and were provided with instructions for completing sleep diaries. A digital photograph of each eligible participant was taken during this session. Participants were instructed to complete internet-based sleep diaries for seven days, but typically failed to do so on consecutive days. After seven days of diary data were obtained (five weekdays and two weekend days) average weekday wake time was calculated in order to schedule the two subsequent study sessions.

Participants were scheduled four hours after their average weekday wake time for their peak time session and 16 hours after their average weekday wake time for their bedtime session. During these sessions, participants completed two computerized decision making tasks: the Ultimatum Game (UG) and the Balloon Analogue Risk Task (BART). Participants also completed questionnaires assessing their level of sleepiness and current mood. The participant's temperature was measured at the beginning of each session using a tympanic thermometer to serve as a physiological indicator of circadian phase. Heart rate was measured throughout the second and third sessions and included three assessment periods: a seven minute resting baseline, a four to five minute serial subtraction task (stress condition), and during the decision making tasks. The order of the sessions and the order of the decision making tasks within the sessions were randomized by allowing subjects to pick out of a hat.

Participants were compensated for their time. Participants recruited through flyers earned $5 for completing the baseline session, 5% of their earnings on the Ultimatum Game, and 50% of their earnings from the BART. Participants recruited through the

University of Arizona Psychology Department's experiment website were awarded two experimental credits for completing the baseline session and were offered the choice of receiving two additional credits per follow-up session or receiving the same cash payment schedule as participants recruited from the flyer. All participants were compensated upon the conclusion of their participation in the study.

Measures

Questionnaires. The demographic questionnaire consists of sixteen questions, including demographic information, current medical and psychiatric illness and treatment, and sleep quality (see Appendix A). The medical information questionnaire includes seven items and assesses medical, psychiatric, and substance use history (see Appendix A). The Beck Depression Inventory – 2nd Edition (BDI-II; (A. C. Beck, R. A. Steer, G. K. Brown, 1996) is a 21-item self-report measure widely used for assessing the presence and severity of symptoms of depression. Multiple-choice Items are scored from 0-3 in terms of the intensity of the symptom, with total scores ranging from 0-63; the cutoff for "minimal" depressive symptoms is 14 (A. C. Beck, R. A. Steer, G. K. Brown, 1996). The BDI-II has been shown to have high internal consistency and construct validity, and is able to distinguish depressed from non-depressed individuals (Richter et al., 1997).

The Beck Anxiety Inventory (BAI; (A. T. Beck, Epstein, Brown, & Steer, 1988) is a 21-item self-report questionnaire designed to assess the presence and severity of symptoms of anxiety. Similar to the BDI-II, each item (or symptom) on the BAI is rated

on a scale of 0-3 for intensity of the symptom, resulting on a range of possible total scores of 0-63. A total score of 8 or below represents “minimal anxiety” (Leyfer, Ruberg, & Woodruff-Borden, 2006). The measure has been shown to have good concurrent and discriminant validity, and is able to distinguish between individuals with and without anxiety disorders (A. T. Beck et al., 1988).

The Horne-Östberg Morningness-Eveningness Questionnaire (MEQ; (Horne & Ostberg, 1976) is a 19-item questionnaire which assesses individual differences in the time of day at which people prefer to engage in various activities (see Appendix A). It is used in this study as a trait-level measure of circadian phase preference. The MEQ has high reliability and external validity (Horne & Ostberg, 1976), and allows for the categorization of individuals into groups based on their circadian phase preference (see Data Analysis section).

The Penn State Worry Questionnaire (PSWQ; (Meyer, Miller, Metzger, & Borkovec, 1990)a 16-item scale assessing propensity to worry. Each item is rated on a 5-point scale ranging from 1 (“*not at all typical of me*”) to 5 (“*very typical of me*”), allowing for a total score ranging from 16 to 80. Items include statements that reflect a tendency towards excessive worry (e.g., “I worry all the time”). The PSWQ has been shown to be a reliable and valid measure of worry in both clinical and non-clinical samples (Meyer et al., 1990).

The Positive and Negative Affect Scale (PANAS; (Watson, Clark, & Tellegen, 1988) is a 20-item assessment of both positive and negative mood states. Each item consists of an adjective with a positive or negative valence which is rated on a scale of 1

(“*very slightly/not at all*”) to 5 (“*extremely*”) according to what participants’ are experiencing in the present moment. There are 10 items each for positive and negative affect, and these scales are scored separately. Scores for each scale range from 10 to 50, with larger numbers indicating higher levels of affect. The PANAS has been shown to be a reliable and valid measure of current mood (Watson et al., 1988).

The Stanford Sleepiness Scale (SSS; (Hoddes, Dement, & Zarcone, 1971) is a self-rating scale used to quantify subjective sleepiness (see Appendix A). The scale consists of seven statements denoting increasing degrees of sleepiness; participants are asked to select the statement that best describes their current state. The SSS has been shown to be sensitive to changes in levels of sleepiness in as little as 15 minute between assessments (Hoddes et al., 1971), and is highly correlated with performance on mental tasks (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973). The SSS was administered before beginning the computer tasks, between the two tasks, and following the second task in order to evaluate differences is sleepiness across and between sessions.

Respiratory Sinus Arrhythmia (RSA). Participants’ electrocardiograms (EKG) were recorded using Grass self-adhesive silver-silver chloride electrodes (Model F-E8SD, Astro-Med, Inc. Product Group, West Warwick, RI 02893) attached in a Lead II setup (an electrode on the right collarbone and left ankle), with the right ankle used as a ground site. Each site was cleaned with alcohol and mild abrasive (Nuprep Skin Prepping Gel, D.O. Weaver & Co., Aurora, CO 80011). The signal was recorded with a multi-channel AC amplifier system of a Grass Polygraph, Aurora Model and Twin 3.2 Software (Grass Instrument Division, Astro-Med, Inc., West Warwick, RI 02893). Data was sampled at a

rate of 500 Hz and amplified by 20K. Low frequency filters will be set at 0.1 Hz, and high frequency filters will be set at 50 Hz. Participants' EKG was recorded throughout both testing sessions. Immediately following the start of EKG recording, participants were asked to sit quietly with their eyes closed for seven minutes. Next, participants were asked to engage in a serial subtraction task for four to five minutes. EKG was recorded throughout the decision making tasks. Because breathing rate can influence both heart rate and RSA, respiration was be monitored using a Grass upper airway transducer (Model 2401, Astro-Med, Inc. Product Group, West Warwick, RI 02893).

EKG data from each participant under each condition will be imported into QRSTool in order to generate an inter-beat interval (IBI) series. Heart series peaks will be detected by finding an average beat, then using the peri-beat filter tool in QRSTool. This tool uses a prototypical EKG waveform to filter the EKG signal and identify r-spikes. The peri-beat filter also corrects for drift in the EKG data, and is robust to signal artifacts. The results of the heart series peak detection will be corrected by visually inspecting the IBI series for any abnormalities and manually removing or adding any missed or incorrect peaks. Following correction of errors, the IBI series will be exported into CMetX (Allen, Chambers, & Towers, 2007). This program converts the IBI series into a time series by sampling data from the IBI series at 10 Hz. A .12 - .40 Hz band pass filter is then applied to the data. The resulting filtered data is used to calculate various metrics of cardiac activity. The metric of primary interest in the present study is respiratory sinus arrhythmia (RSA). CMetX calculates heart rate as the average of the rate-transformed IBIs (as opposed to the rate-transformed average IBI). RSA is calculated

by taking the natural log of the band-limited variance of the IBI time series. Due to the filtering process, data at the beginning and end of the file are lost during analysis (about 12 seconds lost at each end). To prevent the loss of any data of interest, EKG will be recorded throughout the entire session, and 12-second windows of data before and after tasks of interest will be subjected to analysis.

Serial Subtraction Task. The serial subtraction task was used to measure participants' physiological reaction to stress. This task was chosen for this purpose because it requires some cognitive effort, and autonomic responses to the task have been widely researched and hence are well understood (Berntson et al., 1994). The task consisted of participants completing four serial subtraction lists of increasing difficulty for one minute each (i.e. with a different starting point and subtrahend for each minute). The lists and specific tasks differed between testing sessions (see Table 1). If at any time the participant made an error, the experimenter said "Wrong, start over from [first number of the current list]." The participant was seated in an isolated room, and communicated with the experimenter through a microphone and speaker system.

Table 1: Serial subtraction task details.

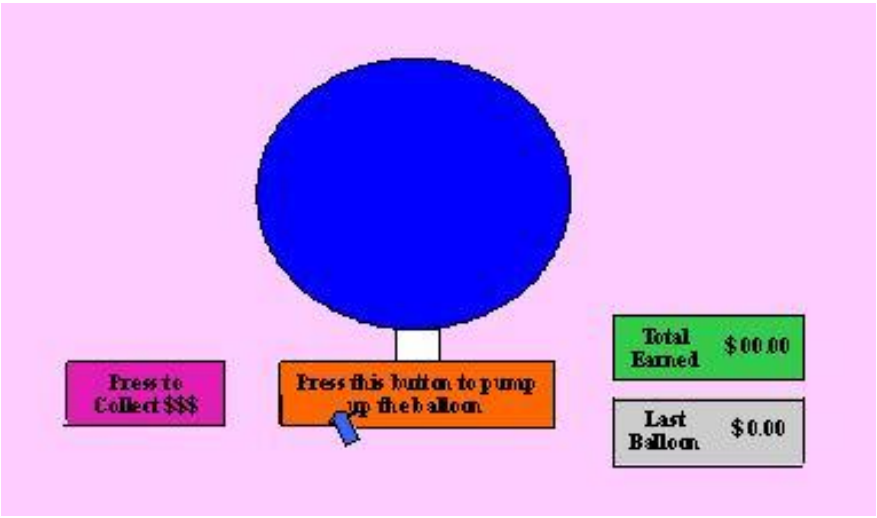
	First Session		**Second Session**	
	Starting Number	Subtrahend	Starting Number	Subtrahend
Minute 1	2694	3	3571	3
Minute 2	1835	7	2944	7
Minute 3	5563	8	6487	8
Minute 4	8632	13	7516	13

Decision Making Tasks

Ultimatum Game. The Ultimatum Game (UG) was administered on a desktop computer using DMDX software (Forster & Forster, 2003). Prior to initiation of the task, participants were reminded of the photograph taken during the baseline session, and told that this photo was shown to other participants in the study. Participants were told that these "other participants" would be their partners in the game. Participants were shown a picture of their partner before each trial. The pictures were displayed on the computer screen for four seconds, and were selected from a pool of actual UG players collected from previous studies (Sanfey et al., 2003). Participants were shown their partner's offer, and allowed a maximum of ten seconds to decide whether to accept or reject that offer. They were instructed to press the left shift key on the keyboard to indicate that they accept the offer, and the right shift key to indicate that they reject it. If subjects did not respond within 10 seconds, the offer will be rejected by default, and the trial was excluded from analyses. Upon responding, participants were presented with both the outcome of the trial and the total amount of money accrued for four seconds. Participants will complete sixteen trials in all. Seven trials were fair offers ($5), six were moderately unfair offers (3 × $4 and 3 × $3), and seven were highly unfair offers (4 × $2 and 3 × $1). Upon completion of the task, the rewards from the trials on which the offer was accepted were summed, and 5% of this amount was given to participants who selected this compensation option. The main dependent variables garnered from the UG were the proportion of offers rejected by participants in the three categories of offers (highly unfair, moderately unfair, and fair).

Balloon Analog Risk Task. The Balloon Analogue Risk Task (BART) will also be administered on a desktop computer using software downloaded from the website of the University of Maryland Center for Addictions, Personality, and Emotion Research, where the task was developed. The details of the task are described elsewhere (Lejuez et al., 2002); see Appendix B). In summary, participants were presented with a simulated balloon, the amount of money they have earned so far, the amount of money they earned on the last balloon, and two choice options: collect money or pump up the balloon (see Figure 1). Each balloon will have a "pot" in which money is accrued. Each pump earns money, but also increases risk of popping the balloon (based on a probability algorithm described by Lejuez et al. (Lejuez et al., 2002); see Appendix B). The main dependent variable taken from the BART is the average adjusted number of pumps applied per balloon (Lejuez et al., 2002).

Figure 1: Sample screen of the BART.



Data Analysis

Repeated measures ANOVAs were conducted to evaluate the role of time of day in decision making and risk taking. Following this primary analysis, exploratory analyses using repeated measures ANOVAs and correlation analyses were performed in order to evaluate potential moderators and mediators of the above relationship, including circadian phase preference and respiratory sinus arrhythmia. Changes in RSA between resting baseline and stress conditions, and their interaction with time of day and circadian phase preference were also examined using repeated measures ANOVAs.

Missing Data Procedures. All analyses were run using listwise deletion for missing data. One participant failed to complete the MEQ, and was subsequently excluded from all analyses involving this measure. Data from the Ultimatum Game during one session were lost for 22 participants due to user error. For 12 participants, these data were lost for the peak time session, for 10 participants, they were lost for the bedtime session.

The serial subtraction task required that participants say their answers aloud, which interfered with the respiration measure to such an extent that breathing rate could not be subsequently analyzed.

RESULTS

Overall Sample Characteristics

Of the 200 participants enrolled into the study, 134 completed all three sessions. 10 participants did not meet study inclusion criteria, 14 withdrew from the study, and 42 were lost during follow-up. Demographic characteristics of the sample are displayed in Table 2. Completers and non-completers did not differ on any baseline variables, including age, sex, race, ethnicity, BAI score, BDI score, PSWQ score, or MEQ score.

Table 2. Overall sample characteristics.

	All participants (n = 190)		Completers (n = 134)		Non-completers (n = 56)		
	M	*SD*	*M*	*SD*	*M*	*SD*	*t*-test*
Age (years)	18.93	1.10	19.02	1.14	18.70	0.97	1.87
Education (years)	13.55	0.87	13.59	0.90	13.44	0.79	1.03
Beck Depression Inventory	4.35	4.01	4.10	3.80	4.95	4.44	1.32
Beck Anxiety Inventory	4.84	4.24	4.70	4.23	5.16	4.29	0.68
Penn State Worry Questionnaire	44.68	13.31	45.25	13.10	43.31	13.81	0.91
Morningness-Eveningness Questionnaire	46.60	8.13	46.51	8.35	46.80	7.64	0.22
							χ^2*
Sex (% female)	60.0		60.4		58.9		0.04
Race (%)							1.01
American Indian or Alaska Native	3.2		3.0		3.6		
Asian	8.5		8.3		8.9		
Native Hawaiian or Other Pacific Islander	1.1		1.5		0		
Black or African American	4.3		4.5		3.6		
White	67.6		67.4		67.9		
Other	15.4		15.2		16.1		
Ethnicity (%)							2.12
Hispanic or Latino	25.0		25.4		24.0		
Not Hispanic or Latino	72.0		72.8		70		
Unknown	3.0		1.8		6.0		

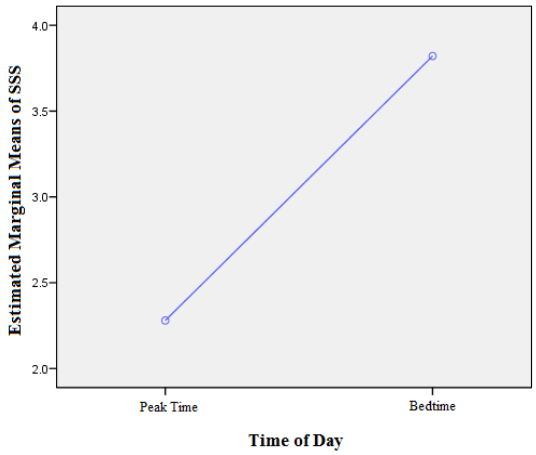
* all *p*s > .10

Participant compensation. Of the 134 participants who completed the study, 35 received monetary compensation for their time, while the remaining 99 received experimental credits. Participants receiving monetary compensation were paid an average of $24 for completing the study.

Subjective Sleepiness

Subjective sleepiness was measured using the Stanford Sleepiness Scale (SSS) three times during each session: before the first decision making task, between the two tasks, and after the second task. A 3x2 repeated measures ANOVA (time of measurement: pre-tasks, between-tasks, post-tasks; time of day: peak, bedtime) was conducted in order to determine changes in subjective sleepiness across and between the sessions. There was a significant main effect of time of day (p<.01; partial η^2=.54), such that participants were more sleepy during the bedtime session than during the peak time session (see Figure 2).

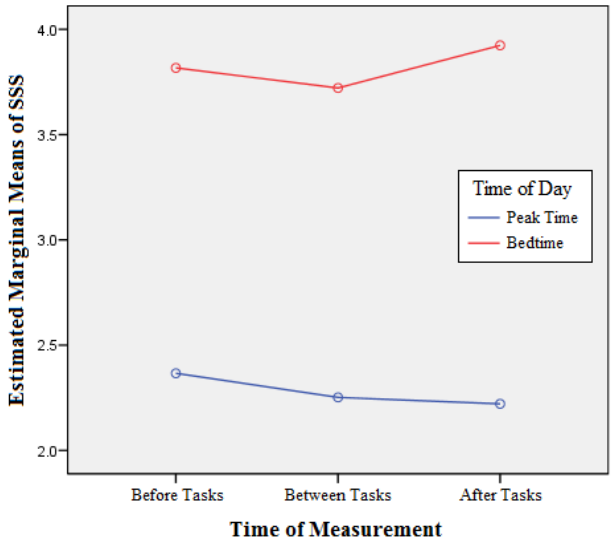
Figure 2. Main effect of time of day on subjective sleepiness.



This main effect was qualified by an interaction between time of measurement and time of day ($p<.05$; partial $\eta^2=.04$), suggesting that there was decline in sleepiness between tasks and the subsequent increase in sleepiness after both tasks seen during the bedtime session, whereas during the peak time session, sleepiness declined as the session progressed (see Figure 3). There was no main effect for time of measurement ($p=.15$).

MEQ group was added as a between-subjects factor into the above analysis to evaluate the influence of self-reported circadian phase on the relationships described above. Results revealed a significant main effect of time ($p<.01$; partial $\eta^2=.37$), such that participants were more sleepy at the bedtime session than at the peak time session. There were no main effects for timing of measurement ($p=.12$) or MEQ group ($p=.31$). The interaction between time of measurement and time of day was no longer significant ($p=.28$), and there were no other significant interactions (all ps$>.10$).

Figure 3. Interaction between time of measurement and time of day on subjective sleepiness.



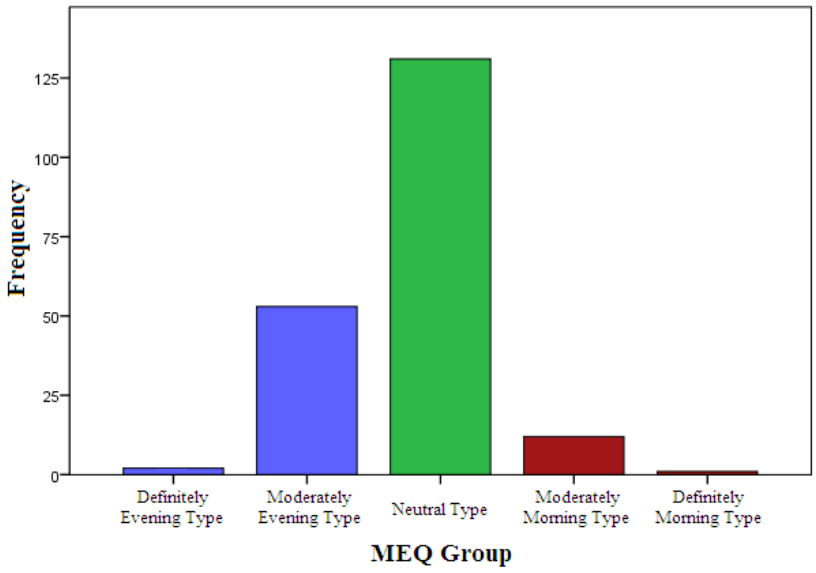
Indicators of Circadian Phase

Physiological measurement of circadian phase. Participants'' tympanic temperature was taken at both testing sessions in order to serve as a physiological indicator of circadian phase. Body temperature typically rises throughout the morning, peaks around mid-day, and declines in the evening and night hours (Colquhoun, 1971; Kleitman, 1963). Participants' body temperature therefore should have been higher during the peak session than during the bedtime session. Temperature difference scores were calculated by subtracting participants' temperature at bedtime from their temperature at peak time, such that positive values on this difference score would represent a temperature shift in the expected direction. Participants had an average temperature difference score of 0.05 (SD=1.67, range=-4.0 to 5.0). Participants were grouped based on a quartile split of their temperature difference score in order to classify temperature changes in both the expected (positive difference) and unexpected (negative difference) directions. This categorization resulted in four temperature difference groups: large negative difference (*n*=33), small negative difference (*n*=35), small positive difference (*n*=32), and large positive difference (*n*=33).

Self-reported circadian phase. Self reported circadian phase was measured by the Morningness-Eveningness Questionnaire (MEQ). In their original presentation of the MEQ, Horne and Östberg (Horne & Ostberg, 1976) provided scoring criteria which allow for classification into five "types": extreme morning types, moderate morning types, neutral type, moderate evening type, and extreme evening type. To allow for analyses based on circadian phase preference in the present study, participants were classified into

groups according to these criteria. This grouping variable will hereafter be referred to as MEQ group. Figure 4 represents the distribution of participants on this variable. Two participants scored in the "extreme evening type" range, and one participant scored in the "extreme morning type" range. Because the small size of these cells was likely to affect the power of subsequent analyses, the "extreme" types were combined with the respective "moderate" types, resulting in three more broadly defined MEQ groups: evening types (henceforth referred to as "owls"; *n*=39), neutral types (*n*=86), and morning types (henceforth referred to as "larks"; *n*=9).

Figure 4. Frequency distribution of MEQ groups.

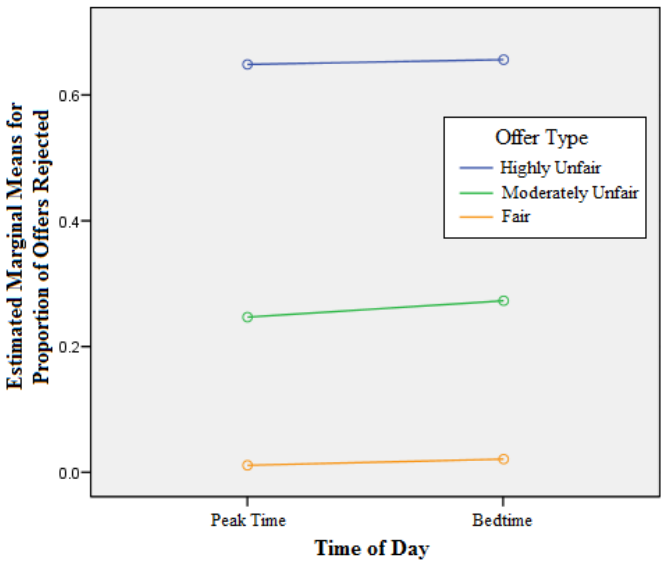


Decision Making Tasks

Ultimatum Game. A 2x3 repeated measures ANOVA (time of day: peak, bedtime; offer: highly unfair, moderately unfair, fair) was conducted to determine the effect of the

time of day manipulation on performance on the Ultimatum Game task. A significant main effect for offer (p>.01; partial η^2=.77) indicated that participants rejected significantly more highly unfair offers than moderately unfair offers, and significantly more moderately unfair offers than fair offers (see Figure 5). There was no main effect for time of day (p=.30), nor was there an interaction between time of day and offer (p=.70).

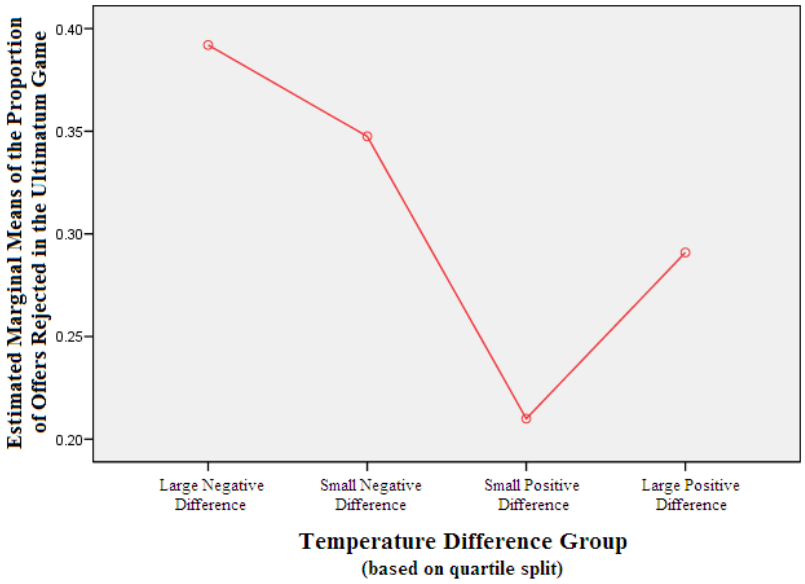
Figure 5: Main effect of offer type in the Ultimatum Game.



In order to determine if self-reported circadian phase had an effect on the relationships between time of day and performance on the Ultimatum Game, MEQ group was entered as a between-subjects factor into the above analysis. The addition of this variable did not alter the results of the initial analysis. Furthermore, results indicated that there was no main effect of MEQ group (p=.96), nor were there any significant interactions (all ps>.20).

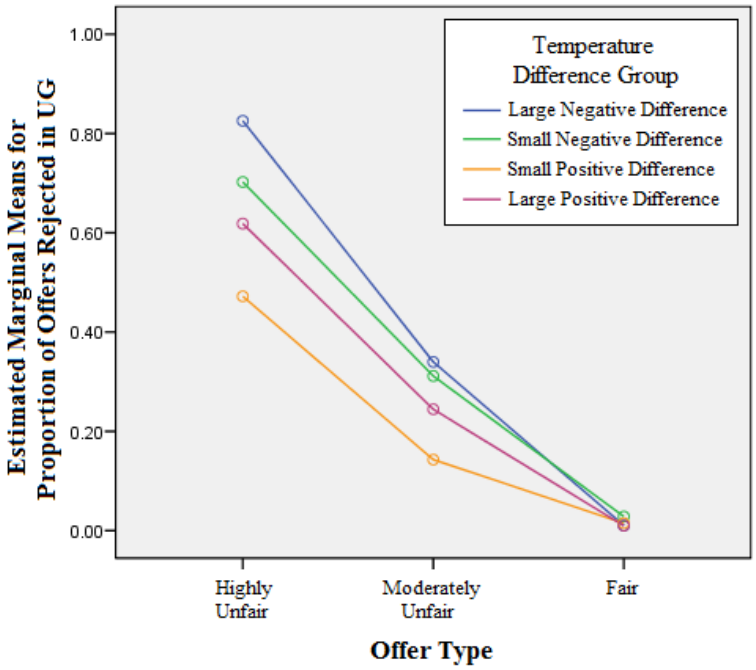
In order to determine if body temperature differences between sessions influenced the relationships between time of day and performance on the Ultimatum Game, temperature difference group was entered as a between-subjects factor into the ANOVA described above. The main effect of offer was unchanged from the initial analysis. In addition there was a main effect for temperature difference group (p<.01; partial η^2=.12) such that participants in the small positive difference group rejected fewer offers than participants in the small and large negative difference groups (see Figure 6).

Figure 6. Main effect of temperature difference group in the Ultimatum Game



These main effects were qualified by an interaction between offer and temperature difference group (p<.01; partial η^2=.09), indicating that the differences observed between temperature groups was present in responses to unfair offers, but not in fair offers. These results are displayed graphically in Figure 7. There were no other significant main effects or interactions (all ps>.20).

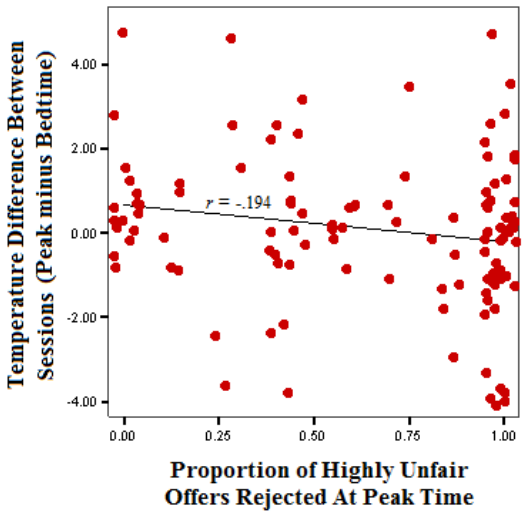
Figure 7. Interaction between offer type and temperature difference group in the Ultimatum Game.



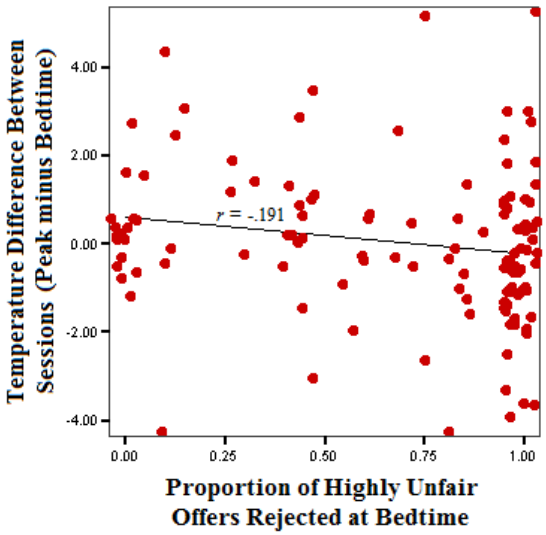
Bivariate correlation analyses were conducted to evaluate the relationship between temperature difference and Ultimatum Game performance in a continuous fashion. Results revealed a negative correlation between temperature difference between session and the proportion of highly unfair offers rejected at both peak time (r=-.194, p<.05; see Figure 8a) and bedtime (r=-.191, p<.05; see Figure 8b). Larger positive temperature difference (i.e., lower temperature at bedtime) was associated with a reduced likelihood of rejecting highly unfair offers. This relationship did not hold with moderately unfair offers.

Figure 8. Relationship between temperature difference and the proportion of highly unfair offers rejected in the Ultimatum Game.

(a) Peak time session



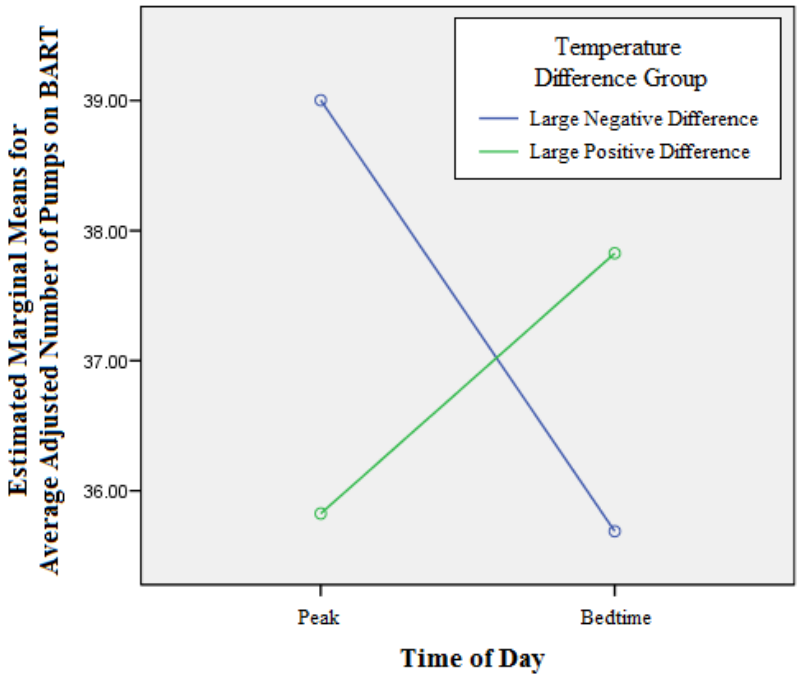
(b) Bedtime session



Balloon Analog Risk Task. A 2-way repeated measures ANOVA (time of day: peak, bedtime) was conducted to determine the effect of the time of day manipulation on risk-taking behavior in the BART. Results revealed no main effect for time of day (p=.54). To determine the role of self-reported circadian phase in the above relationship, MEQ group was added as a between-subjects factor in the above analysis. Again, there was no main effect for time of day (p=.72), nor was there a main effect for MEQ group (p=.90). There was no interaction between time of day and MEQ group (p=.30).

In order to determine if body temperature differences between sessions influenced the relationships between time of day and performance on the BART, temperature difference group was entered as a between-subjects factor into the analysis described above. There were no main effects for time of day (p=.56) or temperature difference group (p=.38), however there was a trend towards an interaction between the two (p=.08; partial η^2=.05). Participants in the large positive difference group had higher BART scores at bedtime vs. peak time; participants in the high negative difference group had lower BART scores at bedtime vs. peak time. When the extremes were examined in isolation (i.e. the ANOVA was run using only the large negative and large positive difference groups), this interaction was significant (p<.01; partial η^2=.12). These results are displayed graphically in Figure 9.

Figure 9. Interaction between time of day and temperature difference group in the BART.



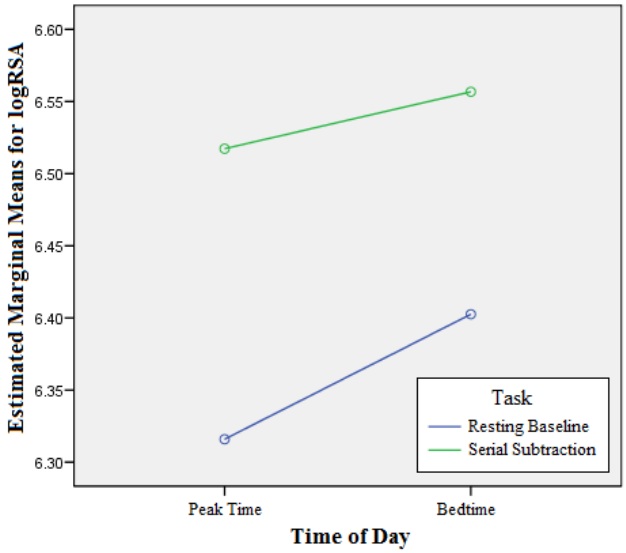
Respiratory Sinus Arrhythmia

Because RSA has a non-normal distribution, a log transformation was used to normalize the data for analysis. Bivariate correlations revealed no significant relationships between RSA and decision making tasks.

Time of day effects. A 2X2 repeated measures ANOVA (time of day: peak, bedtime; task: baseline, subtraction) was conducted in order to determine whether time of day had an effect on RSA during the resting baseline and serial subtraction tasks. Results revealed a significant main effect for task (p<.01; partial η^2=.14), indicating that RSA was higher during serial subtraction than during resting baseline (see Figure 11). There

was no main effect for time of day (p=.39), nor was there an interaction between task and time (p=.39).

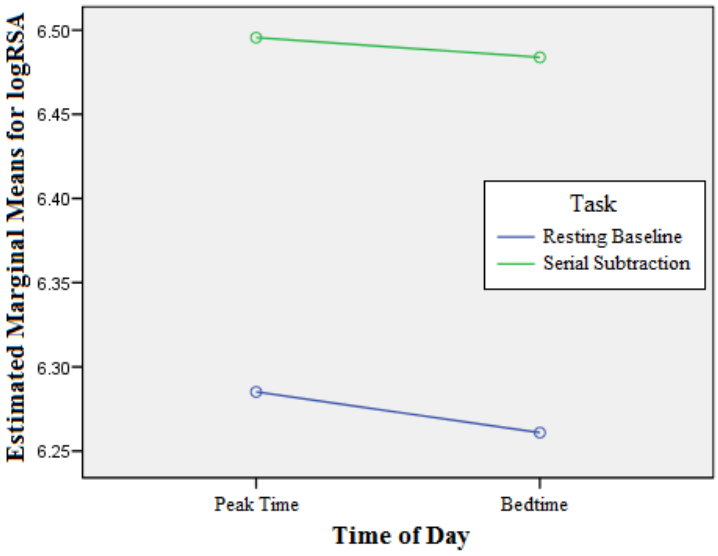
Figure 10. Main effect of task on respiratory sinus arrhythmia.



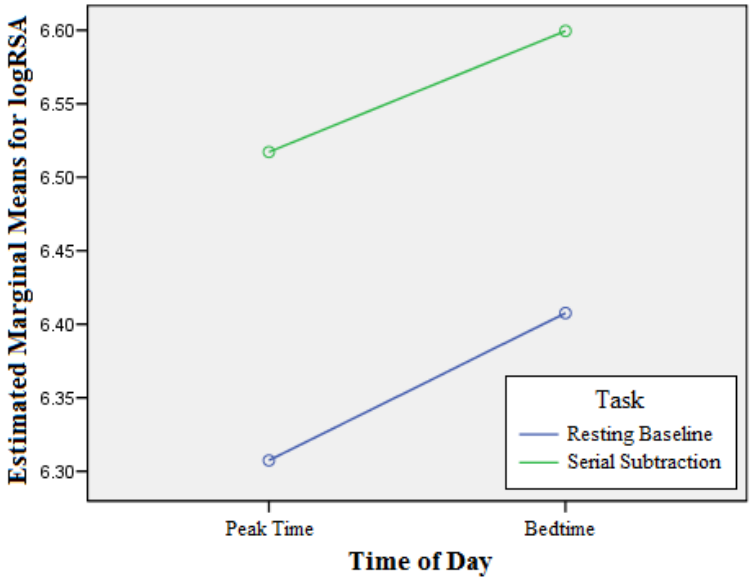
Self-reported circadian phase as a moderator of RSA. In order to determine the role that circadian phase preference plays in the relationship between time of day and RSA, MEQ group was entered as a between-subjects factor into the above analysis. Results showed that there was a significant interaction between task and MEQ group (p<.05; partial η^2=.05), indicating that RSA was higher during serial subtraction than during resting baseline in owls and neutral types, but the opposite pattern was observed in larks (i.e., RSA was higher during resting baseline than during serial subtraction). There was also a significant interaction between time of day and task (p<.05; partial η^2=.05) indicating that RSA during resting baseline was higher at bedtime then at peak time, but there was no difference in RSA during the serial subtraction task between time

points. These two interactions were qualified by a three-way interaction between task, time, and MEQ group (p<.05; partial η^2=.05). Owls and neutral types showed the same pattern of results: RSA was higher during the serial subtraction task than during resting baseline, and there was no significant difference in RSA between time points for either task (see Figures 11a and 11b, respectively). Larks showed a different pattern in that RSA was the same during resting baseline and the serial subtraction task at peak time, but at bed time RSA was higher during the resting baseline than during the serial subtraction task (see Figure 11c). There were no main effects for task (p=.20), time of day (p=.47), or MEQ group (p=.65), nor was there a time by MEQ group interaction (p=.74).

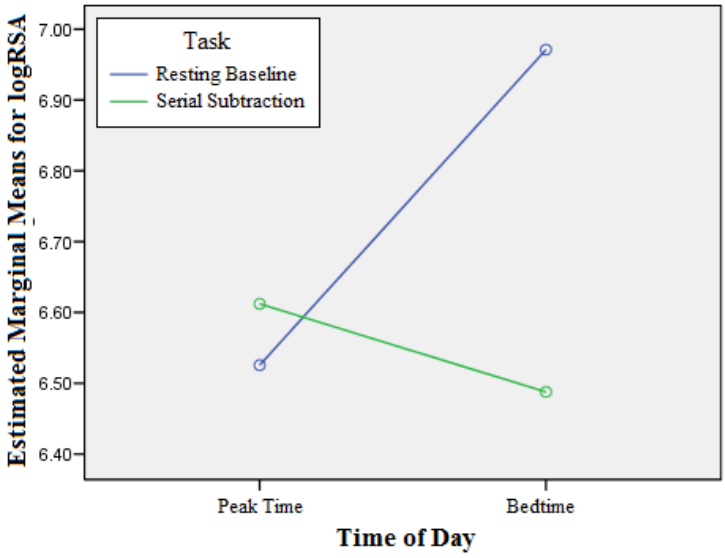
Figure 11. Three-way interaction between task, time of day, and MEQ group on RSA. *(a)* Interaction between task and time of day in owls.



(b) Interaction between task and time of day in neutral types.



(c) Interaction between task and time of day in larks



Differences in body temperature between sessions did not alter the relationships between time of day, task, and RSA. When temperature difference group was entered in

place of MEQ group into the mixed ANOVA described above, there was a significant main effect for task as seen in the initial repeated measures ANOVA (i.e., RSA was higher during serial subtraction than during resting baseline; $p<.01$, partial $\eta^2=.14$). There were no main effects for time ($p=.47$) or temperature difference group ($p=.79$), nor were there any significant interactions (all ps$>.10$).

DISCUSSION

The present study was designed to evaluate the influence of time of day on measures of decision making and risk taking. It was hypothesized that as individuals' circadian phase declines in the evening hours, the relative contributions of the affective, intuitive System 1 and the logical, deliberative System 2 would shift, resulting in fewer irrational" decisions and less risky behavior during the day when compared to nighttime. The study furthermore aimed to examine circadian phase and respiratory sinus arrhythmia as a potential moderator of the relationship between time of day and decision making and risk taking.

Time of Day Manipulation Checks

Participants were brought into the lab at 4 and 16 hours after their average weekday rise time. These time points were chosen based on previous literature (Wertz et al., 2006; Wright et al., 2006) to capture the daytime peak and initial nighttime decline in participants' circadian phase. Measures of sleepiness and body temperature were used to evaluate the effectiveness of this manipulation.

Subjective sleepiness. Subjective sleepiness was measured by the Stanford Sleepiness scale at three time points during the session: immediately prior to the decision making tasks, in between the two tasks, and immediately following completion of the second task. There was some support for the effectiveness of the time of day manipulation in that, as expected, subjects were more sleepy at the bedtime session than

at the peak time session. There was an interaction between time of day and time of measurement, indicating that during the bedtime session, completing the first decision making task activated subjects enough so that they were less sleepy between tasks and sleepiness increased during the second task. The effect size of this interaction was very small (partial $\eta 2=.04$), suggesting that this is unlikely a reliable finding. Furthermore, when self-reported circadian phase was added as a moderator, the interaction between time of day and time of measurement was no longer significant, while the main effect of time of day remained significant.

Body temperature measures. Tympanic temperature was taken during each session to serve as a physiological measure corroborating participants' circadian phase. Previous research suggests that participants' body temperature should be higher during the peak time session than during the bedtime session. In the present sample, body temperature did not differ between the two sessions. For about half of the participants, body temperature followed the expected pattern whereas for the other half, body temperature was actually higher during the bedtime session than during the peak time session. These results indicate that the manipulation failed to capture participants during the peak and decline of their circadian phase.

Body temperature rhythm and self-reported circadian phase.

Participants were administered the MEQ in order to assess self-reported circadian phase as a potential moderator of the relationship between time of day and decision

making. In previous studies, the MEQ has been shown to be highly correlated with physiological measures of circadian phase, including body temperature (Bailey & Heitkemper, 2001; Horne & Ostberg, 1976)In the present study, MEQ scores were not correlated with differences in body temperature between sessions. Circadian phase changes dramatically during adolescence, with a shift from morningness to eveningness (Carskadon, Vieira, & Acebo, 1993; Gau & Soong, 2003; Laberge et al., 2001). The participants in the present study were likely in the midst of this shift. Additionally, the majority of the sample was college freshmen in the process of adjusting to new, less rigorous school schedules. These transitions may create ambiguity about circadian preferences resulting in uncertainty or difficulty in responding to items on the MEQ, making the measure unsuitable for use in this age group. It is possible that in the present sample, body temperature rhythms represent a more concrete physiological circadian phase which could not be captured by the self-report nature of the MEQ. Individuals whose body temperature was higher at peak time than at bedtime (i.e., whose body temperature changed in the expected direction) may be physiologically akin to “morning types”, while those whose body temperature showed the opposite patter (i.e., higher at bedtime than at peak time) may represent physiological “evening-types”. The fact that study results differ depending on which measure is used in the analysis (i.e., body temperature or MEQ score) lends credence to this hypothesis.

The Ultimatum Game

Participants showed the expected main effect of offer type in the Ultimatum Game in that they rejected more highly unfair offers than moderately unfair offers, and more moderately unfair offers than fair offers. The time of day at which the task was completed did not influence performance. This could be due in part to the fact that participants were not studied at the actual peaks and declines of their circadian rhythms, as discussed above. An alternative explanation for the lack of difference between testing sessions is that the Ultimatum Game was designed as a single-session task, and is not frequently used in repeated measures designs. The task may lack the sensitivity to distinguish the subtle differences that could occur between time points. While sessions were separated by at least one day, memory effects may contribute to the lack of findings.

Self-reported circadian phase (as measured by the MEQ) did not contribute any additional information to the above findings. Body temperature rhythms did contribute to performance on the Ultimatum Game through an interaction with the type of offer presented. Individuals whose body temperature was slightly higher during the peak time session (i.e., the expected change) rejected fewer unfair offers than individuals whose body temperature was higher during the bedtime session than during peak time session. Participants who showed a large positive shift in body temperature between bedtime and peak time fell between these groups and were not significantly different from the three other groups of subjects. These results could indicate that individuals who show a physiological propensity for morningness (i.e., body temperature higher during peak time than bedtime) are more likely to employ the logical, deliberative System 2 when making

decisions in the Ultimatum Game. It is unclear why these differences did not occur in a linear fashion (i.e., with participants with large positive differences in body temperature rejecting fewer offers than those with small positive differences); however, the very small effect size (partial η^2=.09) indicates that these results are unlikely to be replicable. Furthermore, the time of day at which the session was conducted remained noncontributory to performance.

Bivariate correlations between Ultimatum Game performance and body temperature differences between sessions suggest that individuals whose body temperature shifted in the expected direction (i.e., higher at peak time than at bedtime) were less likely to reject highly unfair offers than were those with higher body temperature at bedtime than at peak time. While these correlations were small, they support the above findings that individuals with a physiological propensity for morningness may be more likely to utilize System 2 when making decisions in the Ultimatum game.

The Balloon Analog Risk Task

Initial analyses reveal no effect of time of day on performance on the BART. Inclusion of self-reported circadian phase as a moderator in the model yielded similar null results. Using the difference in temperature between sessions as a moderator in the model yielded an interaction between temperature difference and time of day in which individuals with large shifts in the expected direction displayed less risky behavior during the peak time session than during the bedtime session. Participants with the opposite

temperature pattern displayed more risky behavior during the peak time session than during the bedtime session. These results suggest that individuals with a physiological propensity for morningness are more apt to engage in risky behavior at night than during the day whereas individuals with a physiological propensity for eveningness may act more riskily during the day. These results are consistent with previous literature on body temperature rhythms and cognitive performance (Colquhoun, 1971; Kleitman, 1963), in that performance appears to be more impaired when body temperature is lower, and could represent relative activation of System 1 and System 2 at different times of day for individuals with different circadian phases. The logical, deliberative systems of the prefrontal cortices may be more activated during the day in morning-types and more activated at night in evening-types.

Respiratory Sinus Arrhythmia

Respiratory sinus arrhythmia (RSA) is a physiological indicator of parasympathetic activation and is thought to index emotion regulation. RSA was measured during two conditions at each study session: a resting baseline and a serial subtraction task designed to act as a stressor. RSA was found to be unrelated to measures of decision making and risk taking. Because parasympathetic activation is associated with the "rest and digest" portion of the "fight or flight" response, it is expected to decrease in response to stress (while sympathetic "fight or flight" activation is expected to increase). Accordingly, previous literature indicates that RSA tends to be reduced during stressful tasks (Berntson et al., 1994; Berntson et al., 1996); however in the present study RSA

was higher during the serial subtraction task than during the resting baseline. These results suggest that in the present sample, participants had higher parasympathetic activation during the serial subtraction than during resting baseline. Rate of respiration has also been shown to influence measurement of RSA. While attempts were made to control for this variable, these data were compromised by the act of participants speaking aloud during the serial subtraction task. The effect that speaking aloud had on the measurement of respiration made the data uninterpretable; therefore the unexpected effects seen in response to the stressor may be due in part to differences in respiration rate between the tasks.

Further analyses revealed interactions between RSA, task (i.e., baseline or subtraction), and time of day. These results demonstrated that evening- and neutral-types show similar patterns in that RSA was higher during serial subtraction than during resting baseline, and that this phenomenon did not change depending on the time of day. Morning-types showed a distinctly different pattern: RSA was approximately the same during resting baseline and serial subtraction at the peak time session, but during the bedtime session RSA was higher during resting baseline than during serial subtraction (and higher during resting baseline than during either task at peak time). These results suggest that morning-types may show a diurnal rhythm of RSA where resting RSA is lower at night than it is during the day, while this rhythm is not seen in evening- and neutral-types. Furthermore, morning-types appear to show a task-dependent vagal withdrawal in response to stress at bedtime as compared to peak time, whereas evening- and neutral-types show a vagal enhancement. The effect seen in morning-types could be

due to an overall vagal withdrawal throughout the subtraction task, or could be due to between-group differences in rates of recovery from the stressor. Analyses to determine the rates of recovery from the stressor will be conducted at a later date. When difference in temperature between sessions was examined as a moderator of RSA, no significant results were found. This further supports the hypothesis that body temperature and the MEQ are measuring two different constructs in this sample.

Study Limitations

The present study had several limitations that may restrict the interpretation of the results. First, due to financial and time constraints, study sessions were scheduled solely based on participants' habitual wake times, which may not be indicative of their internal circadian phase. Future studies should aim to pinpoint the peak and decline of circadian phase using established measures such as examining core body temperature under constant routine conditions or evaluating dim light melatonin onset. Second, individuals were exposed to social interaction with the experimenter upon arrival at the lab. While the manipulation achieved the expected effects on sleepiness, this social interaction may have had an alerting effect that could have altered their performance on the tasks presented during the session. Third, analyses of respiration rate could not be completed due to the effects of speaking aloud on the measurement of respiration. Analyses of RSA should be interpreted with caution, as respiration rate is known to influence RSA.

Conclusions

While there are several limitations to the present study, some valuable conclusions can be drawn. Time of day does not appear to have an effect in and of itself on decision making. This could be due to the possibility that the manipulation of scheduling sessions 4 and 16 hours after habitual wake time did not capture the peak and decline of participants' circadian phase. Circadian phase may interact with time of day to impact performance. Participants in the present study showed similar trends to those observed in previous research where performance on the tasks was enhanced at high body temperatures versus lower temperatures. Results also indicate that morning-types (as characterized by the MEQ) may show different physiological responses to stress than to evening- and neutral-types. Future research should aim to clarify the role of body temperature rhythm and/or circadian phase in decision making and RSA reactivity to stress, perhaps by selectively sampling the extremes of these two measures or by using more reliable measures of circadian phase.

Data in the present study suggest that the MEQ and body temperature were measuring two different constructs. These findings may be due in part to the age group sampled in the present study. Adolescents tend to shift from morningness tendencies to eveningness as they age. The lack of correspondence between body temperature rhythms and self-reported circadian phase may be indicative of this shift in that their temperature rhythm may not have "caught up" to their subjective circadian preferences. Further research should investigate the reliability of this finding and seek to determine if the MEQ is a valid measure of circadian phase in this age group.

APPENDIX A

Demographic Questionnaire

Study ID:_____

Contact Information:

Name: _____

Address:_____
_____

Phone Number: _____

Email: _____

Preferred method and time to contact: _____

The following questions will help us determine your eligibility for the study. Please answer them truthfully. Your answers will be kept confidential.

Age: _____

Sex (circle one): Male Female

Marital Status (circle one):

1. Single
2. Married
3. Widowed
4. Separated
5. Divorced

Race (circle all that apply):

1. American Indian or Alaska Native
2. Asian
3. Native Hawaiian or Other Pacific Islander
4. Black or African American
5. White
6. Other:_____
7. Unknown

Ethnicity (circle one):

1. Hispanic or Latino
2. Not Hispanic or Latino
3. Unknown

Years of education: _____

Have you ever had any kind of psychological problems? YES **NO**

Explain:_____
_____

Do you have any current medical problems? YES **NO**

Explain:
_____
_____

Are you currently taking any medications?
(list)_____

How is your sleep quality? Poor Fair Good Excellent
_____

Do you take any medication for sleep? YES **NO**

Medical Information Form

Subject ID: _____ Date: _____

Please answer the following questions concerning your general health by filling in the blank, or putting a check mark in the appropriate column. Responses are confidential as described on the consent form.

1. In the past two years, have you been under the care of a physician for any medical conditions? Y / N
   If yes, what is (are) the condition(s)?
   _____
   _____
   _____

2. Have you ever been under a doctor's care for emotional or nervous problems (anxiety, depression, etc.)? Y / N
   If yes, are you currently in treatment?_____

3. Have you ever had any drug reactions, drug allergies or allergies of any kind? Y / N
   If yes, to what?_____

4. Have you ever had any of the following conditions?:

a. Seizures or loss of consciousness?	Y /N
b. Head injury with loss of consciousness?	Y / N
c. Problems with vision or glaucoma?	Y / N
d. Persistent headaches?	Y / N
e. Persistent dizziness?	Y / N
f. Persistent muscle weakness?	Y / N

5. How much caffeine do you drink on an average day? (Please give numbers for a, b, & c).
   a. _____ cups of coffee per day.
   b. _____ cups of tea (including ice tea) per day.
   c. _____ cans (12 oz.= 1 serving, 32 oz = 3 servings) of caffeinated soda per day (e.g. Coke, Dr. Pepper, Mt. Dew, etc).
   d. _____ cigarettes per day
   e. How many servings (cups, cans) of caffeine have you had in the 12 hours prior to this experiment? _____

6. How many drinks of alcohol do you have each week on average? (Please give numbers for a, b, & c).
   a. _____ bottles of beer per week
   b. _____ glasses of wine per week
   c. _____ shots of liquor per week

7. Do you use any of the following drugs? About how often? If you have used any of the following, please indicate when it was last used in the last column

	Previously Heavily	Never	Once a year	Once a month	Once a week	Daily	How long ago last used? (Circle one)
a. MAJOR TRANQUILIZERS (Mellaril, Thorazine, Stelazine, Haldol, etc.)							Days Weeks Months Years
b. MINOR TRANQUILIZERS (Valium, Xanex, Librium)							Days Weeks Months Years
c. Barbiturates / Sedatives (Amytal, Phenobarbital)							Days Weeks Months Years
d. Amphetamines / stimulants							Days Weeks Months Years
e. Marijuana							Days Weeks Months Years
f. Hashish							Days Weeks Months Years
g. Cocaine / Crack							Days Weeks Months Years
h. Hallucinogens (LSD, mushrooms)							Days Weeks Months Years
i. Other (specify)							Days Weeks Months Years

Horne-□stberg Morningness & Eveningness (Owl & Lark) Questionnaire

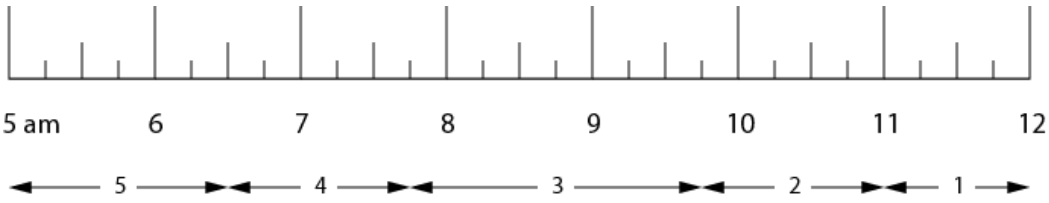
Study ID:_____ Date: _____

Instructions:

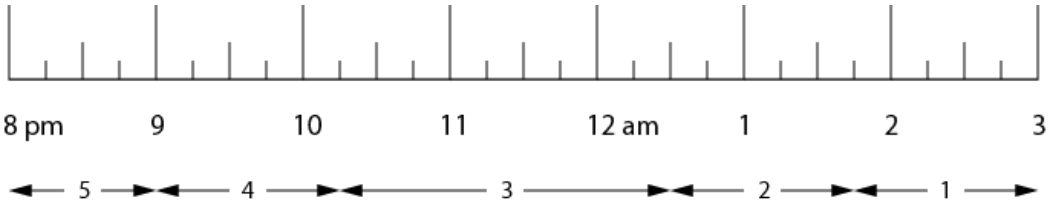
1. Please read each question very carefully before answering.
2. Answer ALL questions.
3. Answer questions in numerical order.
4. Each question should be answered independently of others. Do NOT go back and check your answers.
5. All questions have a selection of answers. For each question choose one answer only. Some questions have a scale instead of a selection of answers. Place a mark at the appropriate point along the scale.

Questions:

1. Considering only your own "feeling best" rhythm, at what time would you get up if you were entirely free to plan your own day?



2. Considering only your own "feeling best" rhythm, at what time would you go to bed if you were entirely free to plan your evening?



3. If there is a time at which you have to get up in the morning, to what extent are you dependent on being woken up by an alarm clock?

   Not at all dependent -> 4
   Slightly dependent -> 3
   Fairly dependent -> 2
   Very dependent -> 1

4. Assuming adequate environmental conditions, how easy do you find getting up in the mornings?

   Not at all easy -> 1
   Not very easy -> 2
   Fairly easy -> 3
   Very easy -> 4

5. How alert do you feel during the first half-hour after having woken in the morning?

   Not at all alert -> 1
   Slightly alert -> 2
   Fairly alert -> 3
   Very alert -> 4

6. How is your appetite during the first half-hour after having woken in the morning?

   Very poor -> 1
   Fairly poor -> 2
   Fairly good -> 3
   Very good -> 4

7. During the first half-hour after having woken in the morning, how tired do you feel?

   Very tired -> 1
   Fairly tired -> 2
   Fairly refreshed -> 3
   Very refreshed -> 4

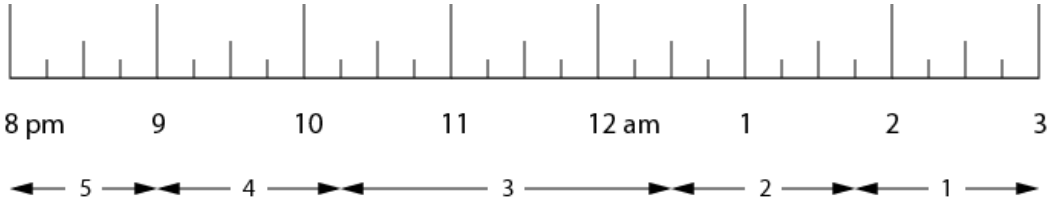
8. When you have no commitments the next day, at what time do you go to bed compared to your usual bedtime?

   Seldom or never later -> 4
   Less than one hour later -> 3
   1-2 hours later -> 2
   More than two hours later -> 1

9. You have decided to engage in some physical exercise. A friend suggests that you do this one hour twice a week and the best time for him is between 7:00 - 8:00 am. Bearing in mind nothing else but your own "feeling best" rhythm how do you think you will perform?

Would be in good form	-> 4
Would be in reasonable form	-> 3
Would find it difficult	-> 2
Would find it very difficult	-> 1

10. At what time do you feel tired and as a result in need of sleep?



11. You wish to be at your peak performance for a test which you know is going to be mentally exhausting and lasting for two hours? You are entirely free to plan your day and considering only your own "feeling best" rhythm which ONE of the four testing times would you choose?

8:00 - 10:00 am.	-> 6
11:00 am. - 1:00 pm.	-> 4
3:00 - 5:00 pm.	-> 2
7:00 - 9:00 pm.	-> 0

12. If you went to bed at 11:00 pm. at what level of tiredness would you be?

Not at all tired	-> 0
A little tired	-> 2
Fairly tired	-> 3
Very tired	-> 5

13. For some reason you have gone to bed several hours later than usual, but there is no need to get up at any particular time the next morning. Which ONE of the following events are you most likely to experience?

    Will wake up at usual time and will NOT fall asleep -> 4
    Will wake up at usual time and will doze thereafter -> 3
    Will wake up at usual time but will fall asleep again -> 2
    Will NOT wake up until later than usual -> 1

14. One night you have to remain awake between 4:00 - 6:00 am. in order to carry out a night watch. You have no commitments the next day. Which ONE of the following alternatives will suit you best?

    Would NOT go to bed until watch was over -> 1
    Would take a nap before and sleep after -> 2
    Would take a good sleep before and nap after -> 3
    Would take ALL sleep before watch -> 4

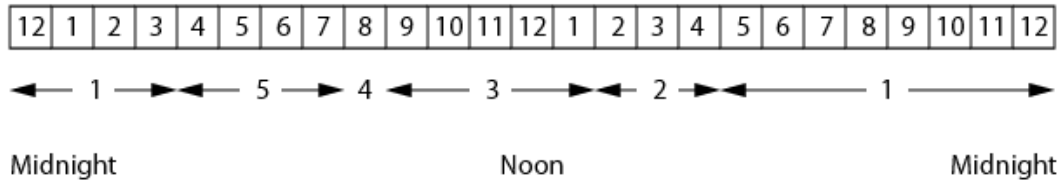
15. You have to do two hours of hard physical work. You are entirely free to plan your day and considering only your own "feeling best" rhythm which ONE of the following times would you choose?

    8:00-10:00 am -> 4
    11:00am -1:00pm -> 3
    3:00-5:00pm -> 2
    7:00-9:00pm -> 1

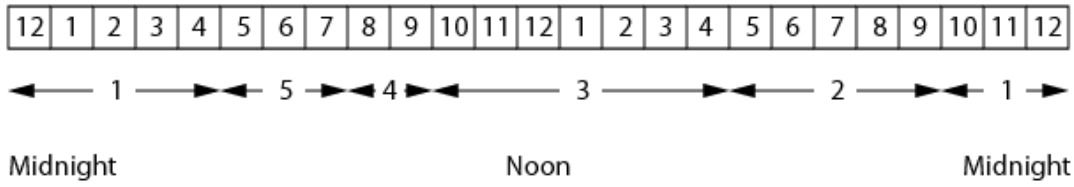
16. You have decided to engage in hard physical exercise. A friend suggests that you do this for one hour twice a week and the best time for him is between 10:00-11:00pm. Bearing in mind nothing else but your own "feeling best" rhythm how well do you think you would perform?

    Would be in good form -> 1
    Would be in reasonable form -> 2
    Would find it difficult -> 3
    Would find it very difficult -> 4

17. Suppose that you can choose your own work hours. Assume that you worked a FIVE-hour day (including breaks) and that your job was interesting and paid by results. Which FIVE CONSECUTIVE HOURS would you select?



18. At what time of the day do you think that you reach your "feeling best" peak?



19. One hears about "morning" and "evening" types of people. Which ONE of these types do you consider yourself to be?

Definitely a "morning" type	-> 6
Rather more a "morning" than an "evening" type	-> 4
Rather more an "evening" than a "morning" type	-> 2
Definitely an "evening" type	-> 0

Stanford Sleepiness Scale (SSS)

Study ID: _____

Session (circle one): peak bedtime

Please circle the most appropriate number based on how sleepy you feel **right now**.

Degree of Sleepiness	**Scale Rating**
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not at peak; able to concentrate	2
Awake, but relaxed; responsive but not fully alert	3
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7
Asleep	X

APPENDIX B

Details of the Balloon Analog Risk Task

As described by Lejuez et al. (Lejuez, Aklin, Jones et al., 2003):

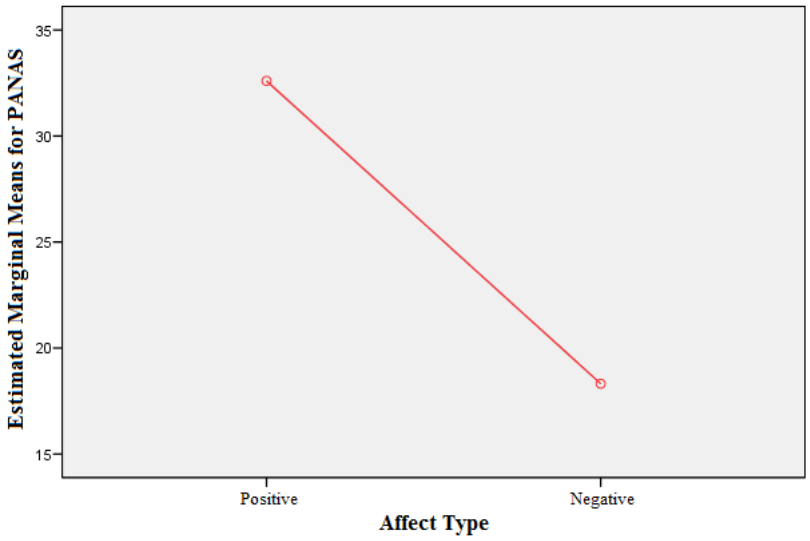
> Each click on the pump inflated the balloon 1° (about 0.125 in. [0.3 cm] in all directions). With each pump, 5 cents were accrued in a temporary reserve (the amount of money in this reserve is never indicated to the participant). When a balloon was pumped past its individual explosion point, a "pop" sound effect was generated from the computer. When a balloon exploded, all money in the temporary bank was lost, and the next uninflated balloon appeared on the screen. At any point during each balloon trial, the participant could stop pumping the balloon and click the *Collect $$$* button. Clicking this button would transfer all money from the temporary bank to the permanent bank, during which the new total earned would be incrementally updated cent by cent while a slot machine payoff sound effect played.
>
> After each balloon explosion or money collection, the participant's exposure to that balloon ended, and a new balloon appeared until a total of [30] balloons (i.e., trials) had been completed… Participants were given no detailed information about the probability of an explosion… They were told that at some point each balloon would explode and that this explosion could occur as early as the first pump all the way up to the point at which the balloon had expanded to fill the entire computer screen…
>
> The probability that a balloon would explode was arranged by constructing an array of *N* numbers. The number 1 was designated as indicating a balloon explosion. On each pump of the balloon, a number was selected without replacement from the array. The balloon exploded if the number 1 was selected. For example, the array for blue balloons contained the integers 1–128. Thus, the probability that a blue balloon would explode on the first pump was 1/128. If the balloon did not explode after the first pump, the probability that the balloon would explode was 1/127 on the second pump, 1/126 on the third pump, and so on up until the 128th pump, at which the probability of an explosion was 1/1 (i.e., 100%). According to this algorithm, the average break point would be 64 pumps. (p.77)

APPENDIX C

Analyses of the Influence of Time of Day and Self-Reported Circadian Phase on Positive and Negative Affect.

In order to determine the influence of time of day on positive and negative affect, a 2x2 repeated measures ANOVA (affect: positive, negative; time of day: peak, bedtime) was conducted. Results revealed a significant main effect for affect (p<.01) such that participants reported more positive affect than negative affect (see Figure C.1).

Figure C.1. Main effect of affect type.



There was a trend towards a main effect for time of day (p=.08) such that participants reported more affect overall at peak time versus bedtime (see Figure C.2), and a trend towards an interaction between affect and time of day (p=.06) such that participants

showed more positive affect at peak time versus bedtime, and about the same amount of negative affect during both sessions (see Figure C.3).

Figure C.2. Main effect of time of day on positive and negative affect.

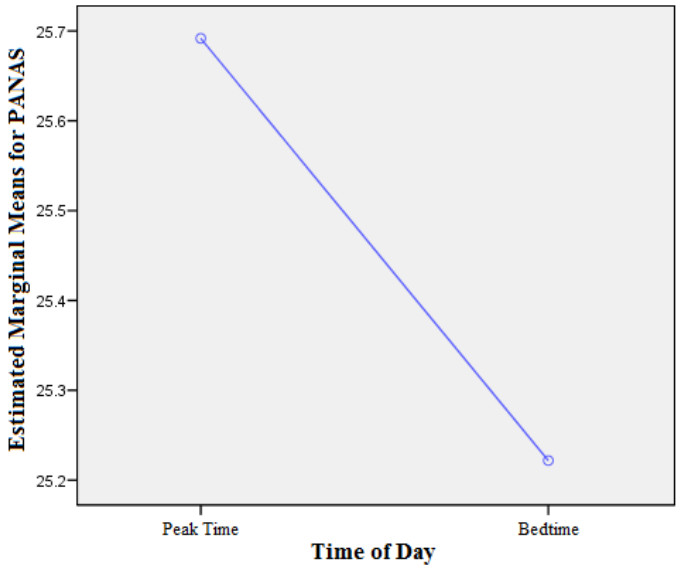
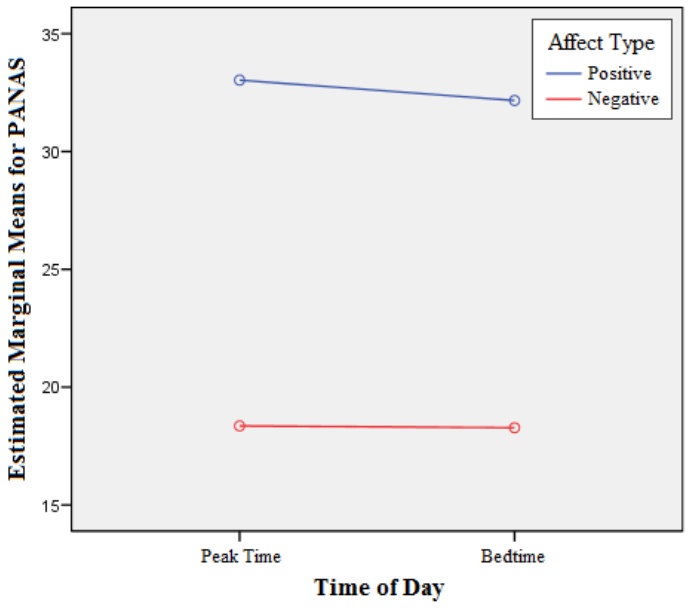
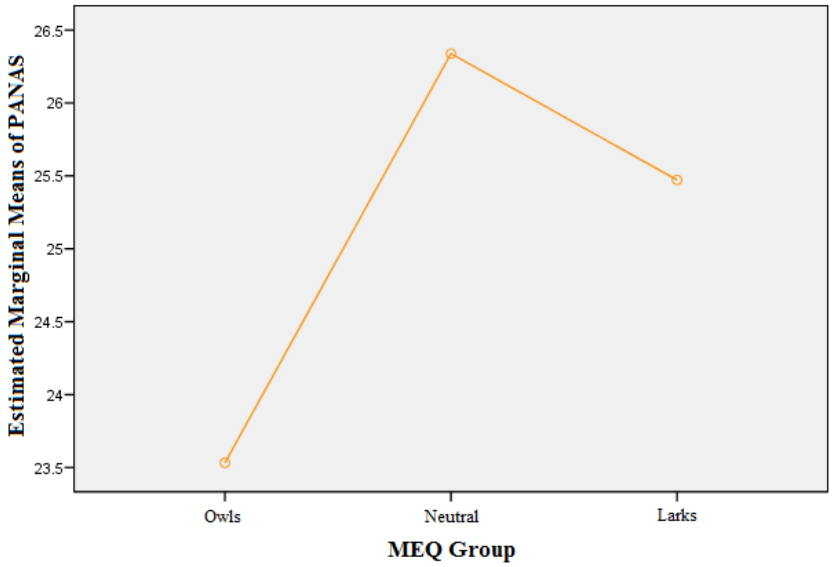


Figure C.3. Interaction between affect type and time of day.



MEQ group was entered as a between-subjects variable into the above analysis to examine the impact of self-reported circadian phase on the relationship between time of day and positive and negative affect. Results revealed a similar main effect for affect type ($p<.01$), and the interaction between affect type and time of day became significant ($p<.05$). There was also a significant main effect for MEQ group ($p<.01$) such that owls had lower scores on the PANAS than either neutral types or larks (see Figure C.4).

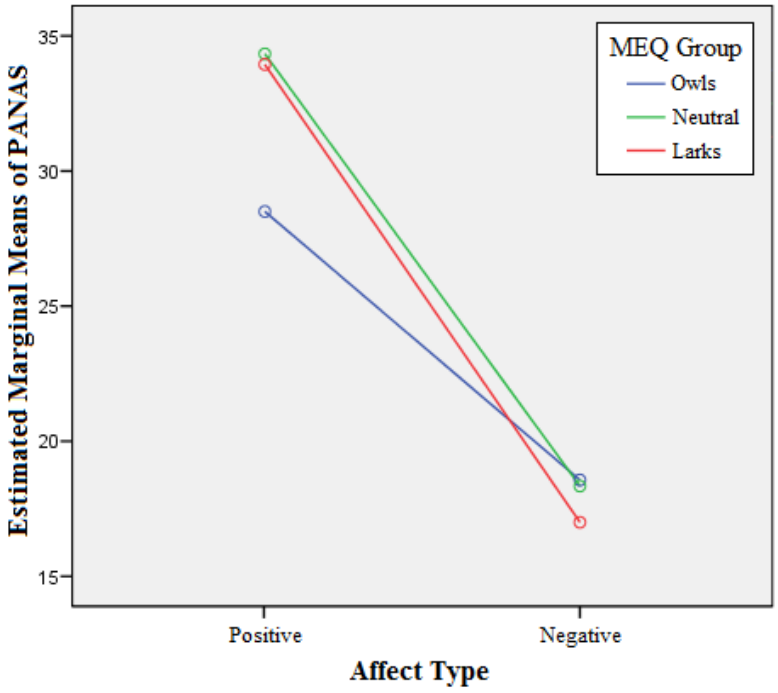
Figure C.4. Main effect of MEQ group on positive and negative affect.



This main effect was qualified by an interaction between affect type and MEQ group ($p<.01$) suggesting that owls reported less positive affect than neutral types and larks, and that all three groups reported approximately the same amount of negative affect (see Figure C.5). There was no significant main effect for time of day ($p=.11$), nor were there

interactions between time of day and MEQ group (p=.78) or time of day, affect, and MEQ group (p=.47).

Figure C.5. Interaction between MEQ group and affect.



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