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Chrononutrition behaviors in relation to diet quality and obesity: do dietary assessment methods and energy intake misreporting matter?

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Abstract

Background Inconsistent epidemiologic findings on the associations of chrononutrition behaviors with diet quality and adiposity measures may be due to the use of different dietary assessment methodologies and a lack of consideration of dietary misreporting. We aimed to investigate the associations by using questionnaires and diaries, with adjustment for energy intake (EI) misreporting.

Methods This cross-sectional study included 1047 Japanese adults aged 20–69 years. We used the Chrono-Nutrition Behavior Questionnaire (CNBQ) or 11-day diaries to assess chrononutrition behaviors (meal frequency, snack frequency, total eating frequency, timing of first eating occasion, timing of last eating occasion, duration of eating window, and eating midpoint) for workdays and non-workdays separately. Eating jetlag was defined as the eating midpoint difference between workdays and non-workdays. Diet quality was assessed using the Healthy Eating Index-2020, based on the Meal-based Diet History Questionnaire (MDHQ) or 4-day weighed food diaries. EI misreporting was evaluated using the Goldberg cut-off principle.

Results Using questionnaire data (CNBQ and MDHQ), we found inverse associations of snack and total eating frequencies, timing of last eating occasion, eating midpoint, and eating jetlag with diet quality ($P < 0.05$), irrespective of adjustment for EI misreporting. Also, we found positive associations of meal, snack, and total eating frequencies and duration of eating window with the prevalence of general obesity (body mass index ≥ 25 kg/m^2), abdominal obesity (waist circumference ≥ 90 cm for males; ≥ 80 cm for females), or both; many of these associations were only evident ($P < 0.05$) after adjustment for EI misreporting. In contrast, using diary data, we found no associations between chrononutrition behaviors and diet quality, general obesity, or abdominal obesity, regardless of adjustment for EI misreporting (except for inverse associations of timings of first and last eating occasions and eating midpoint on workdays with diet quality).

Conclusions The associations of chrononutrition behaviors with diet quality and obesity were dependent on the methodology used to assess these behaviors. Adjustment for EI misreporting radically changed only the associations with obesity in the questionnaire-based analysis. These findings suggest the importance of careful consideration of dietary assessment method selection and EI misreporting in chrononutrition research.

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Keywords Chrononutrition, Meal frequency, Meal timing, Meal regularity, Eating window, Chronotype, Sleep, Diet quality, Misreporting, Obesity

Introduction

Globally, poor dietary intake and obesity remain significant public health concerns. According to the 2017 Global Burden of Disease Study, dietary factors were responsible for 10.9 million deaths and 255 million disability-adjusted life years (22% and 15% of the total, respectively) among adults [1]. Additionally, a high body mass index (BMI) contributed to 4.72 million deaths (8.4% of the total) and 148 million disability-adjusted life years (5.9% of the total) [2]. These findings highlight the importance of understanding modifiable factors, such as eating behaviors, that impact diet quality and obesity. One area of growing focus is chrononutrition, a field that combines nutritional research with chronobiology [3, 4].

Circadian rhythms, controlled by the master clock in the hypothalamus, govern key biological processes such as sleep–wake cycles, feeding behavior, and hormone secretion [5]. These rhythms are influenced by external factors like light, hormones, and food intake [6], and proper circadian function is crucial for metabolic health [7]. An individual's chronotype—whether they are morning or evening-oriented [8]—affects their eating patterns. Evening chronotypes, for example, tend to eat later in the day and consume more energy in the evening [9]. Chrononutrition explores various eating behaviors related to these rhythms, including the timing of the first and last food intake, eating frequency, time-restricted eating (or the duration of the eating window), and regularity of eating [3, 10–13]. However, the specific variables most relevant to chrononutrition research have yet to be fully identified [6].

An increasing number of epidemiologic studies have investigated the associations between chrononutrition behaviors (eating frequency [13–29], timing of eating [13, 19, 20, 23, 24, 26, 28–40], duration of eating window [26, 28, 32, 37, 39, 41], and regularity of eating [37, 39, 42–45]) and adiposity measures. Nevertheless, the results are far from consistent. For example, findings on eating frequency in relation to adiposity measures showed a mixture of inverse [24, 25, 27, 29], null [19, 21, 26, 28], and positive [15–18, 20, 22, 23] associations. Studies assessing the associations between these chrononutrition behaviors and dietary intake and quality have also yielded inconclusive results [24, 40, 41, 43, 46–51]. One study, for instance, showed that a higher eating frequency, an earlier timing of first eating occasion, and a longer duration of eating window were associated with a higher diet quality [51]. In another study, in contrast, there were no associations between any of the chrononutrition behaviors examined (e.g., eating frequency, timing of first and last eating occasions, duration of eating window, and day-to-day variability of these parameters) and diet quality [50].

These inconsistent findings may be due to substantial methodological variations, including the use of different definitions and variables to describe chrononutrition behaviors [11, 14, 42, 52]. Specifically, a wide variety of methods for assessing chrononutrition behaviors have been used, ranging from single (often simple) questions or questionnaires [18, 19, 22, 23, 27, 29, 35, 36, 41, 44] to more detailed, traditional methods of dietary assessment (e.g., 24-h recall [16, 17, 20, 21, 24, 26, 28, 32, 34, 37, 40, 43, 45, 47, 48, 51] and food diary [15, 25, 30, 31, 33, 38, 39, 46, 49, 50]). Considering that only a single dietary assessment method was used in these previous studies, the application of two distinct dietary assessment methods (e.g., questionnaires and diaries) within the same study sample would provide important insights into chrononutrition research. Another important issue is that misreporting of dietary intake, particularly underreporting of energy intake (EI), is highly prevalent in all dietary surveys [53–55]. However, it remains unclear whether chrononutrition parameters are prone to misreporting [9], which is possible considering that, for example, more frequent eating is positively related to EI [15, 16, 22] and later food times tend to be stigmatized [52]. Nevertheless, most studies have not accounted for such potential reporting bias, with the exception of several studies [15–17, 46–48]. In these studies, adjustment for EI misreporting or the exclusion of underreporters radically affected the results of the analysis for adiposity measures [15–17] (but not diet quality [46–48]). As a consequence of these methodological uncertainties, discrepant findings are not surprising and impede an informed evaluation of nature and magnitude of the associations of chrononutrition behaviors with diet quality and adiposity measures. Thus, more robust data analyses are needed to clarify this issue.

The aim of this cross-sectional study was to examine the associations of chrononutrition behaviors with diet quality and general and abdominal obesity, through focusing on the use of two different dietary assessment methods (i.e., questionnaires and diaries) and the confounding of EI misreporting.

Methods

Overview of the study

This cross-sectional analysis was based on data from the Who, What, When, Where, and Why for Healthy Eating Study (5W Study). The study schedule is shown in Fig. 1. First, each participant was asked to answer the first and second web-based questionnaires (using the Google Forms platform). Then, 7-day diaries of food timing and 4-day diaries of food intake (i.e., weighed dietary record) were conducted. The final component was the third web-based questionnaire (to collect information on eating motivation, depressive symptoms, perceived stress, and food insecurity), which was not used in the present analysis. During the study period, anthropometric measurement was also conducted.

For the questionnaire-based analysis, we used a newly developed Chrono-Nutrition Behavior Questionnaire (CNBQ) to assess chrononutriton behaviors and a previously validated Meal-based Diet History Questionnaire (MDHQ) [56–59] to assess diet quality and EI misreporting. For the diary-based analysis, we used 11-day diaries of eating [60, 61] (consisting of 7-day diaries of food timing and 4-day diaries of food intake) to assess chrononutrition behaviors and 4-day diaries of food intake [59, 62] to assess diet quality and EI misreporting.

Who, What, When, Where, and Why for Healthy Eating Study (5W Study)

Participants

The 5W Study was a cross-sectional study conducted between February and April 2023 in 26 (of 47) prefectures in Japan. The target population comprised of apparently healthy Japanese aged 20–69 years living in private households. We decided to include 110 individuals for each of sex-specific, five 10-year age categories (i.e., 20–29, 30–39, 40–49, 50–59, and 60–69 years), resulting in 1110 individuals in total. While the 5W Study was designed to include multiple research objectives, the main one was a comprehensive examination of the relative validity of the MDHQ using the 4-day diaries of food intake for each of the 10 sex- and age-stratified categories. Thus, the sample size for each category ($n = 110$) was determined based on the recommendation made by Cade et al. that for validation studies, a sample size of 100 or more is desirable [63]. In recruiting, we excluded dietitians and individuals living with a dietitian, given that their dietary habits may differ considerably from those of the general population. We also excluded individuals who have been recently receiving dietary counselling from a doctor or dietitian, those taking insulin treatment for diabetes, those undergoing dialysis treatment, and pregnant or lactating women, because these conditions could contribute to change in dietary habits. In addition, because the questionnaires were administered online, individuals who did not have adequate internet access or who indicated that they would have difficulty answering questionnaires online were excluded. Only one person per household was permitted to participate.

Using the snowball sampling procedure, the number of individuals approached for this study was 1796, 1110 of which agreed to participate in this study (response rate 61.8%). Each participant received an honorarium to the value of 4000 Japanese yen (US$1.00 = 153.02 Japanese yen as of 2 November 2024) after completing the study. The study was conducted in accordance with the guidelines of the Declaration of Helsinki, and all procedures were approved by the Ethics Committee of the University of Tokyo Faculty of Medicine (protocol code: 2022235NI; date of approval: 24 November 2022). Written informed consent was obtained from all participants.

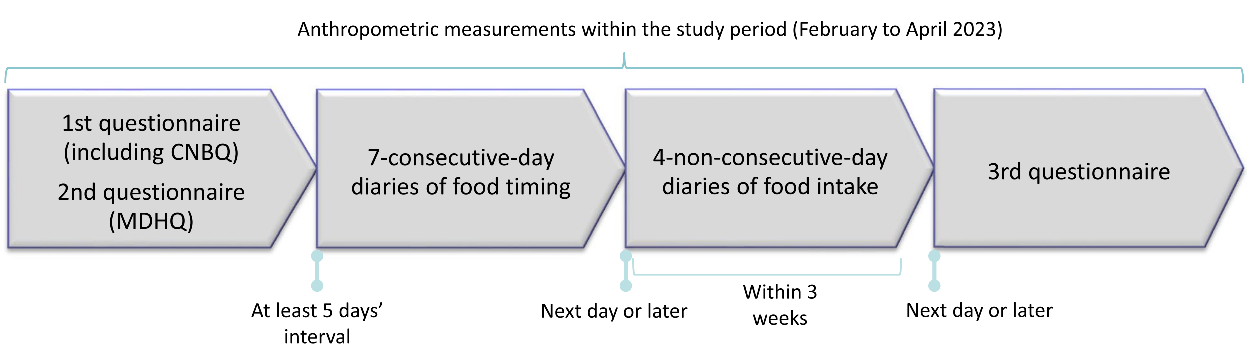

Fig. 1 Schedule of the 5W Study. 5W Study, Who, What, When, Where, and Why for Healthy Eating Study; CNBQ, Chrono-Nutrition Behavior Questionnaire; MDHQ, Meal-based Diet History Questionnaire. For the questionnaire-based analysis, we used the CNBQ to assess chrononutriton behaviors and the MDHQ to assess diet quality and energy intake misreporting. For the diary-based analysis, we used 11-day diaries of eating (consisting of 7-day diaries of food timing and 4-day diaries of food intake) to assess chrononutrition behaviors and 4-day diaries of food intake to assess diet quality and energy intake misreporting. In the present analysis, data derived from the 3rd questionnaire (i.e., eating motivation, depressive symptoms, perceived stress, and food insecurity) were not used

Chrono-Nutrition Behavior Questionnaire

The CNBQ is a newly developed questionnaire for the comprehensive assessment of chrononutrition-related parameters. Development of the CNBQ was informed by existing questionnaires [64–70] and several reviews [9, 11, 71] in the field of temporal patterns of eating and chrononutrition. Supplemental Tables 1 and 2 show the original Japanese and translated English versions of CNBQ, respectively. An in-house pretest was conducted with staff and students from the Department of Social and Preventive Epidemiology, School of Public Health, University of Tokyo, after which some modifications were made. The CNBQ consisted of three parts. Part 1 included general questions on engagement in shift work and the number of paid work (or school) days per week. For participants not in paid employment or attending school (e.g., primary homemakers and caregivers), we asked them to consider the days when their partner was engaged in paid work as workdays and the days their partner was not as non-workdays. This approach was selected considering that their own schedules may be significantly influenced by their partner's work hours. If their partner did not have a paid job or if the participants did not have a partner, we asked them to consider weekdays (Mondays to Fridays) as workdays and weekend days (Saturdays and Sundays) as non-workdays, since it is well known that dietary intake and chrononutrition behavior differ between weekdays and weekend days [72, 73].

Participants were then asked about sleep and chrononutrition behaviors on workdays (in Part 2) and non-workdays (in Part 3) separately. Question items used in this study included sleep habits (sleep time, wake time, and use of alarm clock), based on the concept of Munich ChronoType Questionnaire [74, 75], and timing of eating. For the timing of eating, we provided six pre-specified eating occasion slots (i.e., breakfast, morning snack, lunch, afternoon snack, dinner, and evening snack), since our previous analysis based on 8-day weighed food records collected over a single year (2 days in each season) from a large sample of general Japanese ($n = 4032$) showed clear peaks in the timing of these eating occasions [62]. Also, since snack eating is generally infrequent in Japanese [62], we asked participants to combine their snacking events into one within the eating occasion slots (by averaging the timing of eating). Participants who answered that they worked seven days a week (in Part 1) were not provided with a series of questions on non-workdays (i.e., Part 3). Reference time period in the CNBQ was defined as the preceding month, to correspond with the time frame of the MDHQ [56].

Meal-based Diet History Questionnaire

Details of the MDHQ have been published elsewhere [56–59]. Briefly, the MDHQ is a validated, self-administered questionnaire designed to estimate dietary intake in the previous month. The MDHQ consists of three parts: (1) consumption frequency (during the preceding month) of major food groups for each of main meals (breakfast, lunch, and dinner) and snacks (morning snack, afternoon snack, and evening snack) separately; (2) relative consumption frequency of sub-food groups within the major food groups, with questions on consumption frequency and portion size for alcoholic beverages; (3) general eating behaviors.

Eleven-day diaries of eating

The 11-day diaries of eating [60, 61] used in this study consisted of 7-consecutive-day food timing diaries and 4-non-consecutive-day (2 workdays and 2 non-workdays) weighed food intake diaries. Using this combination, we expected to collect data on a sufficient number of non-workdays (at least 4 days) while not compromising the feasibility and simplicity of the conduct of the survey. After receiving written and verbal instructions by a research dietitian, as well as an example of a completed food timing diary sheet, each participant was requested to maintain a record of food timing (start clock time), both in and out of the home. Participants were also asked to select the most appropriate eating occasion name from the prescribed list (breakfast, lunch, dinner, and snack), as well as to indicate if the recording day was either a workday or a non-workday. The definitions of workdays and non-workdays were identical to those used in the CNBQ. To minimize the burden on participants, they were not asked to provide information about the foods they consumed, nor were they asked to report the occasions on which they consumed only beverages or water. Conversely, participants were asked to record the time of going to bed, time of finishing preparation for sleep, and sleep latency (i.e., the length of time of the transition from full wakefulness to sleep) on the previous day and the time of waking. Research dietitians checked the completeness of the food timing diaries via phone, internet, or in-person three times during the 7-day period (for day 1, days 2–3, and days 4–7), and if necessary, additional information was added. The procedure used to complete the 4-day food intake diaries was similar to the 7-day food timing diaries, but more detailed descriptions were requested (as described below).

Four-day weighed food diaries

Detailed descriptions of the protocol for weighed food diaries are available elsewhere [59, 62]. Briefly, each recording period comprised two workdays and two non-workdays in a non-consecutive manner. Each participant was issued recording sheets and a digital scale (KS-732WT, Dretec, Japan; ± 2 g precision for 0–500 g and ± 3 g precision for 500–2000 g). After receiving written and verbal instructions by a research dietitian, as well as an example of a completed diary sheet, each participant was requested to document and weigh all items eaten or drunk, both in and out of the home, on each of the recording days. On occasions when weighing was problematic (e.g., dining out), they were instructed to document as much information as possible, including the brand name of the food and the consumed portion size (based on typical household measures), as well as the details of leftovers. The recording sheets used in each recording day were submitted directly to the research dietitian after each of the recording was completed, who then reviewed the forms and, whenever necessary, sought additional information or modified the record via phone or in-person interview. All collected records were then reviewed by the research dietitians and trained staff at the study center. In accordance with a standardized procedure, the portion sizes estimated using household measures were converted into weights, and the individual food items were coded based on the 2020 version of the Standard Tables of Food Composition in Japan [76].

Anthropometric measurements

Anthropometric measurements were conducted using standardized procedures. Body height (to the nearest 0.1 cm) and weight (to the nearest 0.1 kg) were measured while participant was wearing lightweight indoor clothes only, without shoes. Waist circumference was measured at the level of the umbilicus (to the nearest 0.1 cm) at the end of a normal respiration while the participant was standing erect and with the arms at the side and the feet together. A 3-m steel tape measure (Echo Metals, Japan; product code: 0536216) and a 1.5-m measuring tape (Pocket, Japan; product code: HE0085) were used to measure height and waist circumference, respectively. Conversely, due to limited economic and logistical resources, it was not possible to use uniform weight-measuring equipment; therefore, we allowed the use of any available scale. To maximize feasibility, measurements could be performed in any setting (e.g., at the research dietitian's work site and at the participant's home). Priority was given to measurements taken by research dietitians, and when not possible, measurements by family members and others were allowed. As a result, approximately 40% of measurements were conducted by research dietitians (43.6% for height, 38.2% for weight, and 40.4% for waist circumference), the remaining 40% by family members (36.5% for height, 39.9% for weight, and 42.9% for waist circumference), and 20% by others (e.g., nurses and fitness club staff; 19.9% for height, 21.9% for weight, and 16.7% for waist circumference).

Assessment of other variables

Information on other variables was collected using the questionnaires.

Data handling

Analytic sample

From the initial sample of 1110 participants (see Supplemental Fig. 1), we retained participants who completed all survey components needed for this analysis (first and second questionnaires and diaries of food timing and of food intake; $n = 1088$). We then excluded participants who provided incomplete (< 7 days) data in the diaries of food timing ($n = 2$) or only 2 days' data in the diaries of food intake ($n = 1$), those whose data in the diaries of food intake were considered insufficient in terms of data quality according to the research dietitian in charge ($n = 1$), and those whose diaries of food intake were conducted in a consecutive manner ($n = 1$). We finally excluded participants who reported 7 days' working per week during the preceding month (because they missed the opportunity to answer a series of questions on non-workdays in the CNBQ; $n = 19$), provided illogical or implausible data in the first questionnaire for one or more variables of interest ($n = 16$), or had < 2 days' data on workdays or < 2 days' data on non-workdays in the 11-day food diaries ($n = 1$). Since exclusion of participants classified as underweight (BMI < 18.5 kg/m^2 [77], $n = 82$) or of those not in paid employment ($n = 63$) did not alter the findings of the present study (data not shown), these participants were retained in the analysis, resulting in a final analysis sample of 1047 participants.

Chrononutrition behaviors

For each of the CNBQ and 11-day diaries of eating, we created chrononutrition-related parameters (including daily meal frequency, daily snack frequency, daily total eating frequency, timing of first eating occasion, timing of last eating occasion, duration of eating window, and eating midpoint) for workdays and non-workdays separately. Detailed descriptions of this process are available in Table 1. In this study, we considered that meals included breakfast, lunch, and dinner while snacks included all other eating occasions including morning snack, afternoon snack, and evening snack [16, 62]. Also, note that all eating occasions recorded in 11-day diaries of eating which consisted of beverages or water only were excluded during this process of variable creation. For diary data, mean values were calculated for each individual and for workdays and non-workdays separately.

Table 1 Chrononutrition behavior variables as well as sleep variables used in this study[a]

Variable	CNBQ[b]	11-day diaries of eating[c]
1) Sleep variables		
1–1. Sleep time (clock time)	Local time of falling asleep (i.e., sleep onset; hh:mm). Answered for workdays (question W01) and non-workdays (question F01) separately	Local time of preparing to sleep (hh:mm) plus the length of time of the transition from full wakefulness to sleep (i.e., sleep onset latency; asked in min)
1–2. Wake time (clock time)	Local time of waking up (hh:mm). Answered on workdays (question W02) and non-workdays (question F02) separately	Local time of waking up (hh:mm)
1–3. Sleep duration (hours/day)	[wake time; variable 1–2] – [sleep time; variable 1–1]. Calculated for workdays and non-workdays separately	[wake time; variable 1–2] – [sleep time; variable 1–1]
1–4. Mid-sleep time (clock time)	[sleep time; variable 1–1] + [sleep duration; variable 1–3]/2. Calculated for workdays and non-workdays separately	[sleep time; variable 1–1] + [sleep duration; variable 1–3]/2
2) Daily eating frequency (number)		
2–1. Meals[d]	Sum of the number of valid answers on the start time of breakfast, lunch, and dinner (possible number: 0, 1, 2, and 3). Calculated for workdays (using questions W04, W06, and W08) and non-workdays (using questions F04, F06, and F08) separately	Sum of the number of mentioning breakfast, lunch, and dinner
2–2. Snacks[d]	Sum of the number of valid answers on the start time of morning snack, afternoon snack, and night snack (possible number: 0, 1, 2, and 3). Calculated for workdays (using questions W05, W07, and W09) and non-workdays (using questions F05, F07, and F09) separately	Sum of the number of mentioning snacks
2–3. Total[d]	[daily eating frequency of meals; variable 2–1] + [daily eating frequency of snacks; variable 2–2] (possible number: 0, 1, 2, 3, 4, 5, and 6). Calculated for workdays and non-workdays separately	[daily eating frequency of meals; variable 2–1] + [daily eating frequency of snacks; variable 2–2]
3) Start time of eating (clock time)		
3–1. First eating occasion[d]	Earliest local time (hh:mm) of the start of first meal or first snack (see variables 3–3 and 3–5). Determined for workdays and non-workdays separately	For each day, local time (hh:mm) of the start of first eating occasion was determined as either the start of first meal or first snack (see variables 3–3 and 3–5)
3–2. Last eating occasion[d]	Latest local time (hh:mm) of the start of last meal or last snack (see variables 3–4 and 3–6). Determined for workdays and non-workdays separately	For each day, local time (hh:mm) of the start of last eating occasion was determined as either the start of last meal or last snack (see variables 3–4 and 3–6)
3–3. First meal	Earliest local time (hh:mm) of the start of eating breakfast, lunch, or dinner. Determined for workdays (using questions W04, W06, and W08) and non-workdays (using questions F04, F06, and F08) separately	For each day, earliest local time of meal (hh:mm) was determined on the basis of start time of eating breakfast, lunch, and dinner
3–4. Last meal	Latest local time (hh:mm) of the start of eating breakfast, lunch, or dinner. Determined for workdays (using questions W04, W06, and W08) and non-workdays (using questions F04, F06, and F08) separately	For each day, latest local time of meal (hh:mm) was determined on the basis of start time of eating breakfast, lunch, and dinner
3–5. First snack	Earliest local time (hh:mm) of the start of eating morning snack, afternoon snack, or night snack. Determined for workdays (using questions W05, W07, and W09) and non-workdays (using questions F05, F07, and F09) separately	For each day, earliest local time of snack (hh:mm) was determined on the basis of start time of snacks
3–6. Last snack	Latest local time (hh:mm) of the start of eating morning snack, afternoon snack, or night snack. Determined for workdays (using questions W05, W07, and W09) and non-workdays (using questions F05, F07, and F09) separately	For each day, latest local time of snack (hh:mm) was determined on the basis of start time of snacks
4) Eating window		
4–1. Duration of eating window (hours)[d]	[start time of last eating occasion; variable 3–2] – [start time of first eating occasion; variable 3–1]. Calculated for workdays and non-workdays separately	[start time of last eating occasion; variable 3–2] – [start time of first eating occasion; variable 3–1]

Table 1 (continued)

Variable	CNBQ[b]	11-day diaries of eating[c]
4–2. Eating midpoint (clock time)[d,e]	[start time of first eating occasion; variable 3–1] + [duration of eating window 1; variable 4–1]/2. Calculated for workdays and non-workdays separately	[start time of first eating occasion; variable 3–1] + [duration of eating window 1; variable 4–1]/2

CNBQ Chrono-Nutrition Behavior Questionnaire

[a] In this study, we considered that meals included breakfast, lunch, and dinner while snacks included all other eating occasions including morning snack, afternoon snack, and evening snack [16, 62]. For 11-day diaries of eating, all eating occasions consisting of beverages or water only were excluded

[b] Question items included in the CNBQ are shown in Supplemental Tables 1 (in Japanese) and 2 (in English)

[c] For all variables, mean values were calculated for each individual and for workdays and non-workdays separately

[d] Variables used in the main analyses

[e] Additionally, we created the variable eating jetlag based on eating midpoint as the absolute difference in eating midpoint between workdays and non-workdays [44], which was also used in the main analyses

Additionally, we created the variable eating jetlag based on eating midpoint as the absolute difference in eating midpoint between workdays and non-workdays [44].

Diet quality

As a measure of diet quality, the Healthy Eating Index (HEI)-2020 [78] was used. The HEI-2020 is an established, 100-point scale to assess compliance with the 2020–2025 Dietary Guidelines for Americans [79], with a higher score indicating a better quality of overall diet. The HEI-2020 consists of nine adequacy components (e.g., total fruits, total vegetables, greens and beans, and whole grains) and four moderation components (e.g., sodium and added sugars). The HEI-2020 completely aligns with the HEI-2015 [78]. In our previous analysis based on data from the Japanese National Health and Nutrition Survey, a higher HEI-2015 was reasonably associated with favorable dietary intake patterns, including higher intakes of protein, dietary fiber, key vitamins and minerals, fruits, vegetables, pulses, nuts, and fish and lower intakes of saturated fats, added sugars, sodium, confectioneries, and soft drinks [80]. Furthermore, the ability of HEI-2015 to detect the inadequacy of nutrient intake was comparable to the Diet Quality Score for Japanese and much better than the Japanese Food Guide Spinning Top score [81]. These results suggest that the HEI-2015 (and HEI-2020) sufficiently aligns with Japanese dietary behavior for assessing diet quality.

The calculation of HEI-2020 was conducted based on the MDHQ and 4-day weighed food diaries separately. On the basis of a series of ad hoc computer algorithms in the MDHQ [56], estimated intakes of food groups were calculated. Estimated intakes of energy and nutrients were calculated using food intake information and the 2015 version of the Standard Tables of Food Composition in Japan [82]. Component scores needed for the calculation of HEI-2020 were calculated using the Japanese version [80] of the US Food Patterns Equivalents Database [83]. These calculations were done for each meal type, and the overall intake was calculated as the sum of the intake of each meal type. The relative validity of the HEI-2020 derived from the MDHQ has been previously examined against a 4-day weighed dietary record among 111 males and 111 females; the correlation coefficients were 0.57 and 0.49, respectively [59].

For 4-day weighed food diaries, estimated intakes of energy and nutrients and component scores needed for the calculation of HEI-2020 were calculated using the 2020 version of the Standard Tables of Food Composition in Japan [76] and the Japanese version [80] of the US Food Patterns Equivalents Database [83], respectively. For all dietary variables, the mean daily values within the 4-day period were used for each individual.

Basic characteristics

In this study, biological sex was self-selected as either male or female. Age at the start of the study was calculated based on birth date. For both CNBQ and 11-day diaries of eating, self-reported information on sleep timing (sleep time and wake time) was collected for workdays and non-workdays separately (see Table 1), based on the concept of Munich ChronoType Questionnaire [74, 75]. Average sleep duration was calculated as follows: [sleep duration on workdays (h/d) × number of workdays per week + sleep duration on non-workdays (h/d) × (7 − number of workdays per week)]/7. Furthermore, chronotype was defined based on the Munich ChronoType Questionnaire concept of chronotype [74], as follows.

- For people whose sleep duration on non-workdays was longer than that on workdays, chronotype was defined as the midpoint of sleep on non-workdays, adjusted for possible sleep debt accumulated on workday nights, namely by subtracting half of the difference between sleep duration on non-workdays and sleep duration on workdays.
- For people whose sleep duration on non-workdays was equal to or shorter than that on workdays, chronotype was defined as the midpoint of sleep on non-workdays.

Self-reported information on the following variables was also used in this study (categorization shown in parentheses): education level (junior high school or high school, junior college or technical school, and university or higher), employment status (none, student, part-time job, and full-time job), annual household income (< 4 million Japanese yen, ≥ 4 to < 7 million Japanese yen, ≥ 7 million Japanese yen, and unknown/do not want to answer), smoking status (never, past, and current), and experience of shift work during the preceding three months (no or yes). Physical activity was categorized as low, middle, and high according to the Japanese short version of the International Physical Activity Questionnaire [84–86].

Misreporting of energy intake

Misreporting of EI derived from the MDHQ and 4-day weighed food diaries was evaluated on the basis of the ratio of EI to basal metabolic rate (BMR), namely Goldberg cut-off principle [54, 87]. Participants were identified as acceptable, under-, or overreporters of EI based on whether the individual's ratio was within, below, or above the 95% confidence limits for agreement between EI:BMR and the respective physical activity level (PAL) assessed by the International Physical Activity Questionnaire [84–86]. For males, PAL values assigned for low, middle, and high activity levels were 1.55, 1.78, and 2.10, respectively; the corresponding values for females were 1.56, 1.64, and 1.82, respectively [54]. BMR was estimated according to an equation specifically developed for Japanese adults, which considered sex, age, body weight, and body height [88, 89]. The 95% confidence limits for agreement (upper and lower cut-off values) between EI:BMR and PAL were calculated, taking into account the number of days for dietary assessment (i.e., 30 days for MDHQ and 4 days for food diaries) and the coefficient of variations in intakes and other components of energy balance (i.e., the within-subject variation in EI, 23%; precision of the estimated BMR relative to the measured BMR, 8.5%; and between-subject variation in PAL, 15%) [87].

Adiposity measures

BMI (kg/m^2) was calculated as body weight (kg) divided by the square of body height (m). General obesity was defined as BMI ≥ 25 kg/m^2 whereas abdominal obesity was defined as waist circumference ≥ 90 cm for males and ≥ 80 cm for females, on the basis of cut-off points for Asian adults according to the World Health Organization [77].

Statistical analysis

Statistical analyses were performed using the SAS statistical software (version 9.4; SAS Institute Inc.). Descriptive data are presented as means and standard deviations (SDs) for continuous variables and as the numbers and percentages of participants for categorical variables. All analyses were conducted based on questionnaire-based data (i.e., CNBQ for chrononutrition behavior variables and MDHQ for diet quality and EI misreporting) and diary-based data (i.e., 11-day diaries of eating for chrononutrition behavior variables and 4-day weighed food diaries for diet quality and EI misreporting) separately. Meanwhile, all analyses were conducted for males and females combined given that prior analyses indicated no clear suggestion of interactions between sex and the associations of chrononutrition behaviors with diet quality, BMI, and waist circumference, as well as generally similar results obtained when males and females analyzed separately (data not shown). Differences between individuals with and without general or abdominal obesity were examined using the independent t-test for continuous variables and the chi-square test for categorical variables. Associations of chrononutrition behavior variables with chronotype and sleep duration were examined using Spearman correlation coefficients. Differences in chrononutrition behavior variables between underreporters and acceptable reporters of EI were examined using the independent t-test (after excluding overreporters due to their small sample size). Associations among chrononutrition behavior variables were examined using Spearman correlation coefficients.

We then examined the associations of chrononutrition behavior variables with diet quality (HEI-2020), BMI, and waist circumference using multiple linear regression. Results were expressed as regression coefficients (with 95% confidence intervals (CIs)) per one point increase of each chrononutrition behavior variable. Separate analyses were conducted for each of the chrononutrition behavior variables. Potential confounding factors considered (in model 1) were sex, age, education level, employment status, annual household income, smoking status, physical activity, experience of shiftwork during the preceding three months, chronotype, and sleep duration, in addition to HEI-2020 for BMI and waist circumference. Further adjustment for EI reporting status was also made (in model 2). The variance inflation factor scores for any variable in any model (range: 1.1–1.7) were within acceptable limits (< 10) [90], suggesting that multicollinearity was not an issue. Finally, we examined the associations of chrononutrition behavior variables with general or abdominal obesity on the basis of multiple logistic regression, with the use of the same potential confounding factors shown above. Results were expressed as odds ratios (with 95% CIs) per one point increase of each chrononutrition behavior variable. All reported *P* values are 2-tailed, and *P* values < 0.05 were considered statistically significant.

Results

Participant characteristics

Basic characteristics of study participants are shown in Table 2. The mean BMI was 23.0 kg/m^2 (SD 3.9) and the mean waist circumference was 81.2 cm (SD 11.0). The prevalence of general and abdominal obesity was 25.6% and 31.1%, respectively. Compared with their counterparts, people who were classified as having general or abdominal obesity had lower mean sleep duration and diet quality (HEI-2020) and were more likely to have undertaken shift work during the preceding three months and underreport EI on the basis of MDHQ. Additionally, people with general obesity were more likely to be male, have full-time jobs, be past or current smokers, and underreport EI on the basis of 4-day weighed food diaries. People with abdominal obesity were also more likely to have a higher mean age, be female, have no full time work, and physically inactive.

Associations of chrononutrition behavior variables with chronotype and sleep duration

In both questionnaire- and diary-based analyses, a later chronotype was associated with lower meal frequencies, later timings for first and last eating occasions, shorter

Table 2 Basic characteristics according to categories of general and abdominal obesity[a]

	All	General obesity[b]			Abdominal obesity[c]		
	All (n = 1047)	No (n = 779)	Yes (n = 268)	P[d]	No (n = 721)	Yes (n = 326)	P[d]
Age (years)	44.4 ± 14.0	44.3 ± 14.1	44.9 ± 13.6	0.54	43.4 ± 14.0	46.7 ± 13.7	0.0003
Body mass index (kg/m^2)	23.0 ± 3.9	21.2 ± 2.1	28.3 ± 3.0	< 0.0001	21.3 ± 2.4	26.8 ± 3.8	< 0.0001
Waist circumference (cm)	81.2 ± 11.0	76.7 ± 7.5	94.1 ± 9.3	< 0.0001	75.9 ± 7.1	92.8 ± 9.1	< 0.0001
Sex				< 0.0001			0.005
Male	530 (50.6)	359 (46.1)	171 (63.8)		386 (53.5)	144 (44.2)	
Female	517 (49.4)	420 (53.9)	97 (36.2)		335 (46.5)	182 (55.8)	
Education level				0.16			0.06
Junior high school or high school	274 (26.2)	193 (24.8)	81 (30.2)		175 (24.3)	99 (30.4)	
Junior college or technical school	354 (33.8)	273 (35.0)	81 (30.2)		243 (33.7)	111 (34.0)	
University or higher	419 (40.0)	313 (40.2)	106 (39.6)		303 (42.0)	116 (35.6)	
Employment status				0.04			0.0008
None	63 (6.0)	48 (6.2)	15 (5.6)		32 (4.4)	31 (9.5)	
Student	24 (2.3)	23 (3.0)	1 (0.4)		22 (3.1)	2 (0.6)	
Part-time job	159 (15.2)	125 (16.0)	34 (12.7)		105 (14.6)	54 (16.6)	
Full-time job	801 (76.5)	583 (74.8)	218 (81.3)		562 (77.9)	239 (73.3)	
Annual household income				0.17			0.08
< 4 million yen	292 (27.9)	205 (26.3)	87 (32.5)		186 (25.8)	106 (32.5)	
≥ 4 to < 7 million yen	348 (33.2)	265 (34.0)	83 (31.0)		245 (34.0)	103 (31.6)	
≥ 7 million yen	375 (35.8)	282 (36.2)	93 (34.7)		264 (36.6)	111 (34.0)	
Unknown/do not want to answer	32 (3.1)	27 (3.5)	5 (1.9)		26 (3.6)	6 (1.8)	
Smoking status				0.01			0.99
Never	678 (64.8)	524 (67.3)	154 (57.5)		466 (64.6)	212 (65.0)	
Past	188 (18.0)	131 (16.8)	57 (21.3)		130 (18.0)	58 (17.8)	
Current	181 (17.3)	124 (15.9)	57 (21.3)		125 (17.3)	56 (17.2)	
Physical activity				0.16			0.009
Low	504 (48.1)	363 (46.6)	141 (52.6)		324 (44.9)	180 (55.2)	
Middle	401 (38.3)	311 (39.9)	90 (33.6)		294 (40.8)	107 (32.8)	
High	142 (13.6)	105 (13.5)	37 (13.8)		103 (14.3)	39 (12.0)	
Experience of shift work during the preceding three months				< 0.0001			0.002
No	803 (76.7)	626 (80.4)	177 (66.0)		573 (79.5)	230 (70.6)	
Yes	244 (23.3)	153 (19.6)	91 (34.0)		148 (20.5)	96 (29.4)	
Reporting status based on MDHQ[e]				< 0.0001			0.03
Underreporting	461 (44.0)	304 (39.0)	157 (58.6)		299 (41.5)	162 (49.7)	
Acceptable reporting	573 (54.7)	462 (59.3)	111 (41.4)		411 (57.0)	162 (49.7)	
Overreporting	13 (1.2)	13 (1.7)	0 (0.0)		11 (1.5)	2 (0.6)	
Reporting status based on 4-d weighed food diaries[e]				< 0.0001			0.13
Underreporting	149 (14.2)	85 (10.9)	64 (23.9)		93 (12.9)	56 (17.2)	
Acceptable reporting	883 (84.3)	681 (87.4)	202 (75.4)		616 (85.4)	267 (81.9)	
Overreporting	15 (1.4)	13 (1.7)	2 (0.7)		12 (1.7)	3 (0.9)	
Chronotype based on questionnaires (clock time; decimal)[f]	3.3 ± 1.5	3.3 ± 1.6	3.3 ± 1.3	0.68	3.3 ± 1.7	3.2 ± 1.2	0.21
Chronotype based on 11-day diaries (clock time; decimal)[f]	3.5 ± 1.3	3.5 ± 1.3	3.5 ± 1.4	0.97	3.6 ± 1.3	3.5 ± 1.3	0.33
Daily sleep duration based on questionnaires (hours; decimal)[g]	6.9 ± 1.1	7.0 ± 1.1	6.8 ± 1.1	0.001	7.0 ± 1.1	6.8 ± 1.2	0.04
Daily sleep duration based on 11-day diaries (hours; decimal)[g]	6.7 ± 1.0	6.8 ± 0.9	6.5 ± 1.0	0.0004	6.8 ± 0.9	6.6 ± 1.0	0.03
HEI-2020 based on MDHQ	49.3 ± 9.1	50.1 ± 9.0	47.1 ± 9.2	< 0.0001	50.0 ± 8.9	47.8 ± 9.4	0.005

Table 2 (continued)

	All ($n=1047$)	General obesity[b] No ($n=779$)	General obesity[b] Yes ($n=268$)	P^d	Abdominal obesity[c] No ($n=721$)	Abdominal obesity[c] Yes ($n=326$)	P^d
HEI-2020 based on 4-day weighed food diaries	50.7 ± 8.8	51.4 ± 8.8	48.9 ± 8.6	< 0.0001	51.2 ± 8.8	49.6 ± 8.8	0.005

MDHQ Meal-based Diet History Questionnaire, *HEI* Healthy Eating Index

[a] Values are means ± standard deviations for continuous variables and numbers (percentages) of participants for categorical variables

[b] General obesity was defined as body mass index ≥ 25 kg/m^2 for both sexes [77]

[c] Abdominal obesity was defined as waist circumference ≥ 90 cm for male individuals and ≥ 80 cm for female individuals [77]

[d] Based on the independent t-test for continuous variables and the chi-square test for categorical variables

[e] Determined using the ratio of reported energy intake to estimated basal metabolic rate, taking into account physical activity level at the individual level [54, 87]

[f] Based on the Munich ChronoType Questionnaire concept of chronotype [74], as follows. For people whose sleep duration on non-workdays was longer than that on workdays, chronotype was defined as the midpoint of sleep on non-workdays, adjusted for possible sleep debt accumulated on workday nights, namely by subtracting half of the difference between sleep duration on non-workdays and sleep duration on workdays. For people whose sleep duration on non-workdays was equal to or shorter than that on workdays, chronotype was defined as the midpoint of sleep on non-workdays. Values are shown in decimal format; for example, 3.3 means 3:18 AM

[g] Values are shown in decimal format; for example, 6.9 means a duration of 6 h and 54 min

durations of eating windows, and later eating midpoints on both workdays and non-workdays (Supplemental Table 3). Additionally, a longer sleep duration was associated with lower snack and total eating frequencies on workdays and non-workdays, a later timing of first eating occasion on workdays, earlier timings of last eating occasions on workdays and non-workdays, and shorter durations of eating windows on workdays and non-workdays.

Chrononutrition behavior variables according to energy intake reporting status

Table 3 shows chrononutrition behavior variables used in this study. Irrespective of dietary assessment methods and for both workdays and non-workdays, compared with participants who were classified as acceptable reporters, those who were classified as underreporters had, on average, lower daily frequencies of meals, snacks, and total eating occasions, later timings of first eating occasions, shorter durations of eating windows, later eating midpoints, and larger eating jetlags. In the diary-based analysis, underreporters also had earlier timings of last eating occasions on both workdays and non-workdays, which was not observed in the questionnaire-based analysis.

Correlations between chrononutrition behavior variables

Correlations between chrononutrition behavior variables were similar for both workdays and non-workdays and irrespective of dietary assessment methods (Supplemental Table 4). The highest correlations were observed between daily snack frequency and total eating frequency (0.89 to 0.92), followed by those between timings of first and last eating occasions and eating midpoint (0.67 to 0.87). Other notable correlations observed were between daily meal frequency and timing of first eating occasion (-0.63 to -0.71), daily meal frequency and duration of eating window (0.55 to 0.66), daily meal frequency and eating midpoint (-0.58 to -0.62), and timing of first eating occasion and duration of eating window (-0.63 to -0.75). Correlations between the same variables on workdays and non-workdays ranged from 0.53 (duration of eating window) to 0.70 (eating midpoint) in the questionnaire-based analysis and from 0.52 (duration of eating window) to 0.72 (daily total eating frequency) in the diary-based analysis.

Associations between chrononutrition behavior variables and diet quality

Table 4 shows associations between chrononutrition behavior variables and diet quality. In the questionnaire-based analysis, after adjustment for potential confounding factors (model 1), a higher meal frequency on non-workdays was associated with a higher diet quality. Additionally, there were inverse associations for snack and total eating frequencies, timing of last eating occasions, and eating midpoints on workdays and non-workdays and eating jetlag. In the diary-based analysis, later timings of first and last eating occasions and eating midpoint on workdays were associated with a lower diet quality. Further adjustment for EI reporting status (model 2) did not impact these results.

Associations between chrononutrition behavior variables and general and abdominal obesity

Associations between chrononutrition behavior variables and general and abdominal obesity are shown in Table 5. In the questionnaire-based analysis, after adjustment for potential confounding factors (model 1), there were significant positive associations of snack and total eating frequencies on workdays and duration of eating windows

Table 3 Chrononutrition behavior variables according to energy intake reporting status[a]

	Questionnaire-based analysis[b]				Diary-based analysis[c]			
	All (n = 1047) [d]	Under-Reporting (n = 461)	Acceptable reporting (n = 573)	P[e]	All (n = 1047)[d]	Under-reporting (n = 149)	Acceptable reporting (n = 883)	P[e]
Workdays								
Meal frequency (number/day)	2.78 ± 0.45	2.66 ± 0.54	2.88 ± 0.33	< 0.0001	2.77 ± 0.39	2.54 ± 0.46	2.81 ± 0.39	< 0.0001
Snack frequency (number/day)	1.21 ± 0.98	0.96 ± 0.91	1.38 ± 0.99	< 0.0001	0.99 ± 0.90	0.51 ± 0.57	1.07 ± 0.90	< 0.0001
Daily total eating frequency (number/day)	3.99 ± 1.13	3.62 ± 1.08	4.26 ± 1.07	< 0.0001	3.77 ± 1.02	3.04 ± 0.75	3.88 ± 1.02	< 0.0001
Timing of first eating occasion (clock time; decimal)	8.06 ± 2.45	8.73 ± 2.98	7.54 ± 1.76	< 0.0001	8.06 ± 2.17	9.23 ± 2.62	7.87 ± 2.17	< 0.0001
Timing of last eating occasion (clock time; decimal)	20.37 ± 1.72	20.35 ± 1.79	20.38 ± 1.67	0.80	20.10 ± 1.24	19.90 ± 1.18	20.13 ± 1.24	0.04
Duration of eating window (hours; decimal)	12.31 ± 2.78	11.62 ± 3.17	12.84 ± 2.30	< 0.0001	12.03 ± 2.31	10.67 ± 2.66	12.26 ± 2.31	< 0.0001
Eating midpoint (clock time; decimal)	14.21 ± 1.59	14.54 ± 1.88	13.96 ± 1.27	< 0.0001	14.08 ± 1.34	14.56 ± 1.53	14.00 ± 1.34	< 0.0001
Non-workdays								
Meal frequency (number/day)	2.73 ± 0.48	2.61 ± 0.54	2.82 ± 0.41	< 0.0001	2.70 ± 0.41	2.39 ± 0.49	2.75 ± 0.41	< 0.0001
Snack frequency (number/day)	1.26 ± 1.01	0.98 ± 0.95	1.47 ± 1.00	< 0.0001	1.06 ± 0.82	0.57 ± 0.55	1.13 ± 0.82	< 0.0001
Daily total eating frequency (number/day)	3.99 ± 1.16	3.59 ± 1.09	4.29 ± 1.12	< 0.0001	3.76 ± 0.99	2.97 ± 0.75	3.87 ± 0.99	< 0.0001
Timing of first eating occasion (clock time; decimal)	9.11 ± 2.18	9.64 ± 2.40	8.71 ± 1.90	< 0.0001	9.05 ± 1.96	10.23 ± 2.40	8.86 ± 1.96	< 0.0001
Timing of last eating occasion (clock time; decimal)	19.81 ± 1.62	19.76 ± 1.67	19.84 ± 1.59	0.39	19.61 ± 1.19	19.36 ± 1.27	19.65 ± 1.19	0.01
Duration of eating window (hours; decimal)	10.69 ± 2.51	10.12 ± 2.66	11.13 ± 2.28	< 0.0001	10.56 ± 2.05	9.12 ± 2.52	10.79 ± 2.05	< 0.0001
Eating midpoint (clock time; decimal)	14.46 ± 1.46	14.70 ± 1.58	14.28 ± 1.33	< 0.0001	14.33 ± 1.25	14.79 ± 1.45	14.25 ± 1.25	< 0.0001
Eating jetlag based on eating midpoint (hours; decimal)	0.89 ± 1.00	1.06 ± 1.17	0.75 ± 0.82	< 0.0001	0.77 ± 0.73	1.02 ± 0.89	0.72 ± 0.73	< 0.0001

[a] Values are means ± standard deviations. Energy intake reporting status was determined using the ratio of reported energy intake (derived from either the Meal-based Diet History Questionnaire or 4-day weighed food diaries) to estimated basal metabolic rate, taking into account physical activity level at the individual level [54, 87]. Meals included breakfast, lunch, and dinner. All time-related variables are shown in decimal format, with the unit of *clock time; decimal* (e.g., 8.06 means 8:04 AM, while 20.37 means 8:22 PM) or *hours; decimal* (e.g., 12.31 means a duration of 12 h 19 min)

[b] Chrononutrition behavior variables were assessed using the Chrono-Nutrition Behavior Questionnaire; reported energy intake was derived from the Meal-based Diet History Questionnaire

[c] Chrononutrition behavior variables were assessed using the 11-day diaries of eating; reported energy intake was derived from the 4-day weighed food diaries

[d] Including overreporters (n = 13 for questionnaire-based analysis and n = 15 for diary-based analysis)

[e] Based on the independent t-test

Table 4 Associations between chrononutrition behavior variables and overall diet quallity[a]

	Questionnaire-based analysis[b]		Diary-based analysis[c]	
	Model 1 (without adjustment for energy intake reporting status)[d]	**Model 2 (with adjustment for energy intake reporting status)[e]**	**Model 1 (without adjustment for energy intake reporting status)[d]**	**Model 2 (with adjustment for energy intake reporting status)[e]**
Workdays				
Meal frequency (number/day)	0.92 (-0.32, 2.16)	0.70 (-0.57, 1.97)	1.24 (-0.12, 2.61)	1.03 (-0.36, 2.41)
Snack frequency (number/day)	-1.61 (-2.17, -1.06)	-1.83 (-2.39, -1.26)	0.03 (-0.54, 0.60)	-0.08 (-0.66, 0.50)
Daily total eating frequency (number/day)	-1.10 (-1.59, -0.61)	-1.34 (-1.85, -0.83)	0.20 (-0.31, 0.71)	0.08 (-0.44, 0.61)
Timing of first eating occasion (clock time; decimal)	-0.15 (-0.38, 0.09)	-0.10 (-0.34, 0.14)	-0.30 (-0.55, -0.05)	-0.26 (-0.52, -0.01)
Timing of last eating occasion (clock time; decimal)	-0.55 (-0.87, -0.23)	-0.56 (-0.89, -0.24)	-0.41 (-0.87, 0.05)	-0.48 (-0.94, -0.01)
Duration of eating window (hours; decimal)	-0.10 (-0.31, 0.10)	-0.15 (-0.36, 0.06)	0.14 (-0.08, 0.37)	0.10 (-0.13, 0.33)
Eating midpoint (clock time; decimal)	-0.51 (-0.87, -0.15)	-0.47 (-0.84, -0.11)	-0.61 (-1.04, -0.18)	-0.58 (-1.01, -0.15)
Non-workdays				
Meal frequency (number/day)	1.40 (0.20, 2.60)	1.24 (0.02, 2.45)	1.20 (-0.15, 2.56)	0.93 (-0.47, 2.32)
Snack frequency (number/day)	-1.20 (-1.74, -0.67)	-1.40 (-1.95, -0.85)	-0.32 (-0.95, 0.31)	-0.46 (-1.11, 0.18)
Daily total eating frequency (number/day)	-0.71 (-1.19, -0.24)	-0.90 (-1.40, -0.41)	-0.05 (-0.58, 0.49)	-0.20 (-0.76, 0.36)
Timing of first eating occasion (clock time; decimal)	-0.27 (-0.56, 0.02)	-0.23 (-0.52, 0.06)	-0.23 (-0.55, 0.09)	-0.18 (-0.50, 0.14)
Timing of last eating occasion (clock time; decimal)	-0.43 (-0.79, -0.08)	-0.46 (-0.82, -0.11)	-0.26 (-0.72, 0.20)	-0.35 (-0.81, 0.12)
Duration of eating window (hours; decimal)	-0.01 (-0.24, 0.22)	-0.05 (-0.28, 0.18)	0.08 (-0.19, 0.35)	0.01 (-0.27, 0.29)
Eating midpoint (clock time; decimal)	-0.66 (-1.10, -0.22)	-0.63 (-1.07, -0.18)	-0.46 (-0.96, 0.05)	-0.43 (-0.94, 0.08)
Eating jetlag based on eating midpoint (hours; decimal)	-0.79 (-1.35, -0.23)	-0.74 (-1.30, -0.18)	-0.54 (-1.27, 0.18)	-0.50 (-1.22, 0.22)

[a] Values are regression coefficients (95% confidence intervals). Regression coefficients mean the change of Healthy Eating Index-2020 with one point increase of each variable listed. Meals included breakfast, lunch, and dinner

[b] Chrononutrition behavior variables were assessed using the Chrono-Nutrition Behavior Questionnaire; the Healthy Eating Index-2020 was derived from the Meal-based Diet History Questionnaire

[c] Chrononutrition behavior variables were assessed using the 11-day diaries of eating; the Healthy Eating Index-2020 was derived from the 4-day weighed food diaries

[d] Adjustment was made for sex (male or female), age (years, continuous), education level (junior high school or high school, junior college or technical school, and university or higher), employment status (none, student, part-time job, and full-time job), annual household income (< 4 million yen, ≥ 4 to < 7 million yen, ≥ 7 million yen, and unknown/do not want to answer), smoking status (never, past, and current), physical activity (low, middle, and high), experience of shiftwork during the preceding three months (yes or no), chronotype (hours, continuous), and sleep duration (hours/day, continuous)

[e] Adjustment was made for variables entered into model 1 and energy intake reporting status (underreporting, acceptable reporting, or overreporting)

on both workdays and non-workdays with the prevalence of abdominal obesity. Further adjustment for EI reporting status (model 2) strengthened these associations but also produced significant associations with the prevalence of general obesity (except for the duration of eating window on non-workdays). Additionally, in model 2, higher meal frequencies on both workdays and non-workdays and higher snack and total eating frequencies on non-workdays were associated with a higher prevalence of abdominal obesity. Furthermore, inverse associations between timing of first eating occasions on both workdays and non-workdays and the prevalence of abdominal obesity and a positive association between timing of last eating occasion on non-workdays and the prevalence of abdominal obesity emerged. Conversely, there were no associations between any of chrononutrition behavior

Table 5 Associations between chrononutrition behavior variables and general obesity and abdominal obesity[a]

	Questionnaire-based analysis[b]		Diary-based analysis[c]	
	Model 1 (without adjustment for energy intake reporting status)[d]	Model 2 (with adjustment for energy intake reporting status)[e]	Model 1 (without adjustment for energy intake reporting status)[d]	Model 2 (with adjustment for energy intake reporting status)[e]
Workdays				
Meal frequency (number/day)				
General obesity	0.85 (0.61, 1.18)	1.04 (0.74, 1.46)	0.81 (0.55, 1.18)	0.93 (0.63, 1.38)
Abdominal obesity	1.21 (0.87, 1.67)	1.41 (1.01, 1.97)	1.21 (0.82, 1.78)	1.35 (0.91, 2.01)
Snack frequency (number/day)				
General obesity	1.06 (0.91, 1.24)	1.19 (1.02, 1.41)	0.94 (0.79, 1.12)	1.01 (0.85, 1.21)
Abdominal obesity	1.17 (1.01, 1.35)	1.27 (1.09, 1.48)	0.99 (0.84, 1.16)	1.04 (0.88, 1.23)
Total eating frequency (number/day)				
General obesity	1.02 (0.89, 1.16)	1.16 (1.001, 1.33)	0.92 (0.79, 1.07)	1.00 (0.85, 1.17)
Abdominal obesity	1.16 (1.02, 1.32)	1.28 (1.12, 1.47)	1.02 (0.88, 1.17)	1.08 (0.93, 1.25)
Timing of first eating occasion (clock time; decimal)				
General obesity	0.98 (0.92, 1.05)	0.94 (0.89, 1.01)	1.01 (0.95, 1.09)	0.99 (0.92, 1.06)
Abdominal obesity	0.95 (0.89, 1.01)	0.92 (0.87, 0.99)	0.95 (0.88, 1.02)	0.94 (0.87, 1.01)
Timing of last eating occasion (clock time; decimal)				
General obesity	1.04 (0.95, 1.13)	1.05 (0.96, 1.15)	1.04 (0.91, 1.19)	1.09 (0.95, 1.25)
Abdominal obesity	1.05 (0.97, 1.15)	1.06 (0.98, 1.16)	0.99 (0.87, 1.13)	1.02 (0.90, 1.16)
Duration of eating window (hours; decimal)				
General obesity	1.03 (0.97, 1.08)	1.06 (1.01, 1.13)	1.00 (0.94, 1.07)	1.03 (0.96, 1.10)
Abdominal obesity	1.06 (1.003, 1.11)	1.08 (1.03, 1.15)	1.04 (0.97, 1.11)	1.06 (0.99, 1.14)
Eating midpoint (clock time; decimal)				
General obesity	1.00 (0.91, 1.10)	0.96 (0.87, 1.06)	1.04 (0.92, 1.17)	1.02 (0.90, 1.15)
Abdominal obesity	0.98 (0.89, 1.07)	0.95 (0.86, 1.04)	0.93 (0.82, 1.05)	0.92 (0.81, 1.04)
Non-workdays				
Meal frequency (number/day)				
General obesity	0.87 (0.63, 1.20)	1.02 (0.73, 1.42)	0.85 (0.58, 1.25)	1.04 (0.69, 1.56)
Abdominal obesity	1.28 (0.93, 1.75)	1.44 (1.04, 1.99)	1.07 (0.73, 1.56)	1.23 (0.83, 1.83)
Snack frequency (number/day)				
General obesity	1.00 (0.87, 1.17)	1.11 (0.95, 1.30)	0.95 (0.79, 1.15)	1.04 (0.86, 1.26)
Abdominal obesity	1.08 (0.94, 1.24)	1.17 (1.01, 1.35)	0.97 (0.82, 1.15)	1.03 (0.86, 1.23)
Total eating frequency (number/day)				
General obesity	0.98 (0.86, 1.12)	1.09 (0.95, 1.25)	0.94 (0.80, 1.10)	1.04 (0.88, 1.22)
Abdominal obesity	1.10 (0.97, 1.24)	1.20 (1.05, 1.36)	0.99 (0.85, 1.15)	1.06 (0.91, 1.23)
Timing of first eating occasion (clock time; decimal)				
General obesity	0.98 (0.90, 1.06)	0.94 (0.86, 1.02)	1.00 (0.91, 1.09)	0.96 (0.88, 1.05)
Abdominal obesity	0.93 (0.86, 1.00)	0.90 (0.84, 0.98)	0.96 (0.88, 1.05)	0.94 (0.86, 1.03)
Timing of last eating occasion (clock time; decimal)				
General obesity	1.03 (0.93, 1.13)	1.05 (0.95, 1.16)	1.04 (0.91, 1.19)	1.10 (0.96, 1.27)
Abdominal obesity	1.09 (0.995, 1.20)	1.11 (1.01, 1.22)	0.98 (0.86, 1.11)	1.02 (0.90, 1.16)
Duration of eating window (hours; decimal)				
General obesity	1.03 (0.96, 1.09)	1.06 (0.995, 1.13)	1.02 (0.94, 1.10)	1.07 (0.98, 1.16)
Abdominal obesity	1.08 (1.02, 1.15)	1.11 (1.04, 1.18)	1.02 (0.95, 1.10)	1.05 (0.98, 1.14)
Eating midpoint (clock time; decimal)				
General obesity	0.99 (0.88, 1.12)	0.97 (0.85, 1.09)	1.02 (0.88, 1.18)	1.01 (0.87, 1.16)
Abdominal obesity	0.98 (0.88, 1.11)	0.97 (0.86, 1.09)	0.94 (0.82, 1.08)	0.94 (0.81, 1.08)

Table 5 (continued)

	Questionnaire-based analysis[b]		Diary-based analysis[c]	
	Model 1 (without adjustment for energy intake reporting status)[d]	**Model 2 (with adjustment for energy intake reporting status)[e]**	**Model 1 (without adjustment for energy intake reporting status)[d]**	**Model 2 (with adjustment for energy intake reporting status)[e]**
Eating jetlag based on eating midpoint (hours; decimal)				
General obesity	0.94 (0.80, 1.09)	0.90 (0.77, 1.04)	1.02 (0.83, 1.25)	0.99 (0.80, 1.22)
Abdominal obesity	0.93 (0.80, 1.08)	0.90 (0.78, 1.05)	0.96 (0.78, 1.17)	0.94 (0.77, 1.15)

[a] Values are odds ratios (95% confidence intervals) for general and abdominal obesity per one point increase of each variable listed. General obesity was defined as body mass index ≥ 25 kg/m^2 for both sexes [77]. Abdominal obesity was defined as waist circumference ≥ 90 cm for male individuals and ≥ 80 cm for female individuals [77]. Meals included breakfast, lunch, and dinner

[b] Chrononutrition behavior variables were assessed using the Chrono-Nutrition Behavior Questionnaire; the Healthy Eating Index-2020 was derived from the Meal-based Diet History Questionnaire

[c] Chrononutrition behavior variables were assessed using the 11-day diaries of eating; the Healthy Eating Index-2020 was derived from the 4-day weighed food diaries

[d] Adjustment was made for sex (male or female), age (years, continuous), education level (junior high school or high school, junior college or technical school, and university or higher), employment status (none, student, part-time job, and full-time job), annual household income (< 4 million yen, ≥ 4 to < 7 million yen, ≥ 7 million yen, and unknown/do not want to answer), smoking status (never, past, and current), physical activity (low, middle, and high), experience of shiftwork during the preceding three months (yes or no), chronotype (hours, continuous), sleep duration (hours/day, continuous), and Healthy Eating Index-2020 (continuous)

[e] Adjustment was made for variables entered into model 1 and energy intake reporting status (underreporting, acceptable reporting, or overreporting)

variables and general and abdominal obesity in the diary-based analysis, irrespective of adjustment for EI reporting status. The overall results were similar when the associations with BMI and waist circumference were examined (Supplemental Table 5).

Discussion

To our knowledge, this is the first study to investigate the impact of dietary assessment methodologies (questionnaires and diaries) and the confounding of EI misreporting on the associations of chrononutrition behaviors with diet quality and adiposity measures. In the questionnaire-based analysis (using CNBQ and MDHQ), a higher meal frequency (on non-workdays only) but a lower snack frequency was associated with a higher diet quality. This finding is consistent with some [46, 48, 49], but not all [47, 50], previous studies and highlights the importance of differentiation of meals and snacks in chrononutrition research. In contrast with some previous studies [24, 51], we found an inverse association between total eating frequency and diet quality, which may be a function of a high correlation between total eating frequency and snack frequency. In terms of other chrononutrition behaviors, later timings of last eating occasions and eating midpoints on both workdays and non-workdays and a larger eating jetlag were associated with a lower diet quality, which is consistent with some [40, 51], but not other [43, 50], previous studies. These associations were not confounded by misreporting of EI, as the results did not change before and after adjustment for EI misreporting, which might be a result of the use of energy-adjusted dietary variables to calculate the HEI-2020.

Based on questionnaire data (CNBQ and MDHQ), higher meal, snack, and total eating frequency on both workdays and non-workdays was associated with a higher prevalence of general and/or abdominal obesity, with stronger associations observed when the misreporting of EI was adjusted for. These findings are consistent with previous studies in which misreporting of EI was considered [15–17]. Additionally, in line with a number of previous studies [19, 20, 23, 24, 26, 29–31, 33–35, 38–41], some of other chrononutrition behavior variables, including timing of last eating occasion on non-workdays and durations of eating windows on workdays and non-workdays, were positively associated with general and abdominal obesity, after adjustment for EI misreporting. Given these findings as well as the clear differences in chrononutrition behaviors and adiposity measures between acceptable reporters and underreporters of EI, this study clearly demonstrated the key importance of adjustment for EI misreporting in the analysis of chrononutrition behaviors and obesity. We also found that earlier timings of first eating occasions on workdays and non-workdays were associated with a higher prevalence of abdominal obesity. This is inconsistent with several previous findings [19, 38, 39] and may be due to the fact that earlier timings of first eating occasions were associated with higher eating frequencies and longer eating windows in this study.

The most important finding of this study was that compared with the questionnaire-based analysis, totally different pictures emerged in the diary-based analysis.

Regardless of adjustment for EI misreporting, we found no associations of chrononutrition behaviors with diet quality and adiposity measures (except for inverse associations of timings of first and last eating occasions and eating midpoint on workdays with diet quality, which are consistent with some [40, 51], but other [43, 50], previous studies). This is somewhat surprising given the nature of food dairies, in which participants' current behavior and experiences are reportedly sampled in their natural environment in real-time, largely independent on recall bias [60, 91–94]. However, it should be noted that while food diary methodologies have been acknowledged as a validated method [11, 91–94], the target of these validations is overall dietary intakes, not chrononutrition behaviors. In particular, the food diary is susceptible to measurement errors due to the erroneous recording and potential changes in eating behavior (i.e., reactivity) [63, 91, 95, 96], which may explain null associations observed here. Nevertheless, solely based on the present findings, it would be naïve to advocate that questionnaire-based tools (such as CNBQ) are superior to food diaries when it comes to the assessment of chrononutrition behaviors. Dietary questionnaires ultimately rely on memory and only measure memory and perception of usual behavior and thus may be particularly vulnerable to exaggeration of good behaviors and underreporting of bad behaviors [42, 63, 97]. Furthermore, null associations between chrononutrition behaviors and diet quality [43, 50] and adiposity measures [19, 21, 26, 29, 36, 37, 43], as observed in the diary-based analysis, are not necessarily uncommon in previous studies. Thus, it remains unclear whether questionnaires or detailed diaries are optimal for the measurement of chrononutrition behaviors, which should be further investigated in future research. In particular, it is imperative to establish whether those questionnaires specifically developed and validated to assess chrononutrition behaviors [64–70], in addition to the CNBQ, are fit-for-purpose.

In this study, all chrononutrition behavior variables were (albeit modestly) correlated with chronotype, sleep duration, or both, irrespective of dietary assessment methods. This is consistent with findings from a number of systematic reviews [4, 10, 11, 71, 98–101]. Given that it is well known that both chronotype and sleep duration are associated with dietary intake and adiposity measures [4, 10, 11, 71, 98–101], this study further reinforced the importance of adjustment for both chronotype and sleep duration when investigating chrononutrition behaviors in relation to diet quality and adiposity measures.

There are several limitations in the present study. First, the cross-sectional nature of the study does not permit the assessment of causality owing to the uncertain temporality of the association. Further studies using a prospective design would provide better understanding of the associations between chrononutrition behaviors and adiposity measures and diet quality. Second, although conducted in diverse regions (26 of 47 prefectures), the participants consisted of volunteers, not a nationally representative sample of the Japanese population. The participants may have been biased toward greater health consciousness, higher socioeconomic status, or both. For example, the education level and annual household income of the participants were higher than those of a nationally representative sample [102, 103]. However, the prevalence of current smokers and mean BMI in the present participants were similar to those of the nationally representative sample [104]. Ideally, further research should be conducted using a more nationally representative sample. Third, not all anthropometric measurements were conducted by trained staff (research dietitians) using standardized instruments, which may lead to some degree of error in the classification of general and abdominal obesity. Nevertheless, this issue does not seem to explain different associations observed in the questionnaire-based and diary-based analyses.

Fourth, although we adjusted for a variety of potential confounding variables, residual confounding could not be ruled out. Fifth, in view of the multiple analyses, it is possible that some of the findings in the present study occurred by chance. Finally, because of a lack of an objective and valid method to assess chrononutrition behaviors that can be used in free-living settings [105], we used EI misreporting as a marker of dietary misreporting. The selection of PAL category needed to determine the status of self-reported EI was based on self-report (that is, a validated questionnaire [84–86]), which may be susceptible to reporting bias. Furthermore, the role of EI misreporting was mainly evaluated only in terms of underreporting because overreporting occurred in such a low number of cases that no conclusions could be drawn in this regard. More importantly, misreporting of EI is not equal to that of chrononutrition behaviors. This issue is more relevant for the questionnaire-based analysis, in which EI and chrononutrition behaviors were derived from different tools (MDHQ and CNBQ, respectively). Nevertheless, it should be noted that (self-reported) chrononutrition behaviors clearly differed between acceptable reporters and underreporters of EI in both diary-based and questionnaire-based analyses.

Despite these limitations, the novelty and strengths of the present study include the use of two distinct dietary assessment methods (questionnaires and diaries) to assess various and clearly defined chrononutrition-related parameters for workdays and non-workdays separately, taking into account EI misreporting and other important confounding factors (such as chronotype and sleep duration [4, 10, 11, 71, 98–101]). As such, the present findings are highly relevant to the growing interest in temporal patterns of eating and chrononutrition in the discussion of nutrition, health, and chronic disease prevention [11–13, 71].

This study also has important implications for future research. First, it is crucial to consider that the associations between chrononutrition behaviors, diet quality, and obesity may depend on the methodology used to assess these behaviors. Second, since misreporting of EI is clearly associated with chrononutrition behavior variables, implementing procedures to identify and separately analyze individuals who report dietary data of poor validity would improve the precision and accuracy of results in studies of chrononutrition behaviors. Third, given the interrelated nature of chrononutrition behavior variables demonstrated in this study, future research should explore chrononutrition behavior patterns using techniques such as cluster analysis [19] and latent profile analysis [106]. These data reduction methods would help define what constitutes "good" versus "poor" chrononutrition behaviors, improving the interpretability of findings and providing actionable insights for both research and practical applications.

Conclusions

In this cross-sectional study, we demonstrated that the associations of chrononutrition behaviors with diet quality and adiposity measures are a function of the methods to assess chrononutrition behaviors (i.e., questionnaires vs diaries), as well as potential importance of adjustment for EI misreporting. Thus, future studies should be conducted with careful consideration of dietary assessment methodology and taking into account dietary misreporting to enable justifiable conclusions to be drawn with regard to the associations of chrononutrition behaviors with diet quality and adiposity measures. Through these practices, the emerging research field of chrononutrition would move forward to higher levels.

Abbreviations

BMI	Body mass index
BMR	Basal metabolic rate
CI	Confidence interval
CNBQ	Chrono-Nutrition Behavior Questionnaire
EI	Energy intake
HEI	Healthy Eating Index
MDHQ	Meal-based Diet History Questionnaire
PAL	Physical activity level
SD	Standard deviation
5W Study	Who, What, When, Where, and Why for Healthy Eating Study

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
KM contributed to the concept and design of the survey and data collection and management, formulated the research, analyzed and interpreted the data, prepared the first draft of the manuscript, and had primary responsibility for the final content; NS contributed to the concept and design of the survey and data collection and management, interpreted the data, and provided critical input into the final draft of the manuscript; MBEL and TAM provided critical input into the final draft of the manuscript; and SM and SS contributed to the design of the survey and managed the study-field establishment, recruitment, and fieldwork. All authors read and approved the final manuscript.

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Data availability
The datasets generated and analyzed during the current study are not publicly available but may be made available by the corresponding author on reasonable request and upon approval by the Ethics Committee of the University of Tokyo Faculty of Medicine.

Declarations

Ethics approval and consent to participate
The study was conducted in accordance with the guidelines of the Declaration of Helsinki, and all procedures were approved by the Ethics Committee of the University of Tokyo Faculty of Medicine (protocol code: 2022235NI; date of approval: 24 November 2022). Written informed consent was obtained from all participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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