# LONGITUDINAL EXAMINATION OF SLEEP AND CHRONONUTRITION

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**Title**

Longitudinal Examination of Sleep and Chrononutrition

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

**DOCTOR OF PHILOSOPHY**

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**ABSTRACT**

Chrononutrition (i.e., circadian timing of food intake) offers promising opportunities to improve weight management strategies, but many fundamental aspects of chrononutrition are still unknown. While research to date has suggested that unhealthy chrononutrition behaviors are linked to weight gain, chrononutrition preferences are markedly understudied, and research has not yet determined whether chrononutrition preferences and behaviors are variable or stable over time in the natural environment. Potential mechanisms underlying chrononutrition's impact on weight are still being explored. Recent evidence suggests that weight gain is the result of an imbalance of energy consumption and expenditure that is influenced by sleep duration. Though short sleep duration may undermine weight loss efforts, lead to increased preference for energy-dense foods, and even alter chrononutrition, chrononutrition's role in energy balance has been less studied. The purpose of the present online study was therefore to examine chrononutrition, sleep duration, and body mass index (BMI) in the natural environment, over time, in a sample of healthy, non-shift working adults. Participants completed a series of measures online and self-reported their body weight and height three times, approximately every six months, for one year. This longitudinal study showed that chrononutrition preferences were largely stable over time, while chrononutrition behaviors were more variable over the study period. Results also showed that, contrary to our hypotheses, chrononutrition was not a significant predictor of later BMI, and chrononutrition did not mediate the relationship between sleep duration and later BMI. This study provided a novel examination of fundamental aspects of chrononutrition, knowledge of which may be vital for the development of obesity prevention and treatment strategies.

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# INTRODUCTION

Over the past 50 years, obesity has become alarmingly prevalent in the United States; the number of adults classified as having obesity has more than doubled (Fryar, Carroll, & Ogden, 2012). Today, as many as 36% of American adults over 20 years of age have obesity (body mass index (BMI) $\geq 30$ kg/m$^2$), while an additional 33% fall in the overweight category (BMI of 25.0-29.9 kg/m$^2$) (Flegal, Kruszon-Moran, Carroll, Fryar, & Ogden, 2016). This excess weight is associated with numerous adverse health outcomes, including hypertension, type 2 diabetes, and premature mortality (Hruby & Hu, 2015). Thus, obesity carries a high economic cost; obesity-associated illnesses cost roughly $190 billion per year (2005 USD) (Cawley & Meyerhoefer, 2012). In fact, obesity and obesity-related illnesses accounted for an estimated one-fifth of healthcare spending in recent years (Lehnert, Sonntag, Konnopka, Riedel-Heller, & König, 2013). As a result of these substantial costs, much research has been devoted to understanding the biobehavioral factors that influence weight gain and obesity, which, in turn, can help inform effective obesity prevention and treatment strategies.

Despite decades of such research chiefly focused on dietary intake, obesity rates continue to rise. Most existing weight loss and weight management initiatives target the quality and quantity of food intake (e.g., MyPlate (U.S. Department of Agriculture)), but these strategies often fail to achieve lasting results (Kraschnewski et al., 2010). Circadian science offers new avenues to extend knowledge of obesity-related behavioral factors and can inform novel weight management strategies.

## Chrononutrition and Circadian Rhythms

While many existing dietary intervention efforts have focused on the role of *what* and *how much* is eaten, emerging evidence has suggested that *when* food intake occurs may be just as important to consider. Chrononutrition (i.e., the circadian timing of food intake (Arble, Bass, Laposky, Vitaterna, & Turek, 2009)) is a developing field of study centered around the notion that *when eating occurs* may be just as important to examine as *what* and *how much* is eaten. Chrononutrition is regulated by the feeding/fasting cycle, one of the most essential circadian rhythms for human health and function (Dunlap, Loros, & DeCoursey, 2004). Circadian rhythms are approximately 24h patterns of physiological and behavioral adaptations which occur in synchrony with the Earth's rotation around its axis (Dunlap et al., 2004). Because these cycles are, by definition, not exactly 24 hours, the body's circadian system must rely on Zeitgebers, or "time-givers" to synchronize to the 24h day. Fluctuations in response to Zeitgebers ensure that the body meets the changing energy demands throughout the 24h day. However, in modern society, many humans are eating, sleeping, working, and socializing throughout the 24h day. Engaging in these behaviors at the "wrong" time of the 24h day (i.e., a time misaligned with the light/dark cycle) disrupts one's natural circadian rhythms (Dunlap et al., 2004). Current research has suggested that circadian rhythms are a key regulator of metabolic processes (Riede, van der Vinne, & Hut, 2017): in particular, feeding/fasting cycles enable synchronization of the body's liver clock to the environment (Hara et al., 2001; Stokkan, Yamazaki, Tei, Sakaki, & Menaker, 2001). This process is designed to ensure that numerous biological processes (e.g., lipid metabolism (Masri et al., 2014), glucose homeostasis (Gachon, Loizides-Mangold, Petrenko, & Dibner, 2017)) occur at the "right" times of the 24h day. Hence, chrononutrition could substantially impact an array of metabolic processes, including gluconeogenesis and lipid digestion, by altering synchronization of the liver clock. As such, scientists are beginning to explore several lines of inquiry to better understand the role of chrononutrition in obesity and the potential utility of chrononutrition in weight management and obesity prevention.

## Chrononutrition Preferences and Behaviors

A review of the existing literature has highlighted six specific chrononutrition behaviors which may influence metabolism and health: 1) eating window, 2) breakfast skipping, 3) largest meal, 4) evening eating, 5) evening latency, and 6) night eating (Veronda, Allison, Crosby, & Irish, 2020). Evidence for each chrononutrition behavior is briefly summarized below.

### Eating Window

This term refers to the duration of time (in minutes) between the first eating event of the day and the last eating event of the day. Mice who were fed during the "wrong" eating window (i.e., the typical rest phase) gained significantly more weight than mice fed during the "right" eating window (i.e., the typical active phase), even though caloric intake was identical across conditions (Arble et al., 2009). Compared to *ad libitum* access to food, a restricted eating window can reduce insulin resistance (Chaix, Zarrinpar, Miu, & Panda, 2014) and mitigate the negative metabolic effects of a high-fat diet in mice (Hatori et al., 2012). Humans who restricted their eating window from 14 to 10-11h/day for 16 weeks lost weight and maintained the weight loss at a one-year follow-up (Gill & Panda, 2015).

Relatedly, preliminary research has indicated that one's **eating midpoint** (represented as the clock time halfway between the first eating event of the day and the last eating event of the day) may also be important to consider, as an "early" eating schedule may promote a healthy weight when coupled with an 11h eating window, compared to a "delayed" eating schedule in an 11h eating window (Allison et al., 2020); however, more research is needed on this construct.

### Breakfast Skipping

While research on the exact health consequences of "breakfast skipping" is mixed (e.g., St-Onge et al., 2017; Lee et al., 2016), evidence has suggested that individuals who regularly skip breakfast are approximately five times more likely to have obesity (Ma et al., 2003) and may exhibit irregular cortisol rhythms and increased systolic and diastolic blood pressure (Witbracht, Keim, Forester, Widaman, & Laugero, 2015). Further, breakfast is typically the first eating event of the day (i.e., after a night of sleep); the time of the first eating event of the day is important, as it sets the phase of the body's liver clock (Hirao et al., 2010), which is vital for synchronizing the timing of an array of metabolic processes (for review, see Reinke & Asher, 2016).

### Largest Meal

"Largest meal" refers to the meal in which individuals consume the greatest amount of calories. Recent evidence has suggested that consuming the largest meal earlier in the day (i.e., breakfast) is linked to lower BMI and lower waist circumference, compared to consuming a later largest meal (i.e., dinner) (Jakubowicz, Barnea, Wainstein, & Froy, 2013; Kahleova, Lloren, Mashchak, Hill, & Fraser, 2017).

### Evening Eating

This term is defined as the time of the last eating event before bed. Food intake earlier in the day, as opposed to in the evening, has been linked to lower BMI, lower waist circumference, and lower total daily caloric intake (Dattilo, Crispim, Zimberg, Tufik, & de Mello, 2010; Reid, Baron, & Zee, 2014). Specifically, eating after 8:00 PM has been associated with increased BMI (Baron, Reid, Kern, & Zee, 2011).

### Evening Latency

Relatedly, "evening latency", or the duration of time between the last eating event of the day and sleep onset, may also be a relevant chrononutrition behavior as it considers evening eating in the context of different sleep schedules, though this has been less studied. In one study, eating within two hours of bed was linked to increased acid reflux symptoms, compared to eating within six hours of bed (Piesman, Hwang, Maydonovitch, & Wong, 2007).

**Night Eating**

"Night eating" refers to waking in the night to eat. Much of the knowledge of effects of eating in the night comes from studies of night eating syndrome (NES), an eating disorder first noted by Stunkard et al. (1955). The disorder is typically characterized by consuming a significant portion of the day's food in the evening, waking in the night to eat, lack of appetite in the morning, and distress or functional impairment (Allison et al., 2010; O'Reardon, Peshek, & Allison, 2005). A key hallmark of NES is that an individual is conscious while consuming food (O'Reardon et al., 2005). It is believed that NES may be caused by a desynchrony between the sleep/wake and feeding/fasting cycles (O'Reardon et al., 2004). NES has been linked to obesity, as well as a variety of other health consequences, such as depression and anxiety (for review, see Cleator, Abbott, Judd, Sutton, & Wilding, 2012).

Taken together, the literature on these chrononutrition behaviors thus far suggests that, for healthy chrononutrition: the majority of energy intake (e.g., largest meal) should typically be confined to a distinct window (e.g., eating window) with food intake occurring earlier in the day (e.g., breakfast consumption), rather than in the evening (e.g., evening eating), close to bedtime (e.g., evening latency), or in the night (e.g., night eating).

Research on chronotype (i.e., sleep/wake timing preferences), a related chronobiological construct, suggests that both individuals' sleep behaviors and sleep/wake timing preferences can influence sleep timing (Roenneberg, Wirz-Justice, & Merrow, 2003). Evidence suggests that sleep behaviors can be highly variable due to environmental (Halperin, 2014) and psychosocial factors (Âkerstedt, 2006), whereas sleep/wake timing preferences (i.e., chronotype) tend to be relatively stable over time (Paine, Gander, & Travier, 2006). Similarly, perhaps one's preferred timing of food intake and one's actual timing of food intake can influence the circadian timing of food intake as well as influence one's ability to change eating patterns. Whereas much of the research to date has examined chrononutrition behaviors in the context of weight gain, chrononutrition preferences have largely been ignored. These preferences may be an independently important predictor of weight gain as they may impact an individual's ability to adhere to recommended eating schedules. Taken together, this small but growing body of research has demonstrated that chrononutrition preferences and behaviors may be meaningful factors to consider in obesity prevention and treatment efforts.

## Chrononutrition as a Pathway to Obesity

In addition to its direct influence on body weight, chrononutrition may also serve as a mechanism by which other biobehavioral factors impact obesity. Notably, sleep is a physiological process prospectively (Patel, Malhotra, White, Gottlieb, & Hu, 2006; Xiao, Arem, Moore, Hollenbeck, & Matthews, 2013) associated with obesity which is also regulated, in part, by the circadian sleep/wake cycle. Short sleep duration is particularly relevant to public health, with over half of American adults reporting sleep duration of less than 7h/night (Liu et al., 2016). Furthermore, short sleep duration has been linked to increased risk of type 2 diabetes (Shan et al., 2015), coronary heart disease (Cappuccio, Cooper, D'Elia, Strazzullo, & Miller, 2011), colorectal cancer (Zhao et al., 2013), and all-cause mortality (Cappuccio, D'Elia, Strazzullo, & Miller, 2010). To date, research has identified several biobehavioral mechanisms by which sleep duration may impact obesity.

The updated energy balance model posits that weight gain is the result of an imbalance of energy consumption and expenditure that is influenced by sleep duration (Penev, 2007; Penev, 2012). Short sleep duration leads to a variety of physiological adaptations that disrupt healthy energy balance, such as changes in ghrelin and insulin levels and a lowered resting metabolic rate (Penev, 2012). These physiological changes then bring about behaviors that either provide the body with energy or conserve energy (e.g., increased food intake (Penev, 2012), increased preference for high fat, sugary, and salty foods (Kant & Graubard, 2014; Kim, DeRoo, & Sandler, 2011; Spaeth, Dinges, & Goel, 2014). Thus, chronic short sleepers who frequently engage in these energy-conserving behaviors may be more likely to experience weight gain, obesity, and a number of related health conditions. Further, evidence suggests that short sleep duration may undermine efforts to modify energy-related behaviors such as diet or exercise behaviors, effectively increasing the difficulty of weight loss or healthy weight management via its impact on homeostatic processes (Nedeltcheva, Kilkus, Imperial, Schoeller, & Penev, 2011; Bromley, Booth, Kilkus, Imperial, & Penev, 2012). Sleep may also impact the timing of food intake.

Although the feeding/fasting cycle and the sleep/wake cycle are regarded as two distinct circadian rhythms, sleep has the potential to affect chrononutrition behaviors significantly. The first eating event after a night of sleep (i.e., the longest fasting period of the 24h day) resets the time of the body's liver clock (Hirao et al., 2010); thus, just a few nights of short sleep can alter timing of numerous metabolic processes and eating events. Short sleep could also impact chrononutrition as a result of neurocognitive deficits (Durmer & Dinges, 2005). For example, evidence has suggested that restricted sleep can impair executive functioning (Lowe, Safati, & Hall, 2017): individuals who experience short sleep duration may have an inability to inhibit unhealthy chrononutrition behaviors and impaired planning of meal times. Collectively, the extant literature has suggested that chrononutrition may serve as a practical alternative for future obesity intervention efforts, but many basic questions about chrononutrition have yet to be answered.

## Chrononutrition: Novel Directions for Research

The present study aimed to build upon prior research in order to evaluate innovative questions and increase knowledge of chrononutrition. Much of chrononutrition research thus far has utilized experimental paradigms. In consequence, a paucity of evidence exists regarding chrononutrition behaviors and chrononutrition preferences in the natural environment. Further, we do not yet know whether chrononutrition behaviors and preferences vary over time. While much of the clinical work on chrononutrition has established its importance in the context of overweight and obesity, these highly controlled studies lack ecological validity. Understanding of chrononutrition patterns in the natural environment and over time may have a great bearing on future intervention work (e.g., identification of high-risk times for poor chrononutrition). The present study also aimed to provide a first step toward extending the energy balance model to include both sleep and chrononutrition. Although it is well-established that circadian rhythms are necessary to ensure that an organism meets the energy demands throughout the 24h day, and recent evidence suggests that chrononutrition in particular is meaningful for metabolic health, the energy balance model does not yet consider the circadian timing of food intake. Inclusion of this construct in future versions of the model may account for some variance not explained by sleep, dietary intake, and physical activity.

Thus, the purpose of this study was to examine chrononutrition preferences, chrononutrition behaviors, sleep duration, and BMI for one year. Specifically, I aimed to:

1. Investigate the stability of chrononutrition preferences and chrononutrition behaviors over time. Given the literature on the similar chronobiological construct of sleep/wake timing

behaviors and preferences, I hypothesized that chrononutrition preferences would remain stable over time, while chrononutrition behaviors would be more variable over the one-year period.

2. Determine the impact of chrononutrition behaviors on weight gain over one year. Based on research suggesting a link between unhealthy chrononutrition behaviors and weight gain, I hypothesized that worse chrononutrition behaviors (i.e., longer eating window, more frequent breakfast skipping, shorter evening latency, more frequent night eating, later largest meal, and later evening eating) would prospectively predict increased BMI.

3. Examine the extent to which chrononutrition serves as a mechanism by which sleep duration influences body weight. Research has suggested that sleep can have both direct and indirect effects on body weight. Further, evidence has indicated that this relationship may be mediated by chrononutrition. Thus, I hypothesized that the relationship between sleep duration and changes in BMI over time would be partially mediated by chrononutrition behaviors.

# METHOD

The present study was a one-year longitudinal study conducted out of North Dakota State University (NDSU) in Fargo, North Dakota. Repeated measurement of chrononutrition preferences and behaviors, sleep, and BMI across three timepoints (each ~6 months apart) allowed us to expand upon prior research and improve understanding of fundamental aspects of chrononutrition in the context of weight gain.

## Participants and Procedure

All study procedures were approved by the NDSU Institutional Review Board (IRB).

### Recruitment and Screening

Participants (n=258 at Time 1) were recruited through Prolific (prolific.co), a web-based platform created for researchers, by researchers, for online survey research. Upon completing their registration for Prolific, Prolific users complete screening questions through the website, which researchers can then use to determine study eligibility. This screening process was utilized for the present study. Individuals were eligible to participate if they read and spoke English; were current residents of the United States; were 18 to 65 years of age; did not report a diagnosis of any chronic diseases such as diabetes, heart disease, stroke, etc.; and did not report shift work. These criteria were selected to reduce potential confounding age- and lifestyle-related factors. Individuals who were eligible to participate received an invitation to enroll in the study via Prolific and could then sign up for their first study session on Prolific. Individuals recruited via Prolific were compensated with a monetary payment upon the conclusion of each wave of the study.

## Data Collection

The informed consent process occurred online. Participants were informed of the study purposes and procedures as well as potential risks in the study consent form, and individuals who agreed to participate signed the consent form electronically. Prolific-based contact information (e.g., Prolific ID, Prolific email address) was obtained to ensure participants could be contacted about future study sessions. Participants then verified eligibility for the study, provided sociodemographic and health-related information (e.g., gender, race, annual household income, marital status), and completed select measures for descriptive purposes and to allow for evaluation of covariates. At each of the three study timepoints (each ~6 months apart), participants were also asked to report their height and weight. Participants received monetary compensation via Prolific after the completion of each study session. A raffle bonus payment was also held after Time 3 for those who completed all 3 study time points.

# Measures

The following variables were measured to evaluate the aims of the study:

## Chrononutrition

Chrononutrition was evaluated using the Chrononutrition Profile – Questionnaire (CP-Q) (Veronda et al., 2020). The CP-Q consists of 18 items which are designed to measure chrononutrition preferences and 7 key chrononutrition behaviors: 1) eating window, 2) eating midpoint, 3) breakfast skipping, 4) largest meal, 5) evening eating, 6) evening latency, and 7) night eating. Questions designed to measure preference begin with, "If you were entirely free to plan your day, what time would you prefer to…", while questions designed to measure chrononutrition behaviors begin with, "On a typical day, what time do you…". The CP-Q is reliable and has demonstrated test-retest reliability (Veronda et al., 2020). Research to date has suggested that, for healthy chrononutrition: the majority of energy intake (e.g., largest meal) should typically be confined to a distinct window (e.g., eating window) with food intake occurring earlier in the day (e.g., breakfast consumption), rather than in the evening (e.g., evening eating), close to bedtime (e.g., evening latency), or in the night (e.g., night eating).

**Sleep Duration**

Sleep duration was assessed using the Pittsburgh Sleep Quality Index (PSQI). The PSQI is a 19-item measure which assesses seven components of sleep, including subjective sleep quality, sleep duration, sleep disturbances (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). PSQI total scores range from 0 to 21. Higher scores on the PSQI are indicative of more sleep quality complaints, and scores > 5 suggest increased risk for insomnia. The reliability and validity of this measure have been well-established (Carpenter & Andrykowski, 1998; Gelaye et al., 2014; Hinz et al., 2017).

**BMI**

Participants were asked to report their height in feet and inches and their weight in pounds to allow for calculation of BMI. These values were converted into meters and kilograms, respectively, to calculate BMI. BMI is calculated as $kg/m^2$.

Measures that were examined for descriptive purposes and considered as potential covariates include: the Composite Scale of Morningness (CSM; Smith, Reilly, & Midkiff, 1989), the International Physical Activity Questionnaire Short Form (IPAQ-SF; Craig et al., 2003), the Patient Health Questionnaire (PHQ-4; Kroenke, Spitzer, Williams, & Löwe, 2009), the 4-item Perceived Stress Scale (PSS4; Cohen, Kamarck, & Mermelstein, 1983), the Rapid Eating Assessment for Patients (REAP; Gans et al., 2003), and the Sleep Hygiene Index (SHI; Mastin, Bryson, & Corwyn, 2006). We chose to include these measures based on evidence that these factors are linked to BMI (e.g., Arora & Taheri, 2015; Föhr et al., 2016).

**CSM**

The 13-item CSM was used to assess individuals' chronotype (Smith et al., 1989). This measure combines and improves upon two existing chronotype assessments: the Diurnal Type Scale (Torsvall & Âkerstedt, 1980) and the Morningness-Eveningness Questionnaire (Horne & Ostberg, 1976). Example CSM items include: "Assuming normal circumstances, how easy do you find getting up in the morning" and "At what time in the evening do you feel tired and as a result, in need of sleep?", and response options for each item range from 1 (*indicating extreme evening chronotype*) to either 4 or 5 (*indicating extreme morning chronotype*). Scores for all items are summed to compute a total score. Total scores may range from 13 to 55, and higher total scores reflect a greater tendency toward a morning chronotype (Smith et al., 1989). This measure has been shown to be valid and reliable (Guthrie, Ash, & Bendapudi, 1995; Natale & Alzani, 2001; Randler, 2008).

**IPAQ-SF**

The IPAQ-SF contains seven items designed to measure the time individuals spend sitting, walking, and engaging in moderate- and vigorous- intensity physical activities over the past week, e.g., "During the last 7 days, how much time did you spend sitting on a week day?" (Craig et al., 2003). Responses can be scored as categorical (low, moderate, or high activity levels) or continuous (multiple of estimated resting energy expenditure). The IPAQ-SF has been determined to be psychometrically sound (Craig et al., 2003).

**PHQ-4**

This measure is designed to serve as a brief screener of depression and anxiety (Kroenke et al., 2009). Participants are asked to report the frequency with which they experience symptoms of depression and anxiety over the past two weeks. The depression subscale consists of two items (e.g., "Over the last two weeks, how often have you been bothered by the following problems? Little interest or pleasure in doing things") and the anxiety subscale also consists of two items (e.g., "Over the last two weeks, how often have you been bothered by the following problems? Not being able to stop or control worrying"). Response options are given on a 4-point Likert scale, ranging from 0 (*not at all*) to 3 (*nearly every day*). Total subscale scores are computed by adding together the item scores of each subscale. A total score of three or greater on either subscale suggests anxiety or depression, respectively. Reliability and validity of the PHQ-4 have been demonstrated in the general population (Kroenke et al., 2009; Löwe et al., 2010).

**PSS4**

This version of the Perceived Stress Scale consists of 4 items which are used to evaluate the extent to which individuals perceive situations in the past month as stressful (Cohen et al., 1983). Example items include "In the last month, how often have you felt that you were unable to control the important things in your life?", and "In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?". For each item, response options range from 0 (*never*) to 4 (*very often*). Scores on each item are summed to compute a total score, and total scores range from 0 to 16, with higher scores indicating greater perceived stress. Though brief, this measure has been shown to be reliable and valid (Cohen et al., 1983; Lee, 2012).

**REAP**

This 31-item measure is designed to serve as a brief assessment of individuals' dietary behaviors (Gans et al., 2003). Participants are asked to report the frequency with which they consume certain foods and nutrients (e.g., intake of fat, sodium, whole grains, fruits and vegetables) in an average week. For example, one item asks, "In an average week, how often do you eat fried foods such as fried chicken, fried fish, or French fries?". This measure also asks participants about their engagement in various eating behaviors, such as skipping breakfast and shopping and preparing one's own food. Response options range from Usually/Often (1) to Rarely/Never (3). Score on items are then summed to compute a total score, such that higher scores are indicative of a healthier diet. This measure has been validated and is a reliable method of assessing dietary intake (Gans et al., 2006).

**SHI**

The Sleep Hygiene Index consists of 13 items which measure participants' engagement in sleep hygiene, i.e., behavioral and environmental factors that may affect sleep quality (Mastin et al., 2006). For this measure, individuals are asked to report the extent to which they engage in behaviors believed to affect sleep, with response options ranging from never (0) to always (4). Example items include "I get out of bed at different times from day to day", "I do something that may wake me up before bedtime (for example: play video games, use the internet, or clean)", and "I think, plan, or worry when I am in bed". Total scores range from 0 to 52, and higher scores are indicative of poorer sleep hygiene. This measure has been reported to be valid and reliable (Mastin et al., 2006).

In addition, participants were asked to report the frequency with which they binge drink, take daytime naps, drink caffeinated beverages, and smoke cigarettes or e-cigarettes to provide further insight into behaviors which may affect sleep, chrononutrition, and metabolism. We also included various questions to assess impacts of the COVID-19 pandemic (e.g., financial impacts of the pandemic, childcare and work/school responsibilities during the pandemic) and considered these as potential covariates as well.

Participants were asked to complete the above measures and to self-report their height and weight again for study sessions two and three (each ~6 months apart). Eligibility information and contact information were collected at each session to allow for tracking of eligibility criteria and to ensure participants could be reached for the upcoming study session.

**Data Analysis**

Prior to data analysis, data were examined descriptively, and missing data patterns were analyzed to identify any systematic patterns (Schafer, 1997). If individuals were missing no more than one timepoint of data, multiple imputation was used to impute missing data.

The first study aim was to investigate the stability of chrononutrition preferences and chrononutrition behaviors over time. Hypothesis one stated that chrononutrition preferences would remain stable over time, while chrononutrition behaviors would be more variable over the study period. To evaluate this aim, variance components from different sources (person, timepoint, person by timepoint, and error) were calculated first (Cranford et al., 2006). Next, these variance components were used to calculate within-person ($R_C$) reliability (i.e., an individual's change or stability over time) using the following formula (Cranford et al., 2006):

$$R_c = \frac{[\sigma^2_{PERSON*time\ point}]}{[\sigma^2_{PERSON*time\ point}]+[\sigma^2_{ERROR/Km}]}.$$

High within-person reliability would indicate that an individual's chrononutrition remains relatively stable over time.

The second study aim was to determine the impact of chrononutrition behaviors on weight gain. Hypothesis two stated that worse chrononutrition behaviors (e.g., longer eating window, more frequent breakfast skipping, later evening eating, later eating midpoint) would prospectively predict increased BMI. To analyze this aim, I used a mixed-effects model with lagged observations of the chrononutrition behavior at $time_T$ to predict BMI at $time_{T+1}$, while controlling for BMI at $time_T$.

The third study aim was to examine the extent to which chrononutrition serves as a mechanism by which sleep duration influences body weight. Hypothesis three stated that the relationship between sleep duration and changes in BMI over time would be partially mediated by chrononutrition behaviors. I evaluated this aim using a simple mediational model. In order to establish temporal precedence, I used sleep duration at $time_T$, changes in chrononutrition behaviors from $time_T$ to $time_{T+1}$, and BMI at $time_{T+2}$ while controlling for BMI at $time_T$. The proposed mediational model is shown in Figure 1.

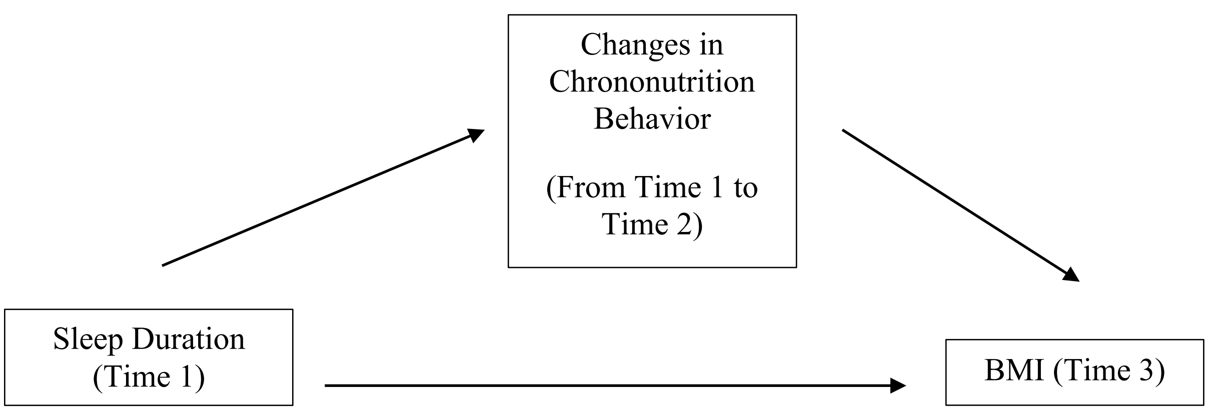


*Figure 1*. Proposed mediational model using sleep duration at $time_T$, changes in chrononutrition behaviors from $time_T$ to $time_{T+1}$, and BMI at $time_{T+2}$ while controlling for BMI at $time_T$.

For these analyses, the PROCESS macro was used to conduct a simple mediation analysis (model #4) in SPSS. The independent variable was sleep duration, the mediating variable was changes in chrononutrition behaviors, and the dependent variable was BMI. Each chrononutrition behavior was evaluated individually (breakfast skipping; largest meal; and weekend/free day and work/school day first eating event, evening eating, evening latency, eating window, eating midpoint) resulting in a total of 12 mediation models run.

## Sample Size Determination

As statistical power was limited by Aim 3, power estimates for a mediation model to achieve 80% power were determined. Two hundred fifty-eight individuals were recruited for Time 1. I estimated that 75% of Time 1 participants would return for Time 2, and 75% of Time 2 participants would return for Time 3. Thus, a sample size of 258 at Time 1 was selected to account for this attrition and to provide 80% power to detect small-to-moderate effects (Lemon, Wang, Haughton, Estabrook, Frisard, & Pagoto, 2016) with a proposed final sample size of 165 at Time 3 (Fritz & MacKinnon, 2007)

# RESULTS

## Participant Characteristics

All analyses were conducted using SPSS version 28. 258 participants completed Time 1. 157 participants (60.85%) returned to complete Time 2, and 141 participants (54.65%) completed Time 3 (see Figure 2 for participant flow diagram). A total of 117 participants completed all 3 study timepoints, with 24 individuals completing Time 1 and Time 3 but not Time 2 and 40 individuals completing Time 1 and Time 2 but not Time 3.

**Time 1: November 2020**

n = 258 responses

**Time 2: May 2021**

n = 157 responses

- n = 226 eligible individuals per Prolific guidelines, based on activity within past 90 days
- n = 7 opened survey but did not provide data
- 62 non-responders

**Time 3: November 2021**

n = 141 responses

- n = 229 eligible individuals per Prolific guidelines, based on activity within past 90 days
- n = 2 opened survey but did not provide data
- 86 non-responders

**Analysis: November/December 2021**

Starting n = 258

- n = 117 completed all 3 timepoints
- Multiple imputation: n = 64 for missing either Time 2 or Time 3 data
- Excluded from analysis: n = 77 for completing only Time 1

Final sample for analysis: n = 181

*Figure 2*. Participant flow diagram.

Demographic characteristics of the sample at each time point are shown in Table 1. The mean age of Time 1 participants was 33.4 years (*SD* = 8.64), and half of participants were female. Most participants (74.0%) were Caucasian, and the majority of the sample had earned at least a bachelor's degree (81.0%).

Table 1

*Sample demographics*

| Demographic Variable | Parameter |
|---|---|
| Time 1 | |
| Age | |
| Range | 18-65 |
| Mean (*SD*) | 33.38 (*8.64*) |
| Gender | |
| Male | 126 (48.8%) |
| Female | 117 (50.8%) |
| Prefer not to say | 1 (0.4%) |
| Race | |
| American Indian or Alaska Native | 2 (0.8%) |
| Asian or Pacific Islander | 35 (13.6%) |
| Black or African American | 18 (7.0%) |
| White or Caucasian | 191 (74.0%) |
| Other/Mixed | 10 (3.9%) |
| Did not disclose | 2 (0.8%) |

Table 1. *Sample demographics* (continued)

| Demographic Variable | Parameter |
|---|---|
| Annual Household Income | |
| Less than $25,000/year | 11 (4.3%) |
| $25,000-$49,999/year | 40 (15.5%) |
| $50,000-$74,999/year | 50 (19.4%) |
| $75,000-$99,999/year | 61 (23.6%) |
| $100,000-$124,999/year | 35 (13.6%) |
| $125,000-$149,999/year | 29 (11.2%) |
| $150,000-$174,999/year | 13 (5.0%) |
| $175,000-$199,999/year | 4 (1.6%) |
| $200,000 or more/year | 13 (5.0%) |
| Prefer not to say | 2 (0.8%) |
| Marital Status | |
| Single, never married | 95 (36.8%) |
| Married or domestic partnership | 153 (59.3%) |
| Widowed | 1 (0.4%) |
| Divorced | 9 (3.5%) |
| Highest Level of Education Completed | |
| High school degree or equivalent (e.g., GED) | 14 (5.4%) |
| Some college but no degree | 19 (7.4%) |
| Associate degree | 16 (6.2%) |
| Bachelor’s degree | 126 (48.8%) |
| Graduate degree | 83 (32.2%) |

Table 1. *Sample demographics* (continued)

| Demographic Variable | Parameter |
|---|---|
| Employment Status | |
| Employed, part time (working 1-39 hours/week) | 36 (14.0%) |
| Employed, full time (working 40 or more hours/week) | 214 (82.9%) |
| Not employed, looking for work | 4 (1.6%) |
| Student | 4 (1.6%) |
| Number of People in Household | |
| Range | 1-7 |
| Mean (*SD*) | 2.88 (1.28) |
| Number of Children in Household | |
| Range | 1-5 |
| Mean (*SD*) | 0.75 (0.98) |
| Time 2 | |
| Age | |
| Range | 18-65 |
| Mean (*SD*) | 34.83 (*9.46*) |
| Gender | |
| Male | 76 (48.4%) |
| Female | 81 (5.16%) |
| Race | |
| American Indian or Alaska Native | 1 (0.6%) |
| Asian or Pacific Islander | 19 (12.1%) |
| Black or African American | 12 (7.6%) |
| White or Caucasian | 122 (77.7%) |

Table 1. *Sample demographics* (continued)

| Demographic Variable | Parameter |
| --- | --- |
| Other/Mixed | 3 (1.9%) |
| Annual Household Income | |
| Less than $25,000/year | 7 (4.5%) |
| $25,000-$49,999/year | 29 (18.5%) |
| $50,000-$74,999/year | 26 (16.6%) |
| $75,000-$99,999/year | 36 (22.9%) |
| $100,000-$124,999/year | 16 (10.2%) |
| $125,000-$149,999/year | 20 (12.7%) |
| $150,000-$174,999/year | 13 (8.3%) |
| $175,000-$199,999/year | 3 (1.9%) |
| $200,000 or more/year | 7 (4.5%) |
| Marital Status | |
| Single, never married | 62 (39.5%) |
| Married or domestic partnership | 89 (56.7%) |
| Widowed | 1 (0.6%) |
| Divorced | 5 (3.2%) |
| Highest Level of Education Completed | |
| High school degree or equivalent (e.g., GED) | 12 (7.6%) |
| Some college but no degree | 11 (7.0%) |
| Associate degree | 12 (7.6%) |
| Bachelor's degree | 76 (48.4%) |
| Graduate degree | 45 (28.7%) |
| Did not disclose | 1 (0.6%) |

Table 1. *Sample demographics* (continued)

| Demographic Variable | Parameter |
|---|---|
| Employment Status | |
| Employed, part time (working 1-39 hours/week) | 24 (15.3%) |
| Employed, full time (working 40 or more hours/week) | 127 (80.9% |
| Not employed, looking for work | 3 (1.9%) |
| Student | 3 (1.9%) |
| Number of People in Household | |
| Range | 1-9 |
| Mean (*SD*) | 2.86 (*1.39*) |
| Number of Children in Household | |
| Range | 0-6 |
| Mean (*SD*) | 0.70 (*1.05*) |
| Time 3 | |
| Age | |
| Range | 19 – 66 |
| Mean (*SD*) | 36.13 (*9.34*) |
| Gender | |
| Male | 69 (48.9) |
| Female | 71 (50.4) |
| Prefer not to say | 1 (0.7) |
| Race | |
| American Indian or Alaska Native | 2 (1.4) |
| Asian or Pacific Islander | 18 (12.8) |
| Black or African American | 9 (6.4) |

Table 1. *Sample demographics* (continued)

| Demographic Variable | Parameter |
|---|---|
| White or Caucasian | 108 (76.6) |
| Other/Mixed | 3 (2.1) |
| Did not disclose | 1 (0.7) |
| Annual Household Income | |
| Less than $25,000/year | 7 (5.0) |
| $25,000-$49,999/year | 23 (16.3) |
| $50,000-$74,999/year | 32 (22.7) |
| $75,000-$99,999/year | 25 (17.7) |
| $100,000-$124,999/year | 13 (9.2) |
| $125,000-$149,999/year | 14 (9.9) |
| $150,000-$174,999/year | 9 (6.4) |
| $175,000-$199,999/year | 8 (5.7) |
| $200,000 or more/year | 7 (5.0) |
| Prefer not to say | 2 (1.4) |
| Marital Status | |
| Single, never married | 53 (37.6) |
| Married or domestic partnership | 81 (57.4) |
| Widowed | 1 (0.7) |
| Divorced | 6 (4.3) |
| Highest Level of Education Completed | |
| High school degree or equivalent (e.g., GED) | 9 (6.4) |
| Some college but no degree | 12 (8.5) |
| Associate degree | 9 (6.4) |

Table 1. *Sample demographics* (continued)

| Demographic Variable | Parameter |
|---|---|
| Bachelor's degree | 69 (48.9) |
| Graduate degree | 42 (29.8) |
| Employment Status | |
| Employed, part time (working 1-39 hours/week) | 18 (12.8) |
| Employed, full time (working 40 or more hours/week) | 120 (85.1) |
| Student | 3 (2.1) |
| Number of People in Household | |
| Range | 1 – 8 |
| Mean (*SD*) | 2.64 (*1.34*) |
| Number of Children in Household | |
| Range | 0 – 6 |
| Mean (*SD*) | 0.71 (*1.09*) |

*Note*. N = 258 at Time 1, N = 157 at Time 2, N = 141 at Time 3.

## Initial Examination of Data

Prior to conducting the primary study analyses, data were examined using descriptive statistics. Descriptive statistics of chrononutrition preferences and behaviors, sleep duration, and BMI from each study wave are displayed in Table 2. Table 2 displays the number and percentage of missing data points for each chrononutrition preference variable and chrononutrition behavior variable on work/school or free days.

Table 2

*Descriptive statistics of CP-Q variables, PSQI sleep duration, and BMI*

| Item | Range | Mean | SD | Skewness | # Missing Values (%) |
|---|---|---|---|---|---|
| Time 1 | | | | | |
| Wake Time - WKND | 4:00 – 12:00 | 8:14 | 1:36 | 0.23 | N/A |
| Wake Time - WKDY | 4:00 – 12:00 | 6:46 | 1:15 | 0.41 | N/A |
| Wake Time - PREF | 4:00 – 12:00 | 7:50 | 1:32 | 0.18 | N/A |
| First Eating Event - WKND | 5:30 – 16:00 | 10:04 | 1:58 | 0.46 | 1 (0.39) |
| First Eating Event - WKDY | 4:55 – 19:00 | 9:02 | 2:16 | 1.05 | 2 (0.78) |
| First Eating Event - PREF | 5:30 – 17:00 | 9:28 | 1:57 | 0.73 | 5 (1.94) |
| Evening Latency - WKND | 30.00 – 660.00 | 219.11 | 99.03 | 0.66 | 1 (0.39) |
| Evening Latency - WKDY | 30.00 – 540.00 | 194.57 | 87.37 | 0.51 | 3 (1.16) |
| Evening Latency - PREF | 0.00 – 540.00 | 164.36 | 84.08 | 1.06 | N/A |
| Evening Eating – WKND | 14:00 – 1:00 | 20:05 | 1:47 | 0.18 | N/A |
| Evening Eating – WKDY | 15:00 – 1:00 | 19:46 | 1:37 | 0.24 | 2 (0.78) |
| Evening Eating – PREF | 13:30 – 1:00 | 20:18 | 1:58 | -0.26 | 2 (0.78) |
| Eating Window – WKND | 0.00 – 900.00 | 602.63 | 134.22 | -0.48 | 1 (0.39) |
| Eating Window – WKDY | 0.00 – 1020.00 | 643.23 | 154.60 | -0.85 | 5 (1.94) |
| Eating Window – PREF | 0.00 – 920.00 | 653.02 | 143.24 | -0.81 | 5 (1.94) |
| Eating Midpoint – WKND | 11:15 – 20:00 | 15:05 | 1:29 | 0.57 | 1 (0.39) |
| Eating Midpoint – WKDY | 11:00 – 20:00 | 14:24 | 1:29 | 0.88 | 5 (1.94) |
| Eating Midpoint – PREF | 11:00 – 19:30 | 14:54 | 1:32 | 0.37 | 5 (1.94) |
| Bedtime - WKND | 20:00 – 4:00 | 23:44 | 1:29 | 0.22 | N/A |
| Bedtime - WKDY | 20:00 – 3:30 | 23:00 | 1:11 | 0.41 | N/A |
| Bedtime - PREF | 19:00 – 26:00 | 23:02 | 1:19 | 0.18 | N/A |
| PSQI Sleep Duration | 4.00 – 10.00 | 7.02 | 1.04 | -0.55 | N/A |

Table 2. *Descriptive statistics of CP-Q variables, PSQI sleep duration, and BMI* (continued)

| Item | Range | Mean | SD | Skewness | # Missing Values (%) |
|---|---|---|---|---|---|
| BMI | 16.57 – 52.48 | 25.40 | 5.31 | 1.71 | 9 (3.49) |
| Time 2 | | | | | |
| Wake Time - WKND | 5:00 – 12:00 | 8:08 | 1:28 | 0.38 | N/A |
| Wake Time - WKDY | 4:00 – 11:00 | 6:57 | 1:12 | 0.62 | N/A |
| Wake Time - PREF | 5:00 – 12:00 | 7:49 | 1:25 | 0.13 | N/A |
| First Eating Event - WKND | 5:45 – 19:00 | 10:08 | 2:07 | 0.79 | 2 (1.27) |
| First Eating Event - WKDY | 5:45 – 19:00 | 9:24 | 2:27 | 1.24 | 2 (1.27) |
| First Eating Event - PREF | 5:45 – 15:00 | 9:35 | 1:59 | 0.51 | 4 (2.55) |
| Evening Latency - WKND | 60.00 – 540.00 | 217.69 | 92.55 | 0.38 | 1 (0.64) |
| Evening Latency - WKDY | 45.00 – 360.00 | 201.91 | 81.47 | 0.01 | 2 (1.27) |
| Evening Latency - PREF | 30.00 – 300.00 | 158.40 | 72.96 | 0.15 | 4 (2.55) |
| Evening Eating – WKND | 14:00 – 4:00 | 20:02 | 1:44 | 0.45 | 1 (0.64) |
| Evening Eating – WKDY | 14:00 – 3:00 | 19:39 | 1:37 | 0.49 | 1 (0.64) |
| Evening Eating - PREF | 16:00 – 1:00 | 20:22 | 1:44 | 0.45 | 4 (2.55) |
| Eating Window – WKND | 0.00 – 960.00 | 593.22 | 153.61 | -0.82 | 2 (1.27) |
| Eating Window – WKDY | 0.00 – 960.00 | 614.19 | 171.37 | -1.19 | 2 (1.27) |
| Eating Window – PREF | 150.00 – 890.00 | 646.97 | 135.08 | -0.68 | 4 (2.55) |
| Eating Midpoint – WKND | 11:22 – 20:00 | 15:04 | 1:27 | 0.54 | 2 (1.27) |
| Eating Midpoint – WKDY | 11:22 – 20:30 | 14:31 | 1:31 | 0.79 | 2 (1.27) |
| Eating Midpoint – PREF | 11:30 – 19:00 | 14:59 | 1:28 | 0.16 | 4 (2.55) |
| Bedtime - WKND | 20:00 – 7:00 | 23:40 | 1:23 | 1.03 | N/A |
| Bedtime - WKDY | 20:00 – 2:00 | 23:02 | 1:03 | 0.38 | N/A |
| Bedtime - PREF | 20:00 – 2:00 | 23:01 | 1:11 | 0.33 | N/A |
| PSQI Sleep Duration | 4.00 – 11.00 | 7.20 | 1.05 | -0.02 | 5 (3.18) |

Table 2. *Descriptive statistics of CP-Q variables, PSQI sleep duration, and BMI* (continued)

| Item | Range | Mean | SD | Skewness | # Missing Values (%) |
|---|---|---|---|---|---|
| BMI | 15.00 – 50.29 | 25.68 | 5.81 | 1.68 | N/A |
| Time 3 | | | | | |
| Wake Time - WKND | 3:00 – 15:00 | 8:07 | 1:34 | 0.63 | N/A |
| Wake Time - WKDY | 3:00 – 15:00 | 6:53 | 1:35 | 2.17 | N/A |
| Wake Time - PREF | 4:30 – 10:00 | 7:52 | 1:12 | -0.31 | N/A |
| First Eating Event - WKND | 5:15 – 16:00 | 9:57 | 1:58 | 0.37 | 1 (0.71) |
| First Eating Event - WKDY | 5:15 – 17:00 | 9:13 | 2:22 | 0.93 | 1 (0.71) |
| First Eating Event - PREF | 5:45 – 14:30 | 9:20 | 1:40 | 0.37 | 2 (1.42) |
| Evening Latency - WKND | 30.00 – 540.00 | 237.64 | 96.32 | 0.34 | 1 (0.71) |
| Evening Latency - WKDY | 0.00 – 480.00 | 215.85 | 91.80 | 0.37 | 1 (0.71) |
| Evening Latency - PREF | 30.00 – 390.00 | 152.70 | 76.17 | 0.74 | 1 (0.71) |
| Evening Eating – WKND | 14:00 – 0:00 | 19:48 | 1:48 | -0.25 | 1 (0.71) |
| Evening Eating – WKDY | 15:00 – 0:00 | 19:29 | 1:34 | 0.18 | 1 (0.71) |
| Evening Eating - PREF | 17:00 – 00:20 | 20:30 | 1:38 | 0.08 | 3 (2.13) |
| Eating Window – WKND | 0.00 – 890.00 | 591.39 | 146.43 | -0.47 | 1 (0.71) |
| Eating Window – WKDY | 0.00 – 900.00 | 616.86 | 166.63 | -0.78 | 1 (0.71) |
| Eating Window – PREF | 390.00 – 980.00 | 670.14 | 127.66 | -0.41 | 3 (2.13) |
| Eating Midpoint – WKND | 8:00 – 18:15 | 14:47 | 1:29 | -0.63 | 1 (0.71) |
| Eating Midpoint – WKDY | 10:35 – 20:00 | 14:21 | 1:27 | 0.52 | 1 (0.71) |
| Eating Midpoint – PREF | 12:15 – 18:30 | 14:55 | 1:16 | 0.19 | 3 (2.13) |
| Bedtime - WKND | 20:00 – 5:00 | 23:46 | 1:18 | 0.45 | N/A |
| Bedtime - WKDY | 20:00 – 3:00 | 23:04 | 1:10 | 0.20 | N/A |
| Bedtime - PREF | 20:00 – 2:00 | 23:04 | 1:08 | 0.28 | N/A |
| PSQI Sleep Duration | 4.00 – 12.00 | 7.07 | 1.11 | 0.17 | 1 (0.71) |

Table 2. *Descriptive statistics of CP-Q variables, PSQI sleep duration, and BMI* (continued)

| Item | Range | Mean | SD | Skewness | # Missing Values (%) |
|---|---|---|---|---|---|
| BMI | 17.75 – 58.98 | 26.16 | 6.16 | 2.13 | N/A |

*Note.* CP-Q = Chrononutrition Profile – Questionnaire; PSQI = Pittsburgh Sleep Quality Index; BMI = body mass index; WKND = weekend; WKDY = weekday; PREF = preference.
N = 258 at Time 1; N = 157 at Time 2; N = 141 at Time 3.

Frequencies of CP-Q-assessed breakfast skipping, largest meal, and night eating for each wave of data collection are displayed in Table 3. One participant (0.4% of sample) did not disclose their largest meal at Time 1, and one participant (0.7%) did not disclose their largest meal at Time 3. Lastly, one participant (0.7% of sample) did not disclose their frequency of breakfast skipping at Time 3. While our intention was to evaluate the CP-Q-assessed chrononutrition behavior of night eating, a low base rate of reported night eating (24 participants at Time 1, 9.3% of sample) prevented us from assessing this construct in the present analyses (see Table 3). In addition, the majority of participants reported dinner/supper as their largest meal (i.e., 67.1% at Time 1, 77.1% at Time 2, and 75.2% at Time 3) (see Table 3); because of this unequal distribution, the largest meal variable was dichotomized, such that responses of breakfast, lunch, and other meal were collapsed into one category and dinner/supper was kept as a separate category for analyses regarding largest meal.

Table 3

*Frequencies of CP-Q breakfast skipping, largest meal, and night eating*

| CP-Q Variable | Frequency (%) |
|---|---|
| Time 1 | |
| Breakfast Skipping | |
| 0 days/week | 114 (44.2) |
| 1 day/week | 20 (7.8) |
| 2 days/week | 18 (7.0) |
| 3 days/week | 25 (9.7) |
| 4 days/week | 22 (8.5) |
| 5 days/week | 12 (4.7) |
| 6 days/week | 15 (5.8) |
| 7 days/week | 32 (12.4) |
| Largest Meal | |
| Breakfast | 11 (4.3) |
| Lunch | 72 (27.9) |
| Dinner/Supper | 173 (67.1) |
| Other meal | 1 (0.4) |
| Did not disclose | 1 (0.4) |
| Night Eating | |
| 0 days/week | 234 (90.7) |
| 1 day/week | 9 (3.5) |
| 2 days/week | 8 (3.1) |
| 3 days/week | 5 (1.9) |
| Did not disclose | 2 (0.8) |

Table 3. *Frequencies of CP-Q breakfast skipping, largest meal, and night eating* (continued)

| CP-Q Variable | Frequency (%) |
|---|---|
| Time 2 | |
| Breakfast Skipping | |
| 0 days/week | 61 (38.9) |
| 1 day/week | 13 (8.3) |
| 2 days/week | 14 (8.9) |
| 3 days/week | 12 (7.6) |
| 4 days/week | 15 (9.6) |
| 5 days/week | 10 (6.4) |
| 6 days/week | 7 (4.5) |
| 7 days/week | 25 (15.9) |
| Largest Meal | |
| Breakfast | 7 (4.5) |
| Lunch | 28 (17.8) |
| Dinner/Supper | 121 (77.1) |
| Other meal | 1 (0.6) |
| Night Eating | |
| 0 days/week | 144 (96.2) |
| 1 day/week | 5 (4.5) |
| 6 days/week | 1 (0.6) |
| Time 3 | |
| Breakfast Skipping | |
| 0 days/week | 60 (42.6) |
| 1 day/week | 11 (7.8) |
| 2 days/week | 16 (11.3) |

Table 3. *Frequencies of CP-Q breakfast skipping, largest meal, and night eating* (continued)

| CP-Q Variable | Frequency (%) |
|---|---|
| 3 days/week | 10 (7.1) |
| 4 days/week | 9 (6.4) |
| 5 days/week | 11 (7.8) |
| 6 days/week | 6 (4.3) |
| 7 days/week | 17 (12.1) |
| Did not disclose | 1 (0.7) |
| Largest Meal | |
| Breakfast | 6 (4.3) |
| Lunch | 29 (20.6) |
| Dinner/Supper | 106 (75.2) |
| Other meal | 0 (0.0) |
| Night Eating | |
| 0 days/week | 137 (97.2) |
| 1 day/week | 3 (2.1) |
| 2 days/week | 1 (0.7) |

*Note.* CP-Q = Chrononutrition Profile – Questionnaire.
N at Time 1 = 258; N at Time 1 = 157, and N at Time 3 = 141.

We also analyzed missing data to identify any systematic patterns (Schafer, 1997). Independent samples t-tests ANOVAs, and chi square tests were used as appropriate to evaluate for potential differences between those who completed all 3 study time points and those who did not. Analyses indicated that individuals who completed all 3 time points did not differ in gender, education, race, income, time 1 BMI, time 1 breakfast skipping, and time 1 work/school day and free day first eating event, evening eating, eating window, eating window, and evening latency compared to those who did not complete all study timepoints (all $p$'s > .05). A Pearson Chi-square test revealed that the proportion of people who ate their largest meal earlier (i.e., breakfast or lunch) was greater in those individuals who did not complete all 3 time points, compared to those who did complete all 3 time points, $\chi^2$ (2, N = 258) = 9.60, $p$ =.002. Overall, while this significant difference was seen in the categorical largest meal variable, the more nuanced evaluations of continuous chrononutrition behavior variables were non-significant. A significant difference also existed in age: those who completed all 3 time points were significantly older ($M$ = 35.68 years, $SD$ = 9.65) than those who did not complete all time points ($M$ = 31.43 years, $SD$ = 7.21), $p < .001$.

Multiple imputation was used to impute missing data for individuals missing no more than one timepoint of data (i.e., the 24 individuals completing Time 1 and Time 3 but not Time 2, and the 40 individuals completing Time 1 and Time 2 but not Time 3). Values for key study variables (i.e., chrononutrition preferences, chrononutrition behaviors, sleep duration, and BMI) were imputed, with 20 replications run. More specifically, values for the following chrononutrition preferences and for chrononutrition behaviors on work/school days and weekend/free days were imputed: first eating event, evening eating, eating window, eating midpoint, evening latency. Breakfast skipping frequency and largest meal were also imputed. Because the study aims necessitated repeated measures, individuals who completed only Time 1 of the study (n = 77) were excluded from analyses. This resulted in a sample of 181 participants for analysis.

**Evaluation of Study Aims**

To evaluate aim one, variance components from person, person by timepoint, and error were calculated first. Variance components were calculated using the Variance Components dialog box in SPSS, with Timepoint set as a fixed factor, Participant ID set as a random factor, and the chrononutrition variable set as the dependent variable. A full factorial model was specified, with the intercept included in the model. The MINQUE (minimum norm quadratic unbiased estimation) method was used, with random effect priors set to uniform. It should be noted that the model did not converge for free day evening latency and for work/school day last eating event (i.e., negative error variance and Person*Timepoint variance values were calculated, respectively). These variables were therefore excluded from analyses. Variance component estimates for all other variables are displayed in Table 4. Next, these variance component estimates were used to calculate within-person ($R_C$) reliability based on a formula provided in Cranford et al. (2006), with the constant $m$ set to 1 (i.e., 1 item) and the constant $K$ set to 3 (i.e., 3 timepoints).

Table 4

*Variance component estimates of chrononutrition preferences and chrononutrition behaviors used to calculate reliability characteristics*

| Source of Variance | Chrononutrition Preference | | | | | Chrononutrition Behavior – Work/School Day | | | | Chrononutrition Behavior – Free Day | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | First Eating Event | Last Eating Event | Evening Latency | Eating Window | Eating Midpoint | First Eating Event | Evening Latency | Eating Window | Eating Midpoint | First Eating Event | Last Eating Event | Eating Window | Eating Midpoint |
| $\sigma^2$PERSON | 6425.06 | 5286.34 | 2199.80 | 8211.64 | 3711.94 | 10589.38 | 3684.45 | 13650.67 | 4055.78 | 8348.20 | 5643.75 | 11009.32 | 3718.70 |
| $\sigma^2$PERSON* TIMEPOINT | 3506.42 | 3429.40 | 2622.11 | 6462.50 | 1775.97 | 5566.31 | 222.72 | 2384.81 | 910.18 | 1621.44 | 2539.75 | 35185.69 | 888.26 |
| $\sigma^2$ERROR | 770.08 | 1009.65 | 414.92 | 831.03 | 652.48 | 1153.25 | 2608.02 | 7460.56 | 1661.83 | 2477.59 | 1336.19 | 4692.62 | 1908.55 |

*Note*. Model did not converge for Free Day Evening Latency and for Work/School Day Last Eating Event; these are excluded.

As seen in Table 5, results indicated that chrononutrition preferences displayed high reliability overall within-persons ($R_C$ = .89 - .96). Interestingly, within-person reliability was markedly lower for some chrononutrition behaviors, such as work/school day evening latency ($R_C$ = .20), free day eating midpoint ($R_C$ = .58), and work/school day eating window ($R_C$ = .49). Overall, these results suggest that an individual's chrononutrition behaviors are likely to be more variable over time, while preferences are likely to be more stable.

Table 5

*Reliability coefficients computed from variance component estimates*

| | Reliability of Change (Within Person) ($R_C$) | | |
|---|---|---|---|
| Variable | Chrononutrition Preference | Chrononutrition Behavior – Work/School Day | Chrononutrition Behavior – Free Day |
| First Eating Event | .93 | .94 | .66 |
| Last Eating Event | .91 | -- | .85 |
| Evening Latency | .95 | .20 | -- |
| Eating Window | .96 | .49 | .96 |
| Eating Midpoint | .89 | .62 | .58 |

*Note*. Constant $m$ = 1; constant $K$ = 3.
Model did not converge for free day evening latency and for work/school day last eating event; these were excluded.

The second study aim was evaluated using a mixed-effects model with lagged observations of the chrononutrition behavior at $time_T$ to predict BMI at $time_{T+1}$, while controlling for BMI at $time_T$. Because BMI was positively skewed (see Table 2), a generalized linear mixed effects model with gamma regression was used. The gamma regression uses a Gamma distribution with a log link, which is recommended when a target variable (i.e., BMI) is positively skewed. Results indicated that none of the chrononutrition behaviors (breakfast skipping; largest meal; and weekend/free day and work/school day first eating event, evening eating, evening latency, eating window, eating midpoint) at $time_T$ were significant predictors of BMI at $time_{T+1}$ after controlling for BMI at $time_T$ (all *p*'s > .05).

Study aim three was assessed using a mediational model that used sleep duration at $time_T$, changes in chrononutrition behaviors from $time_T$ to $time_{T+1}$, and BMI at $time_{T+2}$ while controlling for BMI at $time_T$. The models were tested with a percentile bootstrap estimation approach with 5000 bootstrap samples and 95% confidence intervals, using the PROCESS macro version 4.0. The independent variable was sleep duration, the mediating variable was the chrononutrition behavior (breakfast skipping; largest meal; and weekend/free day and work/school day first eating event, evening eating, evening latency, eating window, eating midpoint), and the dependent variable was BMI. Analyses showed that none of the direct effects (i.e., sleep duration predicting BMI) were significant (all *p*'s > .05). Tests of the indirect effect showed that none of the chrononutrition behaviors were significant mediators of the relationship between sleep duration and BMI, as confidence intervals for all effect size measures included zero (all *p*'s > .05).

## DISCUSSION

This longitudinal study sought to accomplish three primary aims: 1) investigate the stability of chrononutrition preferences and chrononutrition behaviors over time, 2) determine the impact of chrononutrition behaviors on weight gain over one year, and 3) examine the extent to which chrononutrition serves as a mechanism by which sleep duration influences body weight. The goal of this study was to provide insight into previously-unstudied aspects of chrononutrition preferences, chrononutrition behaviors, and their relationships to BMI and sleep duration.

In analyzing aim one, comparisons of reliability coefficients for chrononutrition preferences and chrononutrition behaviors revealed that an individual's chrononutrition preferences were overall more stable over time, compared to chrononutrition behaviors. Notably, the reliability coefficients of chrononutrition behaviors displayed a wide range of variability, with certain behaviors changing more over time than others. For instance, work/school day evening latency had the greatest inter-individual variability ($R_C = .20$), with many individuals demonstrating change over time. In addition, within-person variability was also high for eating midpoint, both on work/school days and on free days. Interestingly, within-person reliability of the work/school day first eating event was quite high, but free day first eating event was relatively low; this is likely reflective of consistent work/school start schedules and varying behavioral patterns on free days (Wittmann, Dinich, Merrow, & Roenneberg, 2006). Such variability across chrononutrition behaviors and within individuals may also be indicative of changing social schedules over the course of the one-year testing period (e.g., individuals transitioning into remote, hybrid, or in-person work/school; re-starting attendance of evening social gatherings). Overall, these results support hypothesis one, such that chrononutrition preferences remained quite stable over time, while chrononutrition behaviors were more variable over the study period.

These findings fit within prior research on sleep/wake timing, a related chronobiological field. While sleep/wake timing preferences (i.e., chronotype) tend to be moderately stable over time, with some variation across the lifespan (Paine, Gander, & Travier, 2006; Druiven et al., 2020), both environmental (Halperin, 2014) and psychosocial factors (Âkerstedt, 2006) have been shown to influence sleep/wake timing behaviors night-to-night. In particular, a recent study demonstrated within-person variability in self-reported behavioral sleep midpoint, sleep onset, and wake times across 14 days (Lenneis et al., 2020); taken together with the present study's findings, this suggests that timing of sleep and eating behaviors may not only vary day-to-day and night-to-night but also over longer time periods.

Knowledge of longitudinal patterns of chrononutrition preferences and behaviors is important for future chrononutrition research and intervention efforts because this will help inform the most relevant target for chrononutrition-based interventions. The present study's finding that chrononutrition behaviors are more variable over time while preferences are more stable confirms the approach presently being taken in the literature (e.g., Allison et al., 2020; Wilkinson et al., 2021), with chrononutrition behaviors serving as a more modifiable behavioral target for intervention efforts, rather than chrononutrition preferences. Such findings also indicate that chrononutrition behavior-based interventions may be challenged by limited periods of effectiveness, and therefore more intensive follow-up strategies may be required to help patients maintain healthy chrononutrition. In addition, it is likely advantageous for researchers and healthcare providers to incorporate individuals' chrononutrition preferences in developing interventions, as these are likely to remain relatively stable over time. If an eating schedule intervention is misaligned with an individual's chrononutrition preferences, that person may find it more difficult to follow the prescribed eating schedule, thus decreasing the efficacy of the intervention. Alternatively, an eating schedule intervention tailored to the individual's preferences may maximize a patient's potential for adherence to prescribed eating schedules.

Contrary to our hypothesis for our second study aim, mixed-effects models showed that no chrononutrition behaviors were significant predictors of later BMI. Additional exploratory analyses showed that BMI at Time 1 was weakly correlated with only two chrononutrition behavior variables: free day eating window ($r = -.17$, $p = .023$) and free day evening latency ($r = .17$, $p = .026$), with all other chrononutrition behaviors not significantly associated with BMI (all other $p$'s > .05). Surprisingly, further bivariate correlations revealed that Time 1 BMI was also unrelated to Time 1 depression, anxiety, smoking frequency, physical activity, chronotype, dietary intake, stress, and binge drinking (all $p$'s > .05), although research to date has suggested these factors are associated with BMI (e.g., Arora & Taheri, 2015; Föhr et al., 2016; Harding et al., 2014; Luppino et al., 2010). This lack of relationships between BMI and several known correlates along with chrononutrition suggest that these null findings should be interpreted with caution as they may have resulted from characteristics of the sample or methodology of the present study. For example, the self-report assessment of BMI, the relatively healthy BMI reported by the sample, and the lack of change in self-reported BMI across time may have restricted accurate evaluation of the relationship between chrononutrition behaviors and BMI.

Lastly, evaluation of our third aim did not support our hypothesis, as mediational models indicated that chrononutrition behaviors did not mediate the relationship between sleep duration and BMI. First, it is important to note that direct paths were non-significant, indicating that in this sample, sleep and BMI were not prospectively related. Similar to the non-significant relationships between BMI and other relevant variables, the lack of relationship between sleep and BMI is contrary to existing cross-sectional and longitudinal studies that have supported a link between insufficient sleep and BMI (e.g., Cappuccio et al., 2008; Kohatsu et al., 2006; Park et al., 2018). In light of this non-significant direct pathway between sleep duration and BMI, it is not surprising that the indirect pathways were also non-significant. Though a paucity of evidence exists on chrononutrition's role as a mediator between sleep duration and BMI, perhaps these non-significant effects indicate that the relationships between sleep duration, chrononutrition, and BMI are less pronounced in individuals that are at a healthy weight or only slightly overweight, as the majority of the present sample is. Individuals with obesity may have a differential ability to engage in dietary changes compared to those at a healthy weight, perhaps due to physiological factors, and many dietary-based behavior changes have been shown to have limited periods of effectiveness for weight loss (for review, see Bray, Frühbeck, Ryan, & Wilding, 2016). These non-significant findings could suggest that chrononutrition is most relevant for individuals with obesity, while those with a lower BMI would be less impacted by chrononutrition; however, with more limited research of chrononutrition in lower weight individuals, this remains unclear. In consideration of our primary findings, some limitations of this study should be addressed.

This study is limited by its reliance on self-report data. Particularly, because BMI was self-reported throughout the one-year study, inaccuracies in reported BMI may account for our non-significant findings. Recent work has suggested a link between increased BMI and increased underestimation of weight in both males and females (Olfert et al., 2018). Whereas our participants on average reported unchanged BMI over our study period, other researchers have reported changes in BMI over time (Eek & Östergren, 2009; van Woerden & Bruening, 2018); as such, perhaps the self-reported BMI in this study masked such changes. Further, this study's analyses were based on assessing the change in BMI over time. However, because BMI remained relatively stable, this likely limited our ability to predict changes and evaluate the effects of BMI over time. While we aimed to also assess a wide variety of potential covariates through self-report, there are a number of factors which were not evaluated that could influence the relationship between BMI and sleep duration outside of chrononutrition, such as personality factors (Duggan, Friedman, McDevitt, & Mednick, 2014) cognitive function (Banks & Dinges, 2007) and objective chronobiological factors (e.g., dim light melatonin onset (Baron, Reid, Wolfe, Attarian, & Zee, 2018)).

The remote nature of this study enabled us to gather data from a sample that was fairly age and gender diverse, though the majority of Time 1 participants were employed full time and had completed at least some college. Another limitation of this work was the low prevalence of night eating in this sample; however, this was not entirely unexpected, as night eating syndrome is estimated to occur in only approximately 1.5% of the US population (Rand, Macgregor, & Stunkard, 1997; Striegel-Moore et al., 2005).

Because these data were collected from November 2020 to November 2021, during the height of the COVID-19 pandemic in the United States, it is possible that the timing of behaviors such as eating and sleep differed from those in non-pandemic times, and that the pandemic, coupled with self-reported BMI, may have contributed to these non-significant findings, even when other work has shown significant increases in BMI during the COVID-19 pandemic (Dicken et al., 2021; Bhutani, vanDellen, & Cooper, 2021). To evaluate potential pandemic-related effects in our sample, we assessed the perceived impact of the COVID-19 pandemic on body weight, bedtimes and wake times, and timing of food intake in a subsample of 157 participants. Frequencies were computed to see how many individuals reported a significant change in their body weight, bedtimes and wake times, and timing of food intake; overall, many participants did not report a significant change in behavior compared to their behavior before the pandemic (e.g., February 2020). One hundred forty of 157 participants (89.2%) reported that their timing of food intake either did not change, or changed a little, compared to before the pandemic. One hundred forty-three of 157 participants (91.1%) reported their body weight was either about the same, a little heavier, or a little lighter compared to before the pandemic. Lastly, 105 of 157 individuals (66.9%) reported a bedtime of about the same compared to before the pandemic, and 83 of 157 participants (52.87%) reported a wake time of about the same compared to before the pandemic. Taken together, these descriptive statistics indicate that the majority of participants did not perceive differences in their body weight, sleep/wake timing, and chrononutrition before and during the pandemic.

Despite some limitations, the present study also has a number of strengths which should be acknowledged. Previous research on chrononutrition has largely consisted of experimental paradigms (Gill & Panda, 2015; Hutchison et al., 2019; Parr, Devlin, Ranford, & Hawley, 2020; Ravussin et al., 2019; Wilkinson et al., 2020) over a relatively short duration of time (Martens et al., 2020; Parr et al., 2020; Przulj, Ladmore, Smith, Phillips-Waller, & Hajek, 2021). This study builds upon past research and is - to our knowledge - the first to evaluate both chrononutrition preferences and chrononutrition behaviors in a naturalistic setting. The present longitudinal study also evaluates chrononutrition preferences and behaviors over the longest duration of time to date. Additionally, in contrast to many other observational studies of chrononutrition (Corbalan-Tutau, Madrid, & Garaulet, 2012; Garaulet et al., 2013; Mota et al., 2019) our study utilized a validated, reliable measure designed to assess chrononutrition preferences and chrononutrition behaviors (Veronda et al., 2020). Finally, the present study provides the first step toward extending the energy balance model to include both sleep and chrononutrition (for review, see Veronda, Kline, & Irish, 2021). Despite its null findings, the present study can help inform a future research agenda that builds upon the present study's strengths and addresses its weaknesses.

A number of next steps should be taken to further progress this area of research. To expand upon these findings, future work should evaluate these research questions in individuals with more sociodemographic diversity, such as those without a college education, or in other populations, such as military and healthcare personnel. Additional research with objective sleep duration and BMI is warranted, as is research examining relationships between chrononutrition and potential other factors that were not assessed in the present study. Such research may provide novel insight into environmental influences on chrononutrition and increased understanding of factors which can influence times of high risk for poor chrononutrition (e.g., stress) in a more nuanced manner. Further, given our non-significant associations between chrononutrition and BMI, future clinical weight loss intervention efforts could target chrononutrition behaviors and/or tailor interventions to an individual's chrononutrition preferences to determine the efficacy of chrononutrition as a weight loss tool.

It is also plausible that these non-significant associations between chrononutrition behaviors and BMI indicate that chrononutrition's role in health over the long term may occur via other means, rather than through only body weight (e.g., impaired blood glucose tolerance (Lopez-Minguez, Saxena, Bandín, Scheer, & Garaulet, 2018), inflammation (Chaix et al., 2014), increased blood pressure (Wilkinson et al., 2020)). Therefore, additional longitudinal research centered around these other physiological indicators of health status is necessary to elucidate the role of chrononutrition behaviors in health.

In sum, this study is the first to assess the variability of both chrononutrition behaviors and chrononutrition preferences in the natural environment, over a one-year timeframe. Further, this work serves as an innovative step in increasing knowledge of chrononutrition's role in energy balance. Understanding of chrononutrition patterns in the natural environment and over time may be instrumental in the development and evaluation of future intervention work (e.g., identification of high-risk times for poor chrononutrition) to improve health and increase the effectiveness of weight loss and weight management efforts.

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