

Chrononutrition: exploring determinants and feature importance of eating timing among Brazilian adults

Crononutrição: investigando os determinantes e a importância das variáveis nos horários de alimentação entre adultos brasileiros

Crononutrición: explorando los determinantes y la importancia de las características del horario de alimentación en adultos brasileños

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Abstract Our study aimed to explore factors influencing the timing of food intake, including physiological, behavioral, personal preferences, cultural, and environmental dynamics. Using data from 5,260 Brazilian adults collected through a virtual, exploratory, population-based survey (Sonar-Brazil/2023-24), Lasso regression identified the determinants of the timing of the first and last food intake, lunch, eating midpoint, and weekly breakfast skipping. Random Forest analysis was used to assess the feature importance for the eating midpoint. Chronotype emerged as the primary predictor across all outcomes: as chronotype shifted towards eveningness, the frequency of breakfast skipping increased and food intake timings delayed. While depression, obesity, evening screen time, smoking, caffeine consumption, having dinner as the largest meal, short sleep duration, and working remotely were associated with a later eating midpoint, age, female sex, exercising, evening alcohol consumption, diet quality, working in-office, and higher education were associated with an earlier eating midpoint. Insights into modifiable factors influencing eating timing can inform public health interventions aimed at promoting healthier eating habits aligned with the circadian system, tailored to diverse regional and individual contexts.

Key words Meal timing, Circadian rhythm, Chrononutrition, Food intake

Resumo Este estudo objetivou explorar fatores fisiológicos, comportamentais, preferências pessoais, culturais e ambientais que influenciam o horário de alimentação. Com dados de 5.260 adultos brasileiros de uma pesquisa virtual (Sonar-Brasil/2023-24), a regressão Lasso identificou os determinantes dos horários do primeiro e último episódio alimentar, almoço, ponto médio da alimentação e frequência de pular o café da manhã. A análise Random Forest avaliou a importância das variáveis para o ponto médio da alimentação. O cronotipo foi o principal preditor: à medida que se deslocava para a vespertinidade, aumentava a frequência de pular o café da manhã e os horários de alimentação eram mais tardios. Depressão, obesidade, tempo de tela à noite, tabagismo, cafeína, ter o jantar como a maior refeição, sono curto e trabalho remoto foram associados ao atraso do ponto médio da alimentação. Já idade, sexo feminino, exercícios, consumo de álcool à noite, qualidade da dieta, trabalho presencial e maior escolaridade foram associados ao seu adiantamento. Compreender os fatores modificáveis do horário alimentar pode auxiliar na criação de intervenções de saúde pública que promovam hábitos alimentares saudáveis, alinhados ao sistema circadiano e adaptados a contextos regionais e individuais.

Palavras-chave Horário das refeições, Ritmo circadiano, Crononutrição, Ingestão alimentar

Resumen Nuestro estudio tuvo como objetivo explorar los factores que influyen en el horario de la ingesta alimentaria, incluyendo dinámicas fisiológicas, conductuales, de preferencias personales, culturales y ambientales. Utilizando datos de 5.260 adultos brasileños recolectados a través de una encuesta virtual, exploratoria y poblacional (Sonar-Brasil/2023-24), se empleó regresión Lasso para identificar los determinantes del horario de la primera y última comida, del almuerzo, del punto medio de la alimentación y de la frecuencia semanal de omisión del desayuno. Se utilizó análisis de Bosque Aleatorio (Random Forest) para evaluar la importancia de las características para el punto medio de la alimentación. El cronotipo surgió como el principal predictor en todos los desenlaces: a medida que el cronotipo se desplazaba hacia la vespertinidad, aumentaba la frecuencia de omisión del desayuno y se retrasaban los horarios de las comidas. Mientras que la depresión, la obesidad, el tiempo frente a pantallas por la noche, el tabaquismo, el consumo de cafeína, tener la cena como la comida principal, la duración corta del sueño y el trabajo remoto se asociaron con un punto medio de alimentación más tardío, la edad, el sexo femenino, la práctica de actividad física, el consumo de alcohol por la noche, la calidad de la dieta, el trabajo presencial y un mayor nivel educativo se asociaron con un punto medio de alimentación más temprano. Comprender los factores modificables que influyen en el horario de alimentación puede contribuir a intervenciones de salud pública que promuevan hábitos alimentarios más saludables y alineados con el sistema circadiano, adaptados a contextos regionales e individuales diversos.

Palabras clave Horario de las comidas, Ritmo circadiano, Crononutrición, Ingesta alimentaria

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Introduction

In recent decades, advancements in the field of chrononutrition have underscored the pivotal role of meal timing ('when to eat'), complementing established principles regarding dietary composition ('what to eat') and caloric intake ('how much to eat') for human metabolism¹⁻⁹.

For instance, eating later in terms of both clock hour and relative circadian time, as well as consuming a larger proportion of daily calories later in the day rather than earlier, may disrupt the synchronization of the internal circadian clock^{1-3,5,8}. This disruption is associated with adverse metabolic outcomes, including obesity, diabetes, and cardiovascular diseases^{4,8-11}.

In modern society, skipping breakfast and delaying the eating midpoint have become more common due to longer work hours, increased evening activities, and widespread digital device use. Additionally, circadian preferences shaped by chronotypes influence meal timings, along with cultural, behavioral, and physiological factors^{4,7}.

In Brazil, a country with diverse latitudes, a study observed a tendency for earlier eating times in low-latitude regions, though it did not explore the reasons for these regional differences¹². Data from the same study also demonstrated positive associations between the timing of the first and last food intake, as well as the eating midpoint, and BMI¹³.

Similar associations were observed in the population-based virtual study Sonar-Brazil, designed to explore the chronobiological aspects of sleep and eating habits among Brazilian adults. Early findings revealed significant correlations: skipping breakfast and delaying lunch¹⁴, longer intervals between waking and the first food intake, a later eating midpoint¹⁵, timing of the largest meal¹⁶, and dining closer to the sleep midpoint¹⁷, all linked to higher BMI values.

These findings, consistent with numerous studies globally, highlight the crucial role of meal timing in strategies to promote healthy eating and prevent or manage obesity and related chronic diseases^{3,4,7,18}.

However, developing effective interventions requires understanding the biological, social, and particularly modifiable factors that influence food intake timings across various geographical, cultural, and economic contexts. This understanding is vital for assessing the long-term sustainability of adjusted eating sched-

ules in natural and uncontrolled environments. While most studies have focused on Europe, North America, and Asia, our research aims to comprehensively investigate the determinants of food intake timing across Brazil, examining physiological, behavioral, personal, cultural, and environmental factors.

Methods

Participants and Methods

This cross-sectional study used data from the third cycle of the Sonar-Brazil Survey (2023-2024), conducted from May 2023 to May 2024. The survey is virtual, exploratory, and population-based, focusing on chronobiological aspects of sleep, food, and nutrition among Brazilian adults.

The inclusion criteria for Sonar-Brazil were: 1. Brazilian nationality, 2. Residence in Brazil, 3. Age between 18 and 65, 4. Not pregnant. The survey link was emailed to public and private higher education institutions registered with the Brazilian Ministry of Education, regional councils for nutritionists, dentists, and doctors; health units; media; sleep and nutrition congresses; and scientific events. It was also widely promoted on social media and websites, requesting sharing among eligible contacts. Dedicated social media pages were established to enhance the survey's visibility nationwide.

A total of 5,580 individuals completed the Sonar-Brazil questionnaire. Sixty responses were excluded: 39 did not meet the age criteria (under 18 or over 65), 12 had missing or inconsistent weight and height data, and 9 provided inconsistent data on daily routines. Thus, the final sample included 5,520 Brazilian adults. Night and shift workers were also excluded due to their distinct circadian rhythms and irregular sleep patterns ($n=260$). Consequently, our analysis included 5,260 Brazilian adults.

Brazil is divided into five macro-regions—North, Northeast, Center-West, Southeast, and South—each with distinct climate, economic, and cultural characteristics. The 2022 IBGE Demographic Census¹⁹ reported Brazil's total population as 207,750,291, with regional distributions as follows: North (8.6%), Northeast (26.7%), Southeast (42.0%), South (14.8%), and Midwest (7.9%). Our final sample ($n=5,260$) mirrors this demographic: North (9.1%), Northeast (27.5%), Southeast (41.2%), South (14.3%), and Midwest (7.9%).

Data Collection

Participants completed an online structured questionnaire after agreeing to the informed consent form. The questionnaire covered sociodemographic variables, lifestyle, and health factors, with a focus on sleep and dietary habits. Responses were automatically stored in spreadsheets compatible with Microsoft Office Excel and later exported to Stata 18 for analysis. All data collection procedures were conducted in accordance with the principles outlined in the Declaration of Helsinki and received approval from the Research Ethics Committee.

Dependent Variables: Eating timing and Breakfast Skipping

Using the Chrononutrition Profile Questionnaire, translated and validated in Brazilian Portuguese^{20,21}, participants reported their daily habits over the past month, focusing on typical weekdays and weekends. They provided their usual wake times, bedtimes, and times for the lunch, first and last eating event. Responses were recorded in 30-minute intervals, and the questionnaire specified that the first and last eating events included any food or drink with calories.

From the collected responses, we evaluated the following chrononutrition behaviors as dependent variables: timing of the first eating event (the clock time of participants' first food and/or drink), lunch timing, timing of the last eating event (the clock time of participants' last food and/or drink), and the eating midpoint. The eating midpoint was calculated as follows: $\text{eating midpoint} = [(\text{last eating time} - \text{first eating time})/2] + \text{first eating time}$.

To calculate the weekly average for each variable, we applied the following formula: $[(5 \times \text{weekdays value}) + (2 \times \text{weekend value})]/7$. Participants were also asked to specify on which days of the week they typically have breakfast, and we assessed the weekly frequency of breakfast skipping as a dependent variable.

Each dependent variable was also categorized into tertiles.

Focal independent Variables

Physiological Factors

Physiological factors were assessed through inquiries about participants' age, sex, and whether they had been diagnosed with depression. Additionally, Body Mass Index (BMI) was

calculated based on self-reported weight and height using the formula $[\text{weight (kg)}/\text{height (m)}^2]$. Individuals with a BMI greater than 29.9 kg/m² were classified as having obesity²².

Behavioral and Personal Preferences

Participants reported their engagement in physical exercise, specifying the timing: morning (from 5 am to 11 am), afternoon (from 11 am to 6 pm), and evening (from 6 pm to 10 pm). Additionally, participants were queried about their smoking habits and screen time (cell phones, TV, computers, notebooks, and tablets) before bed.

Food consumption was assessed using a food frequency questionnaire that covered 17 food and beverage categories. Participants reported their typical consumption days from Monday to Sunday, specifying both the frequency and timing of daily consumption (5-11 am, 12-5 pm, 6-9 pm, >9 pm). Each food group received positive scores for healthy choices (e.g., fresh fruits, vegetables, dairy) and negative scores for unhealthy choices (e.g., sweets, fried snacks, sugary drinks). The resulting total score, ranging from 19 to 77, reflected diet quality and was categorized into tertiles: low (19-45), intermediate (46-54), and good (55-77).

Weekly alcohol consumption after 6 pm and daily intake of caffeine sources (coffee, cola-based soft drinks, black tea, guarana powder) were also recorded. Participants identified their largest meal of the day as breakfast, lunch, dinner, none, or other, indicating the meal where they consumed the highest calorie intake.

Sleep duration (h) was calculated by subtracting wake time from bedtime, and weekly averages were computed using the formula $[(5 \times \text{weekdays value}) + (2 \times \text{weekend value})]/7$. Participants were categorized as short sleepers (<7h/night) based on recommendations²³.

We adopted the "midpoint of sleep on free days corrected for sleep extension on free days (MSFsc)" as an indicator of chronotype, which is proposed to clean the chronotype of the confounder sleep debt. For participants whose sleep duration on free days was longer than workdays, the midpoint was calculated as follows: $[\text{bedtime on free days} + (\text{sleep duration on free days}/2)]$. For participants whose sleep duration on free days was shorter than workdays, due to the sleep debt accumulated over the workweek, the corrected midpoint of sleep was applied, and calculated as follows: $[\text{bedtime on free days} + (\text{weekly average sleep duration}/2)]$. Participants were also classified into quartiles based on their MSFsc

values. Values below the 25th percentile were categorized as morning chronotype, above the 75th as evening chronotype, and those between these percentiles as intermediate chronotype²⁴.

Cultural and Environment Factors

Information on work setup (not working, remote, or in-person), educational attainment, marital status (single, married, stable union, widow), and city and state of residence was collected. Based on this data, participants were categorized into Brazil's five political and geographical regions: Northeast, North, Midwest, Southeast, and South.

Statistical Analysis

We assessed participant characteristics across tertiles of eating midpoint (Table 1) and differences in eating timing outcomes across Brazil's regions using ANOVA for continuous variables and the chi-square test for categorical variables. Significant differences among groups were further explored using Bonferroni correction.

To identify predictors of eating behaviors, we employed a series of Lasso regression analyses (Least Absolute Shrinkage and Selection Operator) for each dependent variable: timing of the first eating event, lunch, last eating event, eating midpoint, and weekly frequency of breakfast skipping (Table 2).

The hypothesized determinants analyzed were drawn from existing literature^{4,7}: 1. Physiological: age (years), sex (male vs. female), depression (percent), obesity (percent). 2. Behavioral and Personal Preferences: morning (5 am to 10 am) and evening (6 pm to 11 pm) exercise (percent), evening (after 6pm) screen time before bed (minutes), tobacco smoking (percent), evening (after 6pm) alcohol consumption (days/week), caffeine intake (frequency/day), diet quality (score), largest meal being dinner/supper (percent), chronotype (MSFsc), short (<7 hours/night) sleep duration (percent). 3. Cultural and Environment: work setup (not working as reference, remote vs. in-office work), education (graduate vs. not graduated), marital status (single/widowed vs. married/stable union) and Brazil's macro-region (Northeast as reference).

Lasso regression was chosen for its dual capability of variable selection and regularization, crucial for mitigating overfitting risks, particularly in studies with numerous potential predictors. This method effectively reduces less influential variables' coefficients to zero, promoting

a sparse model that retains only variables with significant coefficients. Within Lasso regression, we applied a cross-validation selection method to iteratively adjust coefficients, minimizing prediction error and optimizing model performance. The resulting models provided coefficients for selected variables, identifying the factors most strongly associated with each outcome by considering the collective impact of multiple predictors.

Additionally, to pinpoint the primary predictors of eating midpoint, we conducted a feature importance analysis using the Random Forest algorithm. Implementing the scikit-learn library, we constructed the model to evaluate the relative importance of each variable in predicting the outcome (Figure 1).

Based on the results of preliminary analyses, restricted cubic splines were employed to illustrate the shape of the association of age, chronotype, diet quality, and screen time with eating midpoint (Figure 2).

Results

A total of 5,260 adults (mean age 36 years, range 18 to 65; 70% women) participated in the study, with an average eating midpoint of 14.69 (± 1.23) hours. Significant differences in participant characteristics were observed across tertiles of eating midpoint (Tertile 1: 13.45 $\pm$ 0.49, Tertile 2: 14.56 $\pm$ 0.27, and Tertile 3: 16.05 $\pm$ 0.90), as detailed in Table 1.

Regarding physiological factors, Tertile 3 (the latest group) was younger, with nearly half of the participants aged 18-29 years. This group also exhibited delayed timings for all eating events, as well as a higher frequency of breakfast skipping compared to Tertiles 1 and 2. Additionally, Tertile 3 showed a higher prevalence of obesity (38.32% vs. 31.07% in Tertile 1 and 30.61% in Tertile 2) and depression (43.28% vs. 26.47% in Tertile 1 and 30.25% in Tertile 2) (all $p < 0.001$) (Table 1).

In terms of behavioral and personal preferences, participants in Tertile 3 had the lowest diet quality score, along with longer screen time before bedtime, higher daily caffeine intake, and later chronotype, wake time, and bedtime compared to those in Tertiles 1 and 2. Additionally, the highest percentages of short sleepers (39%), smokers (51%), and non-exercisers (42%) were found in Tertile 3. Weekly alcohol consumption was also notably higher in Tertiles 2 and 3 compared to Tertile 1 (all $p < 0.001$) (Table 1).

Table 1. Participant Characteristics by Eating Midpoint Tertile (n=5,260).

Variables	Total	Eating Midpoint			P-value
		Tertile 1	Tertile 2	Tertile 3	
Eating Midpoint, decimal time	14.69±1.23	13.45±0.49	14.56±0.27	16.05±0.90	
First eating, decimal time	8.22 1.65	7.05±0.79 ^{a,b,c}	7.84±0.86 ^{a,b,c}	9.79±1.69 ^{a,b,c}	<0.001
Lunch time, decimal time	12.61 0.77	12.38±0.62 ^{a,b,c}	12.60±0.64 ^{a,b,c}	12.86±0.93 ^{a,b,c}	<0.001
Last eating, decimal time	21.15 1.46	19.86±0.93 ^{a,b,c}	21.29±0.87 ^{a,b,c}	22.31±1.31 ^{a,b,c}	<0.001
Age, years	36.39±12.40	39.19±12.42 ^a	36.86±12.35 ^a	33.09±11.65 ^a	<0.001
18-29 years, %	36.18	24.70	31.27	44.04	<0.001
30-49 years, %	46.16	36.66	34.39	28.95	
50-65 years, %	17.66	42.84	35.09	22.07	
Sex, %					
Female	70.32	34.77	33.82	31.41	<0.001
Male	29.68	30.24	32.35	37.41	
BMI, Kg/m ²	25.66 ± 4.92	25.60±4.67	25.54±4.77	25.86±5.31	0.12
Nutritional Status, %					
Normal (BMI<25Kg/m ²)	50.82	33.26	34.27	32.47	0.009
Overweight (BMI:25-29.9Kg/m ²)	32.66	34.87	33.41	31.72	
Obesity (BMI>29.9Kg/m ²)	16.52	31.07	30.61	38.32	
Depression, %					
Yes	13.57	26.47	30.25	43.28	<0.001
No	86.43	34.51	33.88	31.61	
Physical exercise, %					
Yes	73.19	35.19	34.68	30.13	<0.001
No	26.81	28.58	29.86	41.56	
Timing of Physical Exercise, %					
05 am to 11 am	39.60	40.47	36.68	22.85	<0.001
11 pm to 18 pm	37.22	32.07	35.24	32.69	0.07
After 18 pm	25.34	28.51	35.33	36.16	<0.001
Screen time before bed, min	73.63±68.10	66.86±67.19 ^a	71.23±68.97 ^b	82.84±67.17 ^{a,b}	<0.001
Tobacco smoking, %					
Yes	5.82	16.99	32.03	50.98	<0.001
No	94.18	34.44	33.47	32.10	
Alcohol consumption after 6 pm, days/week	1.07±1.48	0.96±1.41 ^{a,b}	1.12±1.51 ^a	1.14±1.52 ^b	<0.001
Caffeine consumption, times/day	2.36±1.57	2.13±1.45 ^{a,b}	2.37±1.48 ^{a,c}	2.57±1.75 ^{b,c}	<0.001
Diet quality, score	49.17±9.13	51.49±8.67 ^{a,b,c}	49.37±8.89 ^{a,b,c}	46.62±9.16 ^{a,b,c}	<0.001
Low (1 st tertile), n (%)	34.30	23.61	32.32	44.07	<0.001
Intermediate (2 nd tertile), n (%)	35.68	33.30	35.16	31.54	
Good (3 rd tertile), n (%)	30.02	44.78	32.49	22.74	
Skipping Breakfast, days/week	1.05±2.17	0.20±0.86 ^{a,b,c}	0.53±1.47 ^{a,b,c}	2.41±2.90 ^{a,b,c}	<0.001
Largest meal, %					
Breakfast	5.80	45.25	35.08	19.67	<0.001
Lunch	80.13	34.00	34.35	31.65	
Dinner	8.38	20.63	23.36	56.01	
None	5.51	32.76	32.76	34.48	
Snacks	0.17	11.11	33.33	55.56	
Chronotype (MSFsc), decimal time	27.38±1.31	26.57±0.96 ^{a,b,c}	27.31±0.99 ^{a,b,c}	28.28±1.34 ^{a,b,c}	<0.001
Early (<p25)	33.61	59.95	27.71	12.33	<0.001
Intermediate (p25-p75)	33.61	30.66	44.34	25.00	
Late (>p75)	32.78	9.05	27.96	62.99	
Wake time, decimal time	6.80±1.18	6.08±0.82 ^{a,b,c}	6.70±0.83 ^{a,b,c}	7.61±1.29 ^{a,b,c}	<0.001
Bedtime, decimal time	23.33±1.21	22.51±0.96 ^{a,b,c}	23.26 0.85 ^{a,b,c}	24.23±1.12 ^{a,b,c}	<0.001
Sleep Duration, hour	7.46±1.11	7.57±1.03 ^{a,b}	7.44±1.05 ^a	7.38±1.24 ^b	<0.001
<7 hours/night, %	29.94	26.79	34.22	38.98	<0.001

it continues

Table 1. Participant Characteristics by Eating Midpoint Tertile (n=5,260).

Variables	Total	Eating Midpoint			P-value
		Tertile 1	Tertile 2	Tertile 3	
≥7 hours/night, %	70.06	36.26	33.03	30.72	
Work setup, %					
Do not work, %	17.98	27.17	29.18	43.66	<0.001
Remote work, %	25.11	29.45	35.96	34.60	
In-office work, %	56.90	37.15	33.58	29.27	
Graduation, %					
Yes	71.29	35.39	34.85	29.76	<0.001
No	28.71	28.54	29.74	41.72	
Married/Stable Union, %					
Yes	43.40	39.25	35.26	25.49	
No	56.60	28.96	31.94	39.10	<0.001
Season, %					
Winter	12.78	37.20	35.12	27.68	<0.001
Spring	18.84	36.63	30.68	32.69	
Summer	9.60	44.75	25.15	30.10	
Autumn	58.78	29.72	35.22	35.06	

Notes: BMI = Body Mass Index. MSFsc = Midpoint of Sleep on Free Days corrected for Sleep Extension on Free Days. Values are shown as means ($\pm$ SDs) or percentages. P-values are derived from one-way ANOVA (for continuous variables) and the chi-square test (for categorical variables). When significant, differences among groups were explored using Bonferroni correction. ^{a,b,c}Different superscript letters indicate significant differences among groups with post hoc Bonferroni correction. Significant associations (P-values<0.05) are shown in bold.

Source: Authors.

Among all participants, lunch was the largest meal, followed by dinner. Moreover, more than half of those who reported dinner as their largest meal belonged to the latest eating midpoint group (56% in Tertile 3), while the majority of those who indicated breakfast as their largest meal were in the earliest group (45% in Tertile 1) (all $p<0.001$) (Table 1).

Work setup also showed significant differences: a higher proportion of the non-working group ate later, with 44% in Tertile 3; remote workers were mostly in Tertile 2 (36%); and in-office workers (37.15%) were in Tertile 1, reflecting earlier eating patterns ($p<0.001$) (Table 1).

A detailed comparison by Brazil's regions is available in Table 3, which highlights significant differences. The eating midpoint was statistically earlier in the Northeast (14.58) compared to the Southeast (14.73) and South (14.81). Participants in the North and Northeast started eating earlier (8.08 and 8.09, respectively), with statistically significant differences compared to the Southeast (8.27) and South (8.43). Lunch timing ranged from 12.45 in the Midwest to 12.68 in the Southeast, and the timing of the last food intake ranged from 20.96 in the Midwest to 21.33

in the North. Lunch consistently constituted the largest meal of the day, with dinner surpassing breakfast in all regions.

The determinants of eating timing and breakfast skipping frequency were identified using Lasso linear models. Table 2 presents the variables with non-zero coefficients, selected through cross-validation, highlighting their association with the outcomes and the direction of the relationship, as indicated by the sign of the beta (positive or negative).

Regarding the physiological variables, older age was associated with a lower frequency of breakfast skipping and earlier timings for first eating, last eating, and eating midpoint, while it was associated with a later lunch. Females were associated with a lower frequency of breakfast skipping, earlier timings for last eating and eating midpoint, but later first eating and lunch. Depression was positively associated with all outcomes, indicating a higher frequency of breakfast skipping and later eating events. Obesity was associated with a higher frequency of breakfast skipping, delayed first eating and eating midpoint, but earlier last eating (Table 2).

Among the behavioral and personal preference variables, later chronotype, smoking, and

Table 2. Lasso Regression Analysis for Physiological, Behavioral, Personal Preferences, Cultural, and Environmental Factors Predicting Weekly Frequency of Breakfast Skipping and Eating Timings (n=5,260).

Variables		Standardized Coefficients				
		Breakfast Skipping	First Eating	Lunch Time	Last Eating	Eating Midpoint
Physiological	Age, years	-0.1427	-0.0085	0.0746	-0.0574	-0.0299
	Sex, Female	-0.0829	0.0117	0.0564	-0.0721	-0.0248
	Depression, yes	0.0475	0.0120	0.0019	0.0332	0.0232
	Obesity, yes	0.0904	0.0837	----	-0.0319	0.0161
Behavioral and Personal Preference	Morning Exercise (between 5 and 10am), yes	-0.1424	-0.1343	-0.0158	-0.0059	-0.0673
	Evening Exercise (after 6pm), yes	-0.0761	-0.0755	----	0.0289	-0.0117
	Screen Time before bedtime, min	0.0509	0.0288	----	----	0.0100
	Smoking, yes	0.1525	0.1174	0.0127	0.0247	0.0703
	Evening Alcohol Consumption, days/week	-0.0011	-0.0225	-0.0029	----	-0.0039
	Caffeine Consumption, freq/day	-0.1067	-0.0413	----	0.1012	0.0269
	Diet Quality, score	-0.2416	-0.1192	----	-0.0467	-0.0837
	Largest Meal is Dinner/Supper, yes	0.2306	0.1584	0.0537	0.0626	0.1086
	Chronotype (MSFsc), decimal time	0.3366	0.7383	0.2166	0.6083	0.6757
	Short Sleep Duration (<7h), yes	0.1106	-0.0872	0.0596	0.2954	0.0989
Cultural and Environment	Brazil's Region (reference: Northeast)					
	North	-0.0516	0.0213	-0.0181	0.0047	0.0008
	Midwest	0.0729	0.0654	-0.0439	-0.0390	----
	Southeast	-0.0249	0.0697	-0.0026	-0.0252	----
	South	0.0471	0.0812	-0.0785	-0.0337	0.0011
	Work Setup (reference: do not work)					
	Remote work	-0.0473	0.0249	0.0221	----	0.0032
	In-office work	-0.0312	-0.0410	----	----	-0.0240
	Education, graduated	-0.0550	-0.0767	-0.0127	----	-0.0318
	Marital Status, married/stable union	----	-0.0137	----	----	----
	Season, Winter/Autumn	-0.0806	-0.1314	----	0.1456	0.0070

Notes: MSFsc = Midpoint of Sleep on Free Days corrected for Sleep Extension on Free Days. ---- coefficient is zero in multiple Lasso regression analysis.

Source: Authors.

individuals who identified dinner as the largest meal were positively associated with all outcomes, indicating more frequent breakfast skipping and delays in all eating events. Morning exercise was associated with a lower frequency of breakfast skipping and earlier timings for all meals. Similarly, evening exercisers showed less frequent breakfast skipping and earlier first eating and eating midpoint, but were also associated with a delayed last eating event. By increasing screen time before bedtime, the frequency of breakfast skipping also increased, along with delays in both first eating and eating midpoint (Table 2).

Evening alcohol consumption was associated with a lower frequency of breakfast skipping and earlier eating timings, except for the last eating timing. Higher caffeine consumption was associated with less breakfast skipping and

earlier first eating times, while being positively linked to delays in both the last eating time and eating midpoint. Better diet quality was associated to a reduced frequency of breakfast skipping and earlier timings for first eating, last eating, and eating midpoint, but showed no association with lunch timing. Short sleepers were associated with a higher frequency of breakfast skipping and an earlier first eating time, but also with delays in lunch, last eating, and eating midpoint (Table 2).

Finally, regarding cultural and environmental determinants, in addition to confirming the variations across regions previously observed, work setup - using the 'not working' group as a reference - was associated with a lower frequency of breakfast skipping for both remote and in-office workers. However, remote work was linked to delayed first eating, lunch time,

Table 3. Eating timing by Brazil's region (n=5,260).

Variables	Total	North	Northeast	Midwest	Southeast	South	P value
	n (%)	5,260 (100)	479 (9.11)	1,446 (27.49)	418 (7.95)	2,166 (41.18)	751 (14.28)
First Eating*	8.22±1.65	8.08±1.41 ^a	8.09±1.68 ^{b,c}	8.24±1.67	8.27±1.66 ^b	8.43±1.68 ^{a,c}	<0.001
Tertile 1	33.75	33.40	38.38	36.36	32.50	27.16	<0.001
Tertile 2	34.47	36.12	32.64	32.06	33.84	40.08	
Tertile 3	31.79	30.48	28.98	31.58	33.66	32.76	
Lunch Time*	12.61±0.77	12.59±0.65	12.65±0.76 ^{a,b}	12.45±0.73 ^{a,c}	12.68±0.82 ^{c,d}	12.46±0.69 ^{b,d}	<0.001
Tertile 1	40.63	35.91	37.68	48.33	38.83	50.20	<0.001
Tertile 2	28.42	34.66	28.35	27.99	26.78	29.56	
Tertile 3	30.95	29.44	33.96	23.68	34.40	20.24	
Last Eating*	21.15±1.46	21.33±1.38 ^{a,b}	21.07±1.49 ^a	20.96±1.37 ^{b,c}	21.19±1.48 ^c	21.18±1.40	<0.001
Tertile 1	34.68	28.60	36.31	42.82	33.98	32.89	<0.001
Tertile 2	32.55	35.07	29.88	31.34	33.47	34.09	
Tertile 3	32.78	36.33	33.82	25.84	32.55	33.02	
Eating Mipoint*	14.69±1.23	14.71±1.09	14.58±1.24 ^{a,b}	14.60±1.16	14.73±1.26 ^a	14.81±1.20 ^b	<0.001
Tertile 1	33.42	30.48	37.62	36.12	32.96	27.03	<0.001
Tertile 2	33.38	34.86	31.33	32.54	33.15	37.55	
Tertile 3	33.19	34.66	31.05	31.34	33.89	35.42	
Largest meal							
Breakfast	5.80	5.64	8.09	5.50	5.22	3.33	0.001
Lunch	80.13	82.25	77.94	81.10	80.29	82.02	
Dinner	8.38	6.26	9.27	6.22	8.59	8.66	
None	5.51	5.85	4.63	6.70	5.72	5.73	
Snacks	0.17	0.00	0.07	0.48	0.18	0.27	

Notes: Values are shown as means (±SDs) or percentages. *Variables refer to time in decimal format. P values are derived from one-way ANOVA (for continuous variables) and the chi-square test (for categorical variables). When significant, differences among groups were explored using Bonferroni correction. ^{a,b,c,d} Different superscript letters indicate significant differences among groups with post hoc Bonferroni correction. Significant associations (P-values<0.05) are shown in bold.

Source: Authors.

and eating midpoint, while in-office work was associated with earlier first eating and eating midpoint. Being graduated was associated with a lower frequency of breakfast skipping, alongside earlier first eating, lunch, and eating midpoint. Being in a stable union was a determinant only for earlier first eating, with no association observed for other variables. Lastly, during the winter and autumn seasons, both the frequency and timing of breakfast skipping were reduced, while the timing of the last eating event and eating midpoint were delayed (Table 2).

We employed the Random Forest algorithm to assess the importance of variables predicting the eating midpoint. Figure 1 displays specific feature importance on the x-axis, with longer bars indicating greater significance. The y-axis labels categorize input names, highlighted in red for physiological features, purple for behavioral

and personal preference features, and green for cultural and environmental features.

Chronotype emerged as the most influential feature (0.474), followed by age (0.089) and diet quality (0.088). Screen exposure before bed (0.060) ranked fourth, followed by daily caffeine consumption (0.051) and evening alcohol consumption (0.033). Region (0.032) and season (0.026) followed closely, alongside short sleep duration (0.020), work setup (0.019), and having dinner as the largest meal (0.015). All other feature importances were ≤0.01. Depression ranked lowest in importance on the list (Figure 1).

Based on these feature importance results, we utilized Restricted Cubic Splines (Figure 2) to visualize the dose-response relationships between age, chronotype, diet quality, and the eating midpoint. Our analysis indicates that the

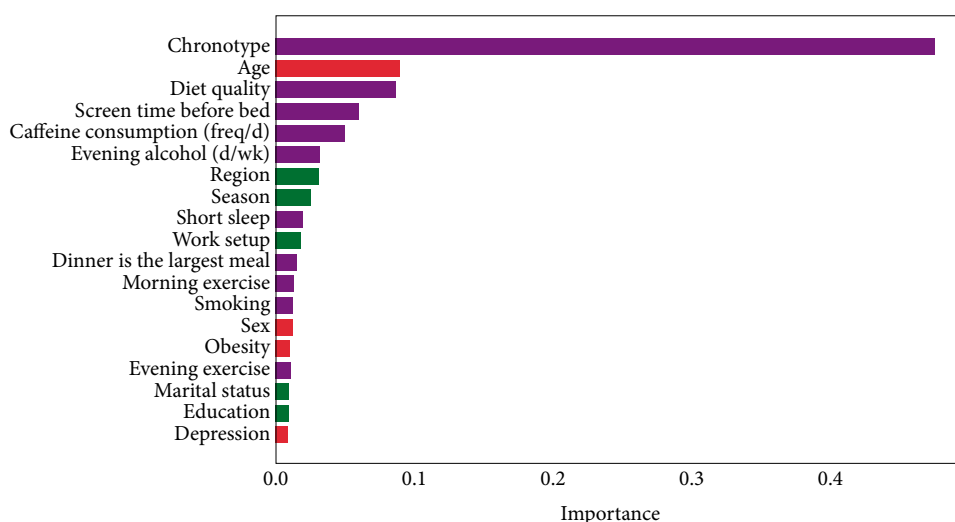


Figure 1. Feature Importance for Predicting Eating Midpoint Using Random Forest (n=5,260).

The colors in the figure represent each group of variables. In purple: Behavioral and Personal Preference, in red: Physiological variables, in green: Cultural and Environmental variables.

Source: Authors.

earliest eating midpoint occurs in the absence of screen time before bedtime.

Discussion

This groundbreaking Brazilian study explores the intricate interplay of physiological, behavioral, personal preferences, cultural, and environmental factors that influence eating timing. By thoroughly investigating these dimensions, our findings not only align with previous research but also reveal novel nuances in these relationships within the Brazilian context.

Physiological Factors

Age was identified as the second most influential factor for eating midpoint in the Random Forest analysis, showing a negative association with both breakfast skipping and eating timings. This may reflect both lifestyle changes and age-related shifts in circadian rhythms, with younger individuals, particularly young adults, exhibiting later chronotypes that naturally shift toward morningness as they age⁴.

Among modifiable physiological conditions, our study revealed that both depression and obesity are associated with delayed first food intake,

a later eating midpoint, and increased frequency of breakfast skipping^{14,25}. Similar findings were observed in population-based cohort studies, indicating that individuals with overweight are more prone to skip breakfast and consume more food in the evening^{4,26}. Although the causal role of food intake timing on mental health among general population awaits further exploration, research suggests a potential link between late-night eating and increased anxiety and depressive symptoms. Thus, our findings may pave the way for future studies to clarify the direction of this association and inform interventions aimed at addressing these conditions²⁷.

Behavioral and Personal Preference

Chronotype emerged as the most influential predictor of eating midpoint, as expected given its central role in regulating circadian rhythms and daily activities, including meal timing. Individuals with an evening chronotype tend to eat later than those with a morning chronotype, consistent with previous studies^{15,28-30}. This natural alignment with endogenous circadian rhythms highlights the need for greater flexibility in work and study schedules to accommodate different chronotypes. Additionally, practices

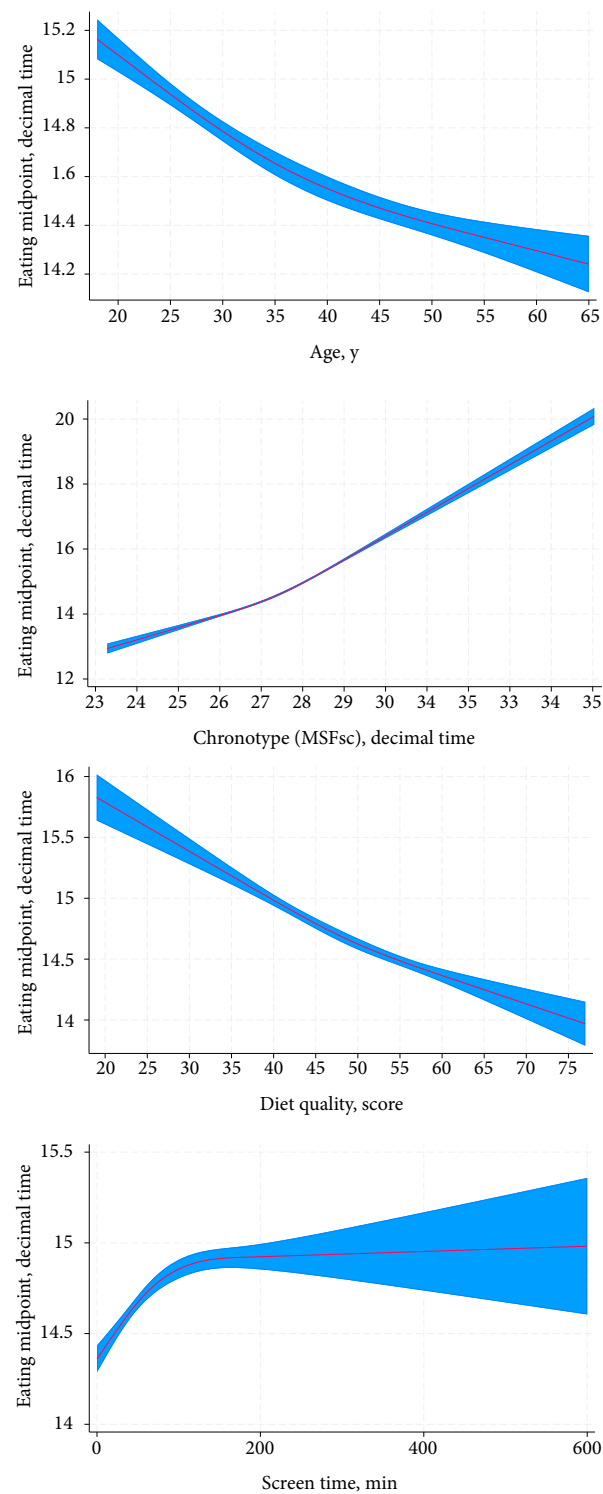


Figure 2. Restricted Cubic Spline Regression represents the association of age, chronotype, diet quality and screen time with eating midpoint among Brazilian adults (n=5,260). Red lines plot the predicted outcome values with 95% confidence intervals (blue fill).

Notes: MSFsc = Midpoint of Sleep on Free Days corrected for Sleep Extension on Free Days. *All the associations are significant (P-values $\leq$ 0.01).

Source: Authors.

such as early morning exposure to natural light can help realign biological rhythms, promoting healthier sleep and eating patterns.

Following chronotype, diet quality, screen use before bed, daily caffeine consumption, evening alcohol consumption, short sleep duration, and having dinner as the largest meal emerged in descending order as the most influential behavioral factors for eating midpoint in the Random Forest analysis.

Diet quality, ranked third, suggests that individuals with healthier diets are more likely to follow structured eating routines, which influence meal timing. Higher diet quality, characterized by increased consumption of fruits, vegetables, and minimally processed foods, was associated with earlier timings for the first, last, and midpoint of eating in our study. This implies that a healthier diet may promote better metabolic regulation through mechanisms such as enhanced satiety from nutrient-dense foods, improved regulation of hunger hormones, and a reduced likelihood of late-night snacking^{31,32}.

The earliest eating midpoint was observed in individuals with no evening screen exposure, whereas longer screen time was associated with delayed first food intake and increased frequency of breakfast skipping. Because circadian clocks rely on light as the primary zeitgeber responsible for synchronizing endogenous biological rhythms to the 24-hour light-dark cycles, artificial light at night may contribute to circadian misalignment, sleep-related problems, and later eating habits. Research on nocturnal rodents has shown that light at night (LAN) increases relative daytime (rest phase) food consumption (56% of food intake with LAN compared to 37% without LAN) and leads to significant weight gain³³. Moreover, excessive screen time, especially engaging in social media scrolling, watching TV shows, or viewing YouTube on smartphones, can lead to bedtime procrastination, which reduces sleep duration. To compensate for lost sleep, individuals may extend morning sleep, potentially leading to skipping breakfast and prolonging morning fasting to accommodate work or study schedules³⁴.

Higher daily caffeine intake and evening alcohol consumption were, respectively, associated with delayed and advanced eating midpoints. While the evidence is limited and requires further investigation⁴, the short-term stimulating effects of caffeine and alcohol on appetite may contribute to shifts in meal timings^{7,32,33}. Caffeine, acting as an adenosine receptor antagonist, can reduce sleep pressure

during wakefulness and delay sleep onset, potentially promoting nighttime eating even when consumed earlier in the day^{34,35}. Research also indicates that nighttime caffeine consumption, particularly when consumed three hours before bedtime, can delay the circadian rhythm of melatonin by approximately 40 minutes, akin to exposure to bright light at night³⁶.

The association of having dinner as the largest meal with both a higher frequency of breakfast skipping and later eating patterns in our study suggests an interconnectedness between eating events³⁷. Indeed, it has been demonstrated that overeating at night might suppress morning appetite, contributing to both breakfast skipping and a later eating midpoint^{38,39}.

While contributing less in the Random Forest analysis, morning exercise also showed an inverse association with all eating events and breakfast skipping. In contrast, individuals who exercised in the evening exhibited a delay in the timing of their last food intake, but the onset and eating midpoint occurred earlier compared to those who did not exercise. Indeed, chronobiological research suggests that exercise influences circadian rhythms and neuroendocrine systems that regulate appetite and metabolism. Moreover, exercise can alter dietary habits, promoting preferences for healthier foods and reducing compensatory behaviors such as emotional eating, thereby influencing daily meal timings⁴⁰.

Cultural and Environment Factors

Results confirmed significant regional and seasonal differences in food intake timings across Brazil¹². Regions at lower latitudes, like the Northeast and North, began eating earlier, with the Northeast having the earliest eating midpoint compared to higher latitude regions like the Southeast and South. Participants in winter and autumn had a later eating midpoint than those in summer and spring.

The observed influence of remote work on delaying the timing of the first meal, lunchtime, and eating midpoint reflects the current post-COVID-19 pandemic work environment, which has fostered this new work arrangement with greater flexibility in both work and meal schedules^{41,42}.

Strengths and Limitations

This study's strengths are rooted in its use of the initial national survey focusing on chrono-

nutrition behaviors, involving a substantial sample from Brazil's population. Previous research has mainly targeted high-income countries, revealing significant diversity in eating behaviors—timing and distribution—across global regions, influenced by cultural norms, seasonal factors, and local work routines⁴³. In this context, our study is both unique and innovative, offering unprecedented insights into regional differences in a country of continental proportions, and underscoring the need for public health strategies tailored to address these disparities. Moreover, to ensure data authenticity reflecting real-life habits, participants completed the questionnaire based on their routines from the previous month. The survey differentiated between weekdays (workdays) and weekends (free days) and calculated weighted aggregate scores to accurately represent weekly patterns.

However, our study faced limitations, including the use of self-reported questionnaires susceptible to underreporting or misreporting. Nevertheless, it's noteworthy that the assessment of chrononutrition behaviors relied on validated questions deemed suitable for online, community-based samples⁴⁴. Another limitation was the absence of data on energy and nutrient intake, which would have allowed for an objective assessment of energy distribution throughout the meals. However, a previous study²⁰ found moderate to strong correlations between aspects of chrononutrition preferences and behaviors assessed using the Chrononutrition Profile Questionnaire and the 24-hour Food Recall Questionnaire. Furthermore, al-

though our study addressed different dimensions of physiological, behavioral, cultural, and environmental variables, including education as a proxy for socioeconomic status, it is possible that confounding factors, such as income or comorbidities, were not fully measured, which could have influenced the findings. Lastly, due to the cross-sectional nature of our data, we cannot establish causality between predictors and eating outcomes.

Conclusions

This pioneering study highlights the intricate interplay of physiological, behavioral, and environmental factors in shaping eating habits, with chronotype emerging as the primary predictor. Additionally, diet quality, evening screen time, daily caffeine consumption were the most influential features for eating midpoint.

Furthermore, our study underscores the significant impact of various modifiable factors on the timing of food intake, underscoring its importance in shaping public health strategies aimed at promoting eating patterns synchronized with the circadian system. While chrononutrition research has primarily focused on timing as predictors of health and circadian outcomes, understanding the determinants of eating behaviors is crucial for effective interventions. This approach enables the development of targeted, proactive, and sustainable strategies essential in combating the obesity epidemic and associated metabolic diseases.

Collaborations

G Longo-Silva: conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; roles/writing - original draft. R Serenini, MO Lima, JS Melo, LL Soares, and RCE Menezes: data curation; formal analysis; and writing - review & editing.

Funding

This study was funded by the Brazilian 'Fundação de Amparo à Pesquisa do Estado de Alagoas - FAPEAL' (Grant: 60030.0000002539/2022) and Brazilian 'Conselho Nacional de Desenvolvimento Científico e Tecnológico' (CNPq), Brazil (Grant: 402368/2024-0). G Longo-Silva received support from the 'Conselho Nacional de Desenvolvimento Científico e Tecnológico' (CNPq), Brazil, through a Postdoctoral Fellowship Abroad (PDE) and a Senior Technological Development Fellowship (DES). MO Lima and LL Soares received support through doctoral fellowships from the FAPEAL, Brazil. JS Melo received support through doctoral fellowships from the 'Coordenação de Aperfeiçoamento de Pessoal de Nível Superior' (CAPES).

Acknowledgements

We extend our gratitude to all Brazilians who participated in the Sonar-Brazil survey and to the universities, institutions, and professionals whose invaluable contributions helped disseminate this research nationwide.

Data availability statement

Data described in the manuscript will be made available upon request pending approval.

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Article submitted 25/09/2024

Approved 28/07/2025

Final version submitted 30/07/2025

Chief editors: Maria Cecília de Souza Minayo, Romeu Gomes, Antônio Augusto Moura da Silva, Vania de Matos Fonseca