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**Is latitude associated with chronotype?**

São Paulo

2025

Daniel Kachvartanian de Azevedo

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**Corrected version**

Thesis presented to the School of Arts, Sciences and Humanities at the University of São Paulo, as a requirement for the degree of Master of Science by the Graduate Program in Complex Systems Modeling.

Area of concentration: Complex Systems.

Supervisor: Prof. Dr. Camilo Rodrigues Neto

São Paulo

2025

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*Nullius in verba*<sup>1</sup>

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<sup>1</sup> The Royal Society. (n.d.). *History of the Royal Society*. <https://royalsociety.org/about-us/history>

## ABSTRACT

Vartanian, D. (2025). *Is latitude associated with chronotype?* [Master's Thesis, University of São Paulo].

Although much is known about circadian rhythms, further research with larger samples is needed to gain a better understanding of the expression of temporal phenotypes. This thesis investigates the hypothesis that latitude influences chronotype expression, based on the premise that polar regions receive less sunlight annually than equatorial regions. This difference in photoperiod suggests a stronger solar zeitgeber in equatorial areas, potentially leading to greater entrainment of circadian rhythms with the light/dark cycle. This, in turn, could reduce the amplitude and diversity of circadian phenotypes, resulting in a higher prevalence of morningness in equatorial populations. To test this hypothesis, data from 65.824 individuals across Brazil, collected in 2017 based on the Munich ChronoType Questionnaire (MCTQ), were analyzed using nested linear regression models. The analysis revealed a negligible effect of latitude on chronotype (Cohen's  $f^2 = 0.0030818242$ , 95% IC[0, 0.0121371208]), a finding that contrasts with recent studies. Although the hypothesis is plausible and consistent with evolutionary theories of temporal biological systems, these results suggest that the phenomenon of entrainment is more complex than previously assumed.

**Keywords:** Complexity science. Complex systems. Chronobiology. Biological rhythms. Chronotypes. Circadian phenotypes. Sleep. Entrainment. Latitude. MCTQ.

## RESUMO

Vartanian, D. (2025). *A latitude está associada ao cronotipo?* [Dissertação de Mestrado, Universidade de São Paulo].

Embora muito se saiba sobre ritmos circadianos, mais pesquisas com amostras maiores são necessárias para obter uma melhor compreensão da expressão de fenótipos temporais. Esta dissertação investiga a hipótese de que a latitude influencia a expressão do cronotipo, com base na premissa de que as regiões polares recebem menos luz solar anualmente do que as regiões equatoriais. Essa diferença no fotoperíodo sugere um *zeitgeber* solar mais forte nas áreas equatoriais, levando potencialmente a um maior *entrainment* dos ritmos circadianos com o ciclo claro-escuro. Isso, por sua vez, poderia reduzir a amplitude e a diversidade dos fenótipos circadianos, resultando em uma maior prevalência de matutuidade em populações equatoriais. Para testar essa hipótese, dados de 65.824 indivíduos em todo o Brasil, coletados em 2017 com base no Questionário de Cronotipo de Munique (MCTQ), foram analisados usando modelos de regressão linear aninhados. A análise revelou um efeito negligenciável da latitude no cronotipo ( $f^2$  de Cohen = 0,0030818242, 95% IC[0; 0,0121371208]), um achado que contrasta com estudos recentes. Embora a hipótese seja plausível e consistente com as teorias evolutivas dos sistemas biológicos temporais, esses resultados sugerem que o fenômeno do *entrainment* é mais complexo do que se imagina.

**Palavras-chaves:** Ciência da complexidade. Sistemas complexos. Cronobiologia. Ritmos biológicos. Cronotipos. Fenótipos circadianos. Sono. Entrainment. Latitude. MCTQ.



## CONTENTS

1	<b>INTRODUCTION</b>	9
2	<b>ON CHRONOBIOLOGY</b>	11
3	<b>ON COMPLEXITY SCIENCE</b>	17
4	<b>ON THE LATITUDE HYPOTHESIS</b>	20
5	<b>IS LATITUDE ASSOCIATED WITH CHRONOTYPE?</b>	25
5.1	ABSTRACT	25
5.2	INTRODUCTION	25
5.3	RESULTS	28
5.4	DISCUSSION	31
5.5	METHODS	34
5.5.1	<b>Measurement Instrument</b>	34
5.5.2	<b>Geographic Parameters</b>	35
5.5.3	<b>Solar Irradiance Data</b>	35
5.5.4	<b>Astronomical Calculations</b>	35
5.5.5	<b>Sample Characteristics</b>	36
5.5.6	<b>Power Analysis</b>	37
5.5.7	<b>Data Wrangling</b>	37
5.5.8	<b>Hypothesis Test</b>	37
5.6	DATA AVAILABILITY	38
5.7	ACKNOWLEDGMENTS	39
5.8	ETHICS DECLARATIONS	39
5.9	ADDITIONAL INFORMATION	39
5.10	RIGHTS AND PERMISSIONS	39
6	<b>CONCLUSION</b>	40
6.1	LIMITATIONS	40
6.2	DIRECTIONS FOR FUTURE RESEARCH	41
	<b>REFERENCES</b>	47

## 1 INTRODUCTION

There has been a long-standing debate in the chronobiology community regarding the relationship between latitude and human circadian phenotypes (chronotypes) (e.g., Bohlen and Simpson (1973); Randler (2008); Leocadio-Miguel et al. (2017); Wang et al. (2023)), with many assuming that this association is well-established. The hypothesis is based on the varying amounts of solar radiation experienced by populations across different latitudes. Since light exposure serves as a primary zeitgeber — a periodic environmental cue that influences or regulates biological rhythms (Aschoff, 1960; Pittendrigh, 1960) — such variations, along with temperature differences, are thought to result in observable differences in chronotype distributions globally. This thesis investigates the so-called latitude or environmental hypothesis in human circadian phenotypes, addressing the question: *Is latitude associated with chronotype?*

The central hypothesis is that *latitude is associated with human chronotype distributions*, with populations closer to the equator exhibiting, on average, a shorter or more morning-oriented circadian phenotype compared to those living near the poles (Bohlen & Simpson, 1973; Horzum et al., 2015; Leocadio-Miguel et al., 2014, 2017; Randler, 2008). The primary objective of this study is to model and test this hypothesis by critically examining whether a significant association exists between latitude and circadian phenotypes in the Brazilian population.

This study emerged from an insightful debate with my former supervisor, sparked by results published in 2017 in the journal *Scientific Reports* (Leocadio-Miguel et al., 2017). In this paper, the authors conclude that there is a significant association between latitude and chronotype in the Brazilian population, consistent with theoretical predictions. However, the results were not as clear-cut as presented, and the methodology used to test the hypothesis was not optimal. This thesis revisits the hypothesis using an improved statistical approach, aiming to provide a more accurate and reliable answer to the research question.

In the following chapters, the latitude hypothesis is tested using Popper's hypothetical-deductive method (Popper, 1979) and an enhanced approach to Null Hypothesis Significance Testing (NHST), rooted in the original Neyman-Pearson framework for data testing (Neyman & Pearson, 1928a, 1928b; Perezgonzalez, 2015).

This involves a series of analyses conducted on a large dataset of 65,824 individuals, collected from the Brazilian population in 2017. The dataset is based on the Munich Chronotype Questionnaire (MCTQ) (Roenneberg et al., 2003, 2012), and includes data on sleep habits and geographical and demographic characteristics from all of Brazil's states.

It is important to emphasize that this thesis does not aim to propose or discuss the mechanisms underlying the latitude–chronotype relationship. Instead, it focuses solely on the statistical association between them concerning only human populations. An association is a necessary precursor to any causal relationship — and this thesis aims to determine whether such an association exists.

The analyses utilized nested multiple regression models to assess the variance explained by latitude in predicting chronotype. This method of procedure builds on the method used in Leocadio–Miguel et al. (2017). The results will contribute to the ongoing debate on the latitude–chronotype relationship, offering new evidence on the influence of environmental factors on human circadian rhythms.

In accordance with the [graduate program regulation](#), this thesis follows an [article-based format](#), inspired by the structure of Reis (2020)'s PhD thesis. Chapters 2, 3, and 4 consist of essays and literature reviews related to the thesis topic that provide essential background for understanding the research. Chapter 5 presents the core investigation, including an article detailing the hypothesis test and addressing the research question. Finally, Chapter 6 offers conclusions, discusses limitations, and proposes directions for future research. Additionally, supplementary materials are provided to offer a richer, more comprehensive understanding of the research. The reader is encouraged to explore them in detail.

All analyses in this thesis are fully reproducible and were conducted using the [R programming language](#) (R Core Team, n.d.) alongside the [Quarto](#) publishing system (Allaire et al., n.d.). Given the thesis's data-centric nature, it is best experienced online. To view the digital version visit <https://danielvartan.github.io/mastersthesis>.

The thesis code repository is available on GitHub at <https://github.com/danielvartan/mastersthesis>, and the research compendium can be accessed via [The Open Science Framework](#) at the following link: <https://doi.org/10.17605/OSF.IO/YGKTS>.

## 2 ON CHRONOBIOLOGY

The dimension of time, manifest in the form of rhythms and cycles, such as the daily alternation of day and night and the annual transition of seasons, has consistently influenced the evolutionary trajectory of humans and all other life forms on our planet. These rhythms and cycles brought with them evolutionary pressures, resulting in the development of a temporal organization enabling organisms to survive and reproduce in response to the conditions imposed within their environments (Aschoff, 1989b; Paranjpe & Sharma, 2005; Pittendrigh, 1981, 1993). An example of this organization can be observed in the presence of different activity–rest patterns among living beings as they adapt to certain temporal niches, such as the diurnal behavior of humans and the nocturnal behavior of cats and some rodents (Aschoff, 1989a; Kronfeld–Schor et al., 2017).

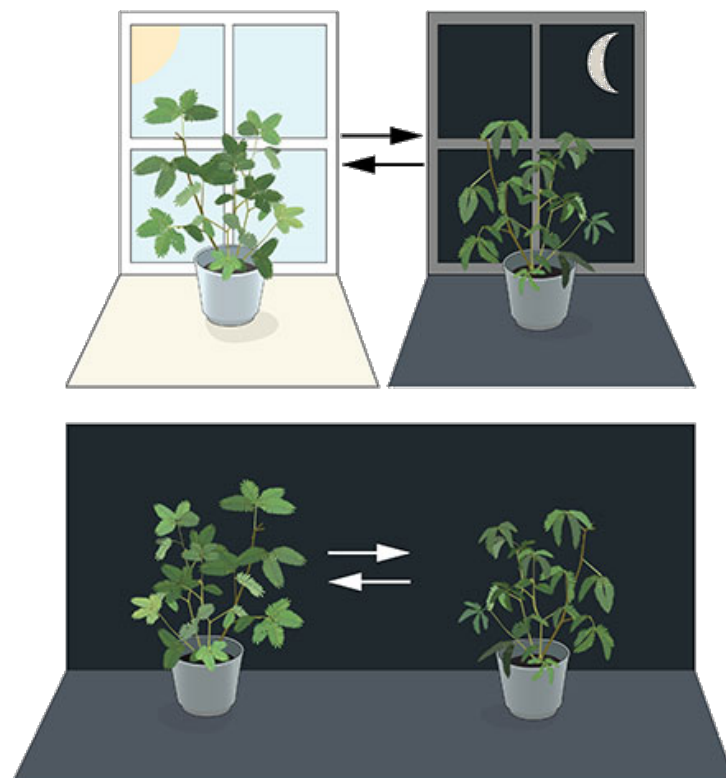
For years, scientists debated whether this organization was solely in response to environmental stimuli or if it was also present endogenously, internally, within organisms (Shackelford, 2022). One of the seminal studies describing a potential endogenous rhythmicity in living beings was conducted in 1729 by the French astronomer Jean Jacques d’Ortous de Mairan. De Mairan observed the movement of the sensitive plant (*Mimosa pudica*) by isolating it from the light/dark cycle and found that the plant continued to move its leaves periodically (Figure 1) (Mairan, 1729; Shackelford, 2022). Charles Darwin also wrote about the movement observed in plants and made thematic explorations of these intriguing “periodical phenomena” (Andrade & Beale, 2024). The search for this internal timekeeper in living beings only began to solidify in the 20th century through the efforts of scientists like Jürgen Aschoff, Colin Pittendrigh, Franz Halberg, and Erwin Bünning, culminating in the establishment of the science known as chronobiology, with a significant milestone being the *Cold Spring Harbor Symposium on Quantitative Biology: Biological Clocks* in 1960 (*chrónos*, from Greek, meaning time; and *biology*, pertaining to the study of life) (Cold Spring Harbor Laboratory, n.d.; Shackelford, 2022)<sup>1</sup>. However, the recognition of endogenous rhythmicity by the global scientific community truly came in 2017 when Jeffrey Hall, Michael Rosbash, and Michael Young were awarded the No–

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<sup>1</sup> Some say the term *chronobiology* was coined by Franz Halberg during the Cold Spring Harbor Symposium (Menna-Barreto & Marques, 2023, p. 21).

bel Prize in Physiology or Medicine for their discoveries of molecular mechanisms that regulate the circadian rhythm in fruit flies (*circā*, from Latin, meaning around, and *dies*, meaning day (Latinium, n.d.) – a rhythm with an approximately 24-hour period) (Nobel Prize Outreach AB, n.d.).

Figure 1 – Illustration of the circadian rhythm in leaf movement of the sensitive plant (*Mimosa pudica*) observed by Jacques d’Ortous de Mairan in 1729.



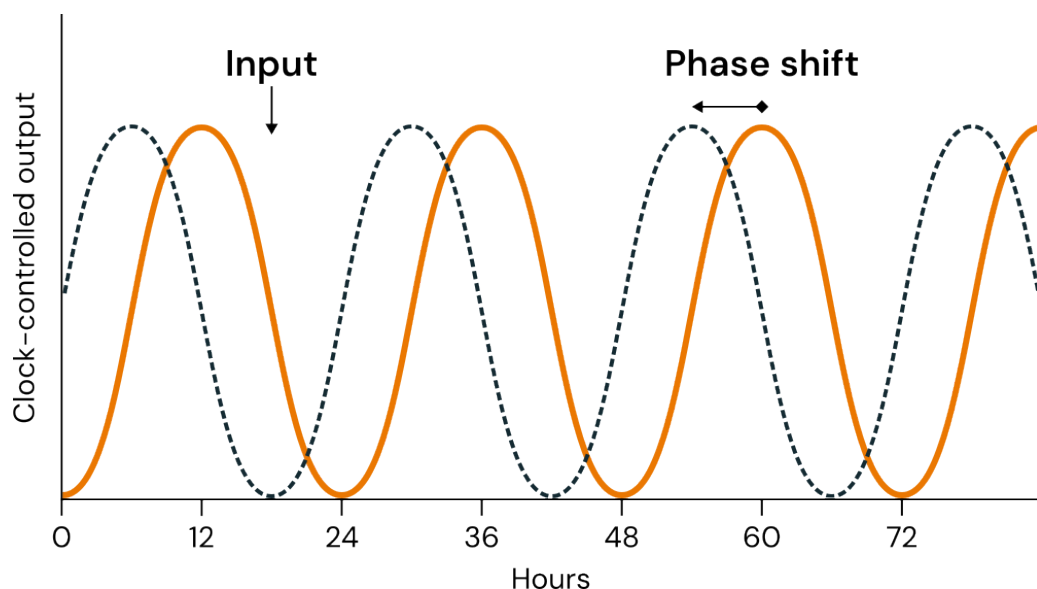
Source: Reproduced from Nobel Prize Outreach AB (n.d.).

Various biological rhythms have already been shown and described by science. These rhythms can occur at different levels, whether at a macro level, such as the menstrual cycle (Ecochard et al., 2024), or even at a micro level, such as rhythms expressed within cells (Buhr & Takahashi, 2013; Sartor et al., 2023). Like many other biological phenomena, these are emergent properties of complex systems found in all living beings – stable macroscopic patterns arising from the collective behavior of the system’s parts, resulting in properties not attainable by the aggregate summation (Epstein, 1999; Holland, 2014). Today, it is understood that en-

ogenous rhythms provide organisms with an anticipatory capacity, enabling them to pre-emptively organize resources and activities (Aschoff, 1989a).

Despite the endogenous nature of these rhythms, they can still be regulated by the external environment. Signals (cues) from the environment that occur cyclically in nature and have the ability to regulate biological rhythmic expression are called zeitgebers (from the German *zeit*, meaning time, and *geber*, meaning donor (Cambridge University Press, n.d.)). These zeitgebers act as synchronizers by entraining the phases of the rhythms (Khalsa et al., 2003; Minors et al., 1991) (Figure 2). Among the known zeitgebers are, for example, meal timing (Flanagan et al., 2021) and changes in environmental temperature. However, the most influential of them is the light/dark cycle (or, simply, light exposure) (Aschoff, 1960; Pittendrigh, 1960; Roenneberg & Merrow, 2016). It is understood that the day/night cycle, resulting from the rotation of the Earth, has provided the vast majority of organisms with an oscillatory system with a periodic duration of approximately 24 hours (Aschoff, 1989a; Roenneberg, Kuehnle, et al., 2007).

Figure 2 – Illustration of a circadian rhythm entrained (Phase-advanced, indicated by a leftward shift) by a zeitgeber (Input).



Source: Adapted by the author from Kuhlman et al. (2018, Figure 2B).

The expression of this temporal organization varies among organisms, even within the same species (Duffy et al. (2011); Silvério et al. (2024)). These variations

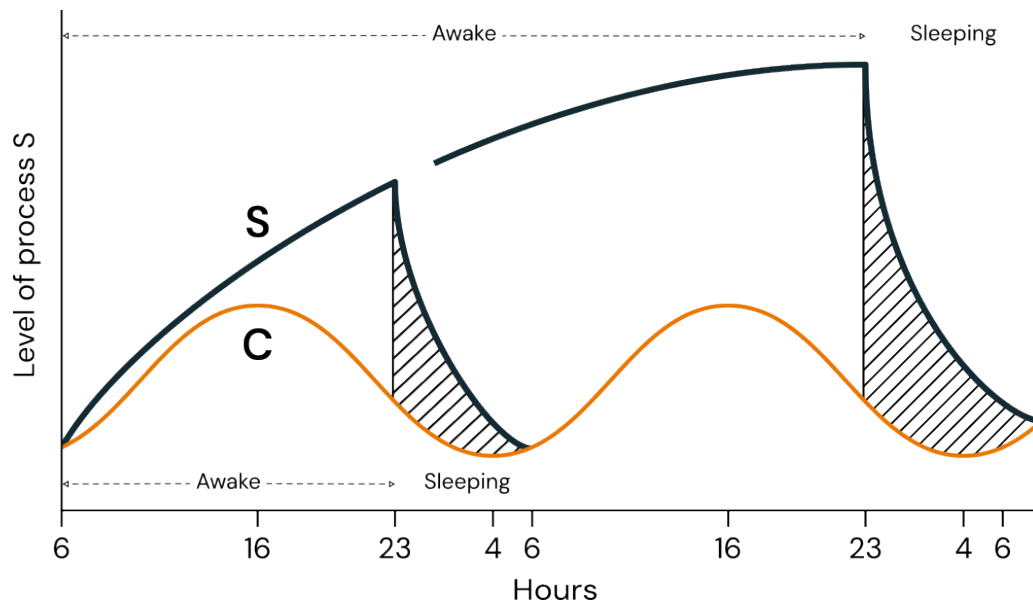
can be attributed to differences in how organisms experience their environment or to differences in their endogenous rhythmicity, a characteristic ultimately influenced by gene expression (Roenneberg, Kumar, & Merrow, 2007). The interplay between environmental influences and genetic predisposition results in an observable characteristic: the phenotype (Frommlet et al., 2016).

The various temporal characteristics of an organism can be linked to different oscillatory periods. Among these are circadian phenotypes, which refer to characteristics observed in rhythms with periods lasting about a day (Foster & Kreitzman, 2005). Another term used for these temporal phenotypes, as the name suggests, is *chronotype* (Ehret, 1974; Pittendrigh, 1993). This term is also often used to differentiate phenotypes on a spectrum ranging from morningness to eveningness (Horne & Östberg, 1976; Roenneberg, Wirz-Justice, et al., 2019).

Sleep is a phenomenon that exhibits circadian expression. By observing the sleep characteristics of individuals, it is possible to assess the distribution of circadian phenotypes within a population, thereby investigating their covariates and other relevant associations (Roenneberg et al., 2003). This is because sleep is understood to result from the interaction of two processes: a homeostatic process (The S process), which is sleep-dependent and accumulates with sleep deprivation, and a circadian process (The C process), whose expression can be influenced by zeitgebers such as the light/dark cycle (Borbély, 1982; Borbély et al., 2016). These two processes are illustrated in Figure 3. Because the circadian rhythm is a component of sleep, its characteristics can be inferred by isolating its effects from those of the S process.

Figure 3 – Illustration of the interaction between Process S (Homeostatic/Sleep-dependent process) and Process C (Circadian rhythm process) in sleep regulation.

The figure depicts two scenarios: One with 17 hours of wakefulness followed by 7 hours of sleep, and another, under sleep deprivation, with 41 hours of wakefulness followed by 7 hours of sleep. The y-axis represents the level of each process. The hatched areas indicate periods of sleep, illustrating the exponential decline of Process S.



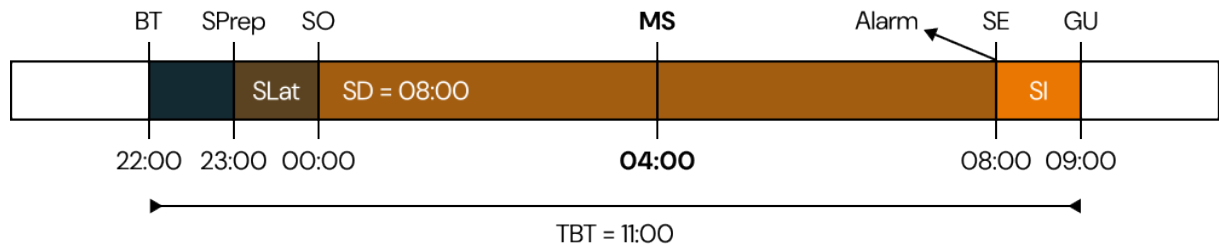
Source: Adapted by the author from Borbély (1982, Figure 4, lower part).

Building on this idea, Roenneberg et al. (2003) developed the Munich Chronotype Questionnaire (MCTQ) to measure the circadian phenotype through sleep patterns. The MCTQ asks individuals about their sleep habits, such as the times they go to bed and wake up on workdays and work-free days. From this information, the MCTQ derives the midpoint of sleep on work-free days, representing the average of sleep onset and offset times (Figure 4). If sleep deprivation is detected on workdays, the scale adjusts the measurement accordingly. This midpoint, reflecting sleep under minimal social constraints, is considered a closer approximation of the intrinsic circadian rhythm and, therefore, a useful proxy for estimating the circadian phenotype (the C process) (Leocadio-Miguel et al., 2014).



Figure 4 – Variables measured by the Munich Chronotype Questionnaire (MCTQ). In its standard version, these variables are collected in the context of workdays and work-free days.

BT = Local time of going to bed. SPrep = Local time of preparing to sleep. SLat = Sleep latency (Duration. Time to fall asleep after preparing to sleep). SO = Local time of sleep onset. SD = Sleep duration. **MS** = Local time of mid-sleep. SE = Local time of sleep end. Alarm = Indicates whether the respondent uses an alarm clock. SI = “Sleep inertia” (Duration. Despite the name, this variable represents the time the respondent takes to get up after sleep end). GU = Local time of getting out of bed. TBT = Total time in bed.



Source: Created by the author.

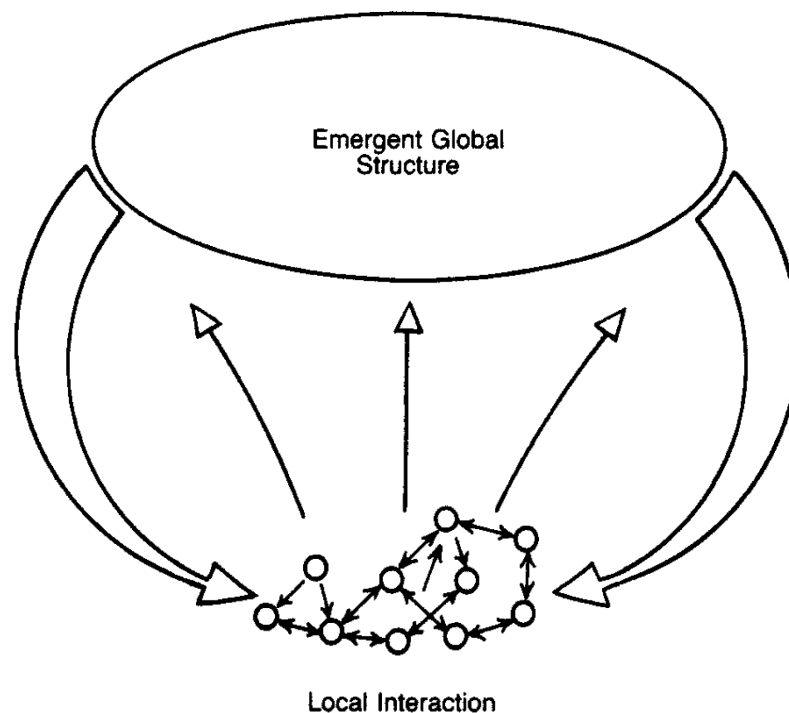
The MCTQ facilitates the evaluation of chronotype in population studies. This thesis employs the MCTQ to assess chronotype using data from a 2017 online survey conducted by the author, which includes responses from 65,824 Brazilians and geographical information such as postal codes. This dataset enables the investigation of potential associations between chronotype and geographic factors.

### 3 ON COMPLEXITY SCIENCE

Complexity science is the science dedicated to understanding emergent phenomena (Krakauer & Wolpert, 2024). Like computer science and chronobiology, it began to take shape in the second half of the 20th century, by the convergence of several fields, such as systems theory, game theory, and nonlinear dynamics (Sayama, 2015)<sup>1</sup>.

At a fundamental level, emergence can be defined as stable macroscopic patterns arising from local interactions (Epstein, 1999). These patterns emerge from the collective actions of a system's parts, which cannot be attained by simply summing them up (Holland, 2014) (Figure 5). They may give rise to new properties in a system, which can only be studied by observing the interactions within it.

Figure 5 – An illustration of the reciprocal action between an emergent phenomenon derived by local interactions.



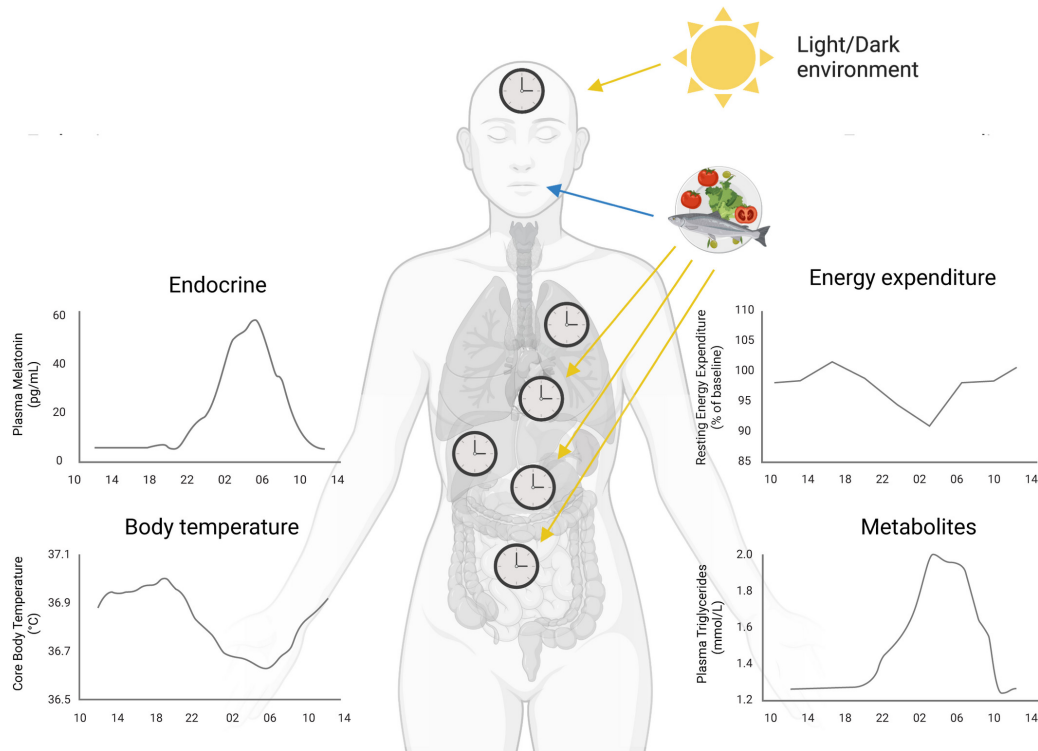
Source: Reproduced from Lewin (1993, Figure 1).

<sup>1</sup> Brian Castellani & Lasse Gerrits created a visual map to illustrate the different fields and components of complexity science. You can find it at [https://www.art-sciencefactory.com/complexity-map\\_feb09.html](https://www.art-sciencefactory.com/complexity-map_feb09.html).

Systems that exhibit emergent properties are considered complex systems (Holland, 2014; Mitchell, 2009). In a general sense, a system can be defined as a set of interacting parts that, through their interactions, produce a global behavior (von Bertalanffy, 1968). While both complicated and complex systems consist of many interacting parts, the defining characteristic of complex systems is that they cannot be fully understood by analyzing their components in isolation (Holland, 1992). This distinction poses significant challenges, as traditional methods for studying systems are often inadequate for capturing the intricate dynamics of complex systems (Holland, 2006).

Biological rhythms are an example of emergent properties produced by a complex system with multiple levels of interaction (Partch et al., 2014). Molecular oscillations are generated at the cellular level (Buhr & Takahashi, 2013; Mellow et al., 2005). These oscillations interact and couple with one another, forming a complex circadian network that coordinates rhythmic physiology and behavior (Foster, 2020; Raj & van Oudenaarden, 2008). Although science has not fully mapped all the pathways, it is understood that in this kaleidoscopic array of simultaneous interactions, a global rhythm emerges. Each rhythm, or clock, is itself an emergent phenomenon, interacting with others to produce a global behavior (Figure 6). As the parts generate these emergences, the emergent feedback to the parts, regulating and modulating functions at all levels (Roenneberg, Kuehnle, et al., 2007).

Figure 6 – An illustration depicting how the human circadian clock system regulate multiple aspects of metabolic physiology, such as: hormone secretion, core body temperature, resting metabolic rate, and plasma metabolite concentration.



Source: Reproduced from Flanagan et al. (2021, Figure 2).

The entrainment of these rhythms with environmental periodicities can involve different mechanisms. For the light/dark cycle, the main zeitgeber, this involves a network of photosensitive retinal ganglion cells (pRGCs) that send signals to the suprachiasmatic nucleus (SCN) in the hypothalamus (Brainard et al., 2001; Thapan et al., 2001). The SCN then sends signals to the pineal gland, which produces melatonin, a hormone that regulates sleep-wake cycles, among other functions (Foster, 2021).

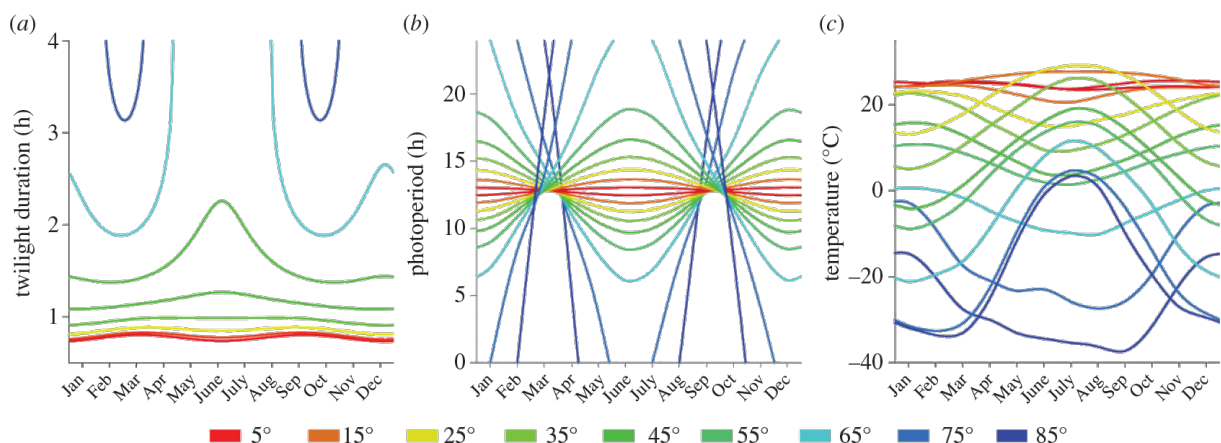
To model this phenomenon, one must understand how complex systems behave and can be studied. This thesis adopts a global approach to understanding the effect of light/dark cycle entrainment on circadian expressions of populations, considering potential interactions for proper system control. Given the thesis's aim to test the latitude hypothesis, a global approach is appropriate. Alternatively, a local approach could explore entrainment in populations by modeling individuals, each with their own circadian clock, and their interactions with the environment.

## 4 ON THE LATITUDE HYPOTHESIS

The first mention of this hypothesis regarding human populations dates back to at least 1973 (Bohlen & Simpson, 1973), with earlier hints of the idea coming from Erhard Haus and Franz Halberg in 1970 (Haus & Halberg, 1970, p. 101), building on discussions initiated by Jürgen Aschoff (Aschoff, 1969). Since then, numerous studies have explored this topic, yielding somewhat conflicting results<sup>1</sup>.

The hypothesis, also called the *environment hypothesis* (Horzum et al., 2015), posits that regions closer to the poles receive, on average, less annual sunlight compared to regions near the equator (Figure 7). Consequently, regions around latitude 0° are thought to have a stronger solar zeitgeber. According to chronobiological theories, this stronger zeitgeber would enhance the entrainment of circadian rhythms with the light/dark cycle, resulting in lower variability of circadian phenotypes (Aschoff (1960); Pittendrigh (1960) Aschoff (1981); Pittendrigh and Takamura (1989); Pittendrigh et al. (1991)). This reduced influence of individual endogenous periods is illustrated in Figure 8.

Figure 7 – Annual variations in (a) Twilight duration, (b) Photoperiod, and (c) Temperature across different latitudes. Each color represents a specific latitude.



Source: Reproduced from Hut et al. (2013, Figure 1).

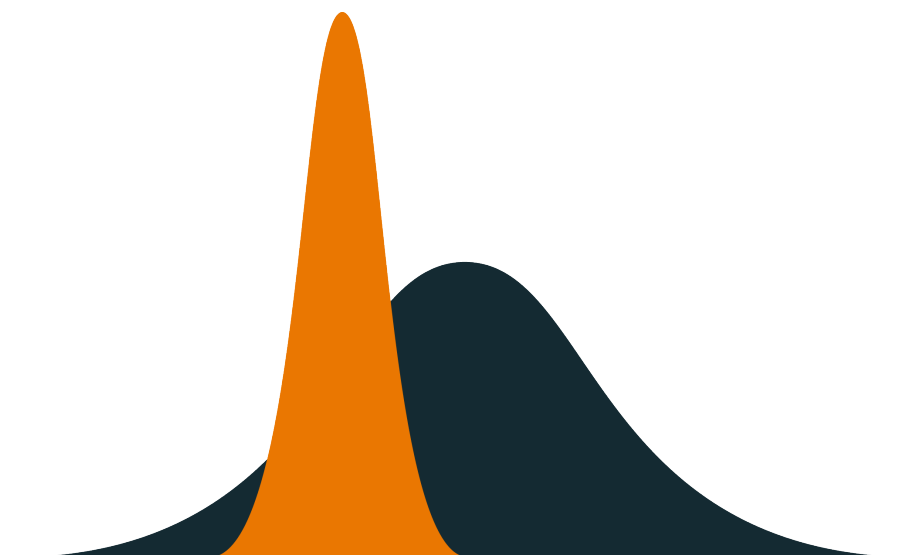
In contrast, populations near the poles would experience a weaker solar zeitgeber, leading to greater variability for the expression of circadian phenotypes. This disparity also would translate into differences in mean chronotype: Equatorial

<sup>1</sup> A systematic review on the subject is provided by Randler and Rahafar (2017).

populations would tend to exhibit a morningness orientation, while populations at higher and low latitudes would tend toward eveningness (Bohlen & Simpson, 1973; Roenneberg et al., 2003).

It's important to emphasize that the latitude hypothesis is grounded in underlying circadian rhythms, not in self-reported morningness–eveningness (ME) *preference*. Self-reported preference can be influenced by extraneous factors, such as social constraints. Reducing this hypothesis to individual preferences undermines its theoretical foundation and introduces unnecessary confounders. Therefore, chronotype scales focusing on the preference aspect of ME may be unsuitable for testing this hypothesis. This is illustrated by Leocadio-Miguel et al. (2014) when discussing differences between the Horne–Östberg (HO) ME questionnaire (Horne & Östberg, 1976), which treats chronotype as a psychological construct (Roenneberg, Pilz, et al., 2019), and the Munich Chronotype Questionnaire (Roenneberg et al., 2003), which addresses chronotype as a biological construct, in the context of the latitude hypothesis.

Figure 8 – Chronotype distributions under the influence of strong (orange) and weak (black) zeitgebers. This visualization reflects the effect proposed by the latitude hypothesis.



Source: Adapted by the author from Roenneberg et al. (2003, Figure 7F).

While there is some compelling evidence for this hypothesis in some insect species (Hut et al., 2013), the same cannot be said for this association in humans.

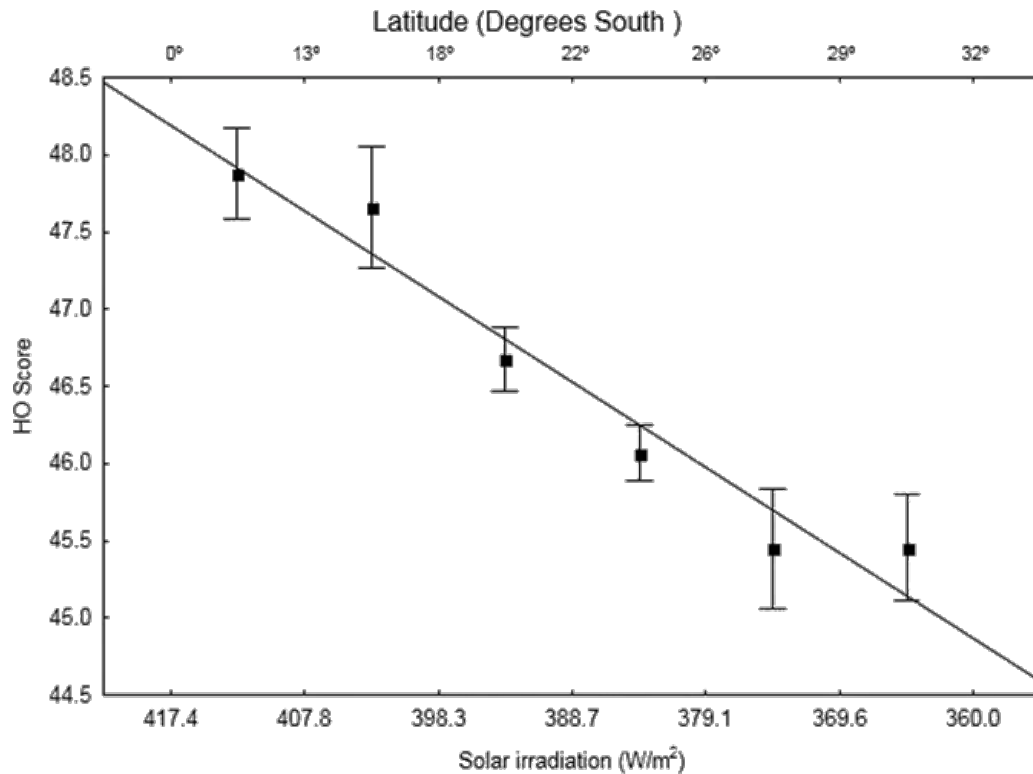
Some authors claim to found such an association (Randler (2008); Leocadio-Miguel et al. (2014); Horzum et al. (2015); Leocadio-Miguel et al. (2017); Wang et al. (2023)), but a closer look at the data reveals that the evidence is not as clear as it seems.

For example, Leocadio-Miguel et al. (2017) claimed to find a significant association between latitude and chronotype in a sample of 12,884 Brazilian participants using the HO questionnaire. However, the reported effect size was too small to be considered practically significant (even by lenient standards), with latitude explaining only approximately 0.388% of the variance in chronotype (Cohen's  $f^2 = 0.004143174$ ) (Figure 9). Considering the particular emphasis that the solar zeitgeber has on the entrainment of biological rhythms (as demonstrated by numerous studies), it is unreasonable to assume that the latitude hypothesis could be supported without at least a non-negligible effect size.

The results from the latitude hypothesis studies highlight common limitations of studies relying on Null Hypothesis Significance Testing (NHST). A  $p$ -value does not measure effect size; rather, it represents the conditional probability of observing the test statistic (or a more extreme value) given that the null hypothesis is true (Cohen, 1994; Wasserstein & Lazar, 2016). As Cohen (1988, p. 16) noted, the goal in NHST is not to test whether the population effect size is literally zero, but rather whether it is negligible or trivial.

Figure 9 – Mean scores ( $\pm$ SE) on the Horne & Östberg (HO) chronotype scale (Horne & Östberg, 1976) across a latitudinal gradient, along with corresponding annual average solar irradiation levels ( $\text{W/m}^2$ ).

The HO scale comprises 19 items, with total scores ranging from 16 to 86; lower scores indicate a stronger evening orientation, while higher scores reflect a greater morning orientation. Notably, the y-axis exaggerates the visual impact of the differences, as it spans a range of only approximately 4 points, which overstate the perceived significance of the effect.



Source: Reproduced from Leocadio-Miguel et al. (2017, Figure 2).

Several factors may undermine this hypothesis, such as selective light exposure and social constraints (Skeldon & Dijk, 2021). To gain a more accurate understanding of the mechanisms underlying chronotype expression, it remains crucial to test this hypothesis in larger samples and with robust statistical procedures. This study aims to address this gap.



The following study was designed for publication in the journal *Scientific Reports* (IF 2023: 3.8/JCR | CAPES: A1/2017–2020) and structured in accordance with the journal's submission guidelines.

## 5 IS LATITUDE ASSOCIATED WITH CHRONOTYPE?

### 5.1 ABSTRACT

**Chronotypes are temporal phenotypes that reflect our internal temporal organization, a product of evolutionary pressures enabling organisms to anticipate events. These intrinsic rhythms are entrain by zeitgebers — periodical environmental stimuli with the ability to regulate biological rhythmic expression, with light exposure being the primary mechanism. Given light’s role in these systems, previous research hypothesized that latitude might significantly influence chronotypes, suggesting that populations near the equator would exhibit more morning-leaning characteristics due to more consistent light/dark cycles, while populations near the poles might display more evening-leaning tendencies with a potentially freer expression of intrinsic rhythms. To test this hypothesis, we analyzed chronotype data from a large sample of 65,824 subjects across diverse latitudes in Brazil. Our results revealed a negligible effect size of latitude on chronotype ( $f^2 = 0.0030818$ , 95% CI[0, 0.0121371]), indicating that the entrainment phenomenon is far more complex than previously conceived. These findings challenge simplified environmental models of biological timing and underscore the need for more nuanced investigations into the mechanisms underlying temporal phenotypes, opening new avenues for understanding the intricate relationship between environmental cues and individual circadian rhythms.**

### 5.2 INTRODUCTION

Humans exhibit a variety of observable traits, such as eye or hair color, which are referred to as phenotypes. These phenotypes also manifest in the way our bodies function.

A chronotype is a temporal phenotype (Ehret, 1974; Pittendrigh, 1993), typically used to refer to endogenous circadian rhythms — biological rhythms with periods close to 24 hours. Chronobiology, the science that studies biological rhythms, suggests that the evolution of these internal oscillators is closely linked to our environment, particularly the day/night cycle. This cycle, alongside human evolution,

created environmental pressures that led to the development of temporal organization within organisms (Aschoff, 1989b; Paranjpe & Sharma, 2005; Pittendrigh, 1981). Such organization allowed organisms to predict events and better manage their needs, such as storing food for winter (Aschoff, 1989a).

For a temporal system to be useful, it must be capable of adapting to environmental changes. Environmental signals capable of regulating biological rhythms are known as *zeitgebers* (from the German *zeit*, meaning time, and *geber*, meaning donor (Cambridge University Press, n.d.)). These *zeitgebers* provide inputs that can shift and synchronize biological rhythms in a process called entrainment (Khalsa et al., 2003; Minors et al., 1991).

The primary *zeitgeber* influencing biological rhythms is the light/dark cycle, or, simply, light exposure (Aschoff, 1960; Pittendrigh, 1960; Roenneberg & Mellow, 2016). Given its significant role in entraining the biological clock, several studies have hypothesized that the latitudinal shift of the sun, due to the Earth's axial tilt, might lead to different temporal traits in populations near the equator compared to those closer to the poles (Bohlen & Simpson, 1973; Horzum et al., 2015; Leocadio-Miguel et al., 2014, 2017; Randler, 2008). This is based on the idea that populations at low or higher latitudes experience greater fluctuations in sunlight and a weaker overall solar *zeitgeber*. This concept is known as the latitude hypothesis, or the environmental hypothesis of circadian rhythm regulation.

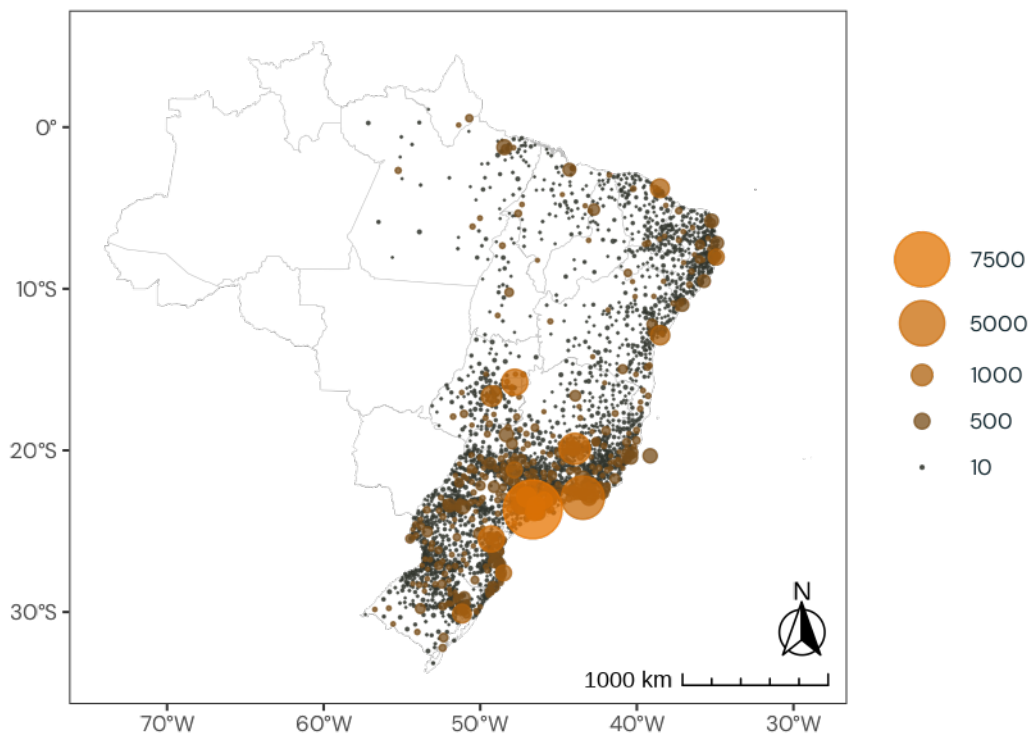
Several studies have claimed to find this association in humans, but the evidence they provide is of very low quality or is misleading (Horzum et al., 2015; Leocadio-Miguel et al., 2014, 2017; Randler, 2008; Wang et al., 2023). A notable attempt was made by Leocadio-Miguel et al. (2017), who measured the chronotype of 12,884 Brazilian subjects across a wide latitudinal range using the Horne-Östberg (HO) Morningness–Eveningness questionnaire (Horne & Östberg, 1976). Although the authors concluded that there was a significant association between latitude and chronotype, their results were too small to be considered practically significant (even by lenient standards), with latitude explaining only approximately 0.388% of the variance in chronotype (Cohen's  $f^2 = 0.004143174$ ). One possible explanation for this result is that the HO measures psychological traits rather than the biological states of circadian rhythms themselves (Roenneberg, Pilz, et al., 2019), suggesting

it may not be the most suitable tool for testing the hypothesis (Leocadio-Miguel et al., 2014).

Building on Leocadio-Miguel et al. (2017), this study offers a novel attempt to test the latitude hypothesis by employing a biological approach through the Munich ChronoType Questionnaire (MCTQ) (Roenneberg et al., 2003) and an enhanced statistical methodology. Additionally, it utilizes the largest dataset on chronotype from a single country, as far as the existing literature suggests, comprising 65,824 respondents, all residing within the same timezone in Brazil and completing the survey within a one-week window (Figure 10).

Figure 10 – Geographical distribution of the sample used in the analysis ( $n = 65,824$ ).

Each point represents a municipality, with its size proportional to the number of participants and its color indicating participant density. The sample includes Brazilian individuals aged 18 or older, residing in the UTC-3 timezone, who completed the survey between October 15th and 21st, 2017 (one-week window). The size and color scale are logarithmic ( $\log_{10}$ ).



Source: Created by the author.

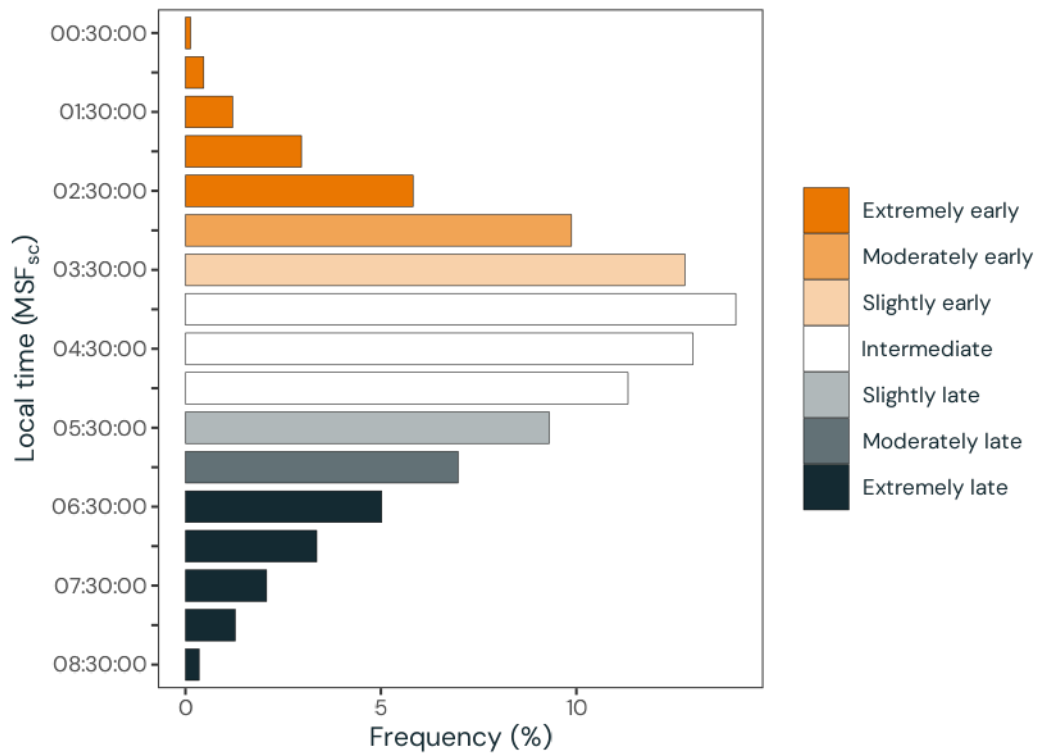
### 5.3 RESULTS

The Munich Chronotype Questionnaire (MCTQ) uses the midpoint between sleep onset (SO) and sleep end (SE) on work-free days ( $MSF_{sc}$ ), with a sleep correction (sc) applied if sleep debt is detected, as a proxy for chronotype (Roenneberg et al., 2003). For example, if an individual sleeps from 00:00 to 08:00, the midpoint would be 04:00. This measure is based on the current understanding of sleep regulation, which comprises a homeostatic/sleep-dependent process (S process) and a circadian process (C process) (Borbély, 1982; Borbély et al., 2016). The midpoint of sleep on free days offers a way to observe unrestrained sleep behavior, thereby minimizing the influence of the S process and providing a better approximation of the circadian phenotype (i.e., the C process).

Our analysis revealed an overall mean  $MSF_{sc}$  of 04:28:41, with an standard deviation of 01:26:13. The distribution is shown in Figure 11.

Figure 11 – Distribution of the local time of the sleep-corrected midpoint between sleep onset and sleep end on work-free days ( $MSF_{sc}$ ), a proxy for chronotype.

Chronotypes are categorized into quantiles, ranging from extremely early (0 | – 0.11) to extremely late (0.88 – 1).



Source: Created by the author, based on a data visualization from Roenneberg, Wirz-Justice, et al. (2019, Figure 1, right part).

This represents the midsleep point for Brazilian subjects living in the UTC–3 timezone, with an intermediate or average chronotype. Considering the 7–9 hours of sleep recommended for healthy adults by the American Academy of Sleep Medicine (AASM) (Watson et al., 2015), one might infer that this average individual, in the absence of social constraints, would typically wake up at approximately 08:28:41.

The study hypothesis was tested using nested multiple linear regressions. The core idea of nested models is to evaluate the effect of including one or more predictors on the model's variance explanation ( $R^2$ ) (Maxwell et al., 2018). This is achieved by comparing a restricted model (without the latitude) with a full model (with the latitude). Cell weights, based on sex, age group, and state of residence, were applied to account for sample imbalances.

To ensure practical significance, the hypothesis test incorporated a minimum effect size (MES) criterion, aligning with the original Neyman–Pearson framework for data testing (Neyman & Pearson, 1928a, 1928b; Perezgonzalez, 2015). The MES was set at a Cohen’s  $f^2$  of 0.02 (equivalent to an  $R^2$  of 0.01960784), a lenient threshold (Cohen, 1988, 1992). Given the well-established influence of the solar zeitgeber on biological rhythm entrainment, it is unlikely that the latitude hypothesis could be meaningfully supported without demonstrating at least a non-trivial effect.

Two tests were conducted, both starting with the same restricted model, which included age, sex, longitude, and the average monthly Global Horizontal Irradiance (GHI) at the time of questionnaire completion as predictors ( $R_{\text{adj}}^2 = 0.0851096$ ,  $F(4, 65818) = 1531.808$ ,  $p\text{-value} < 1e - 05$ ). The first full model (**A**) added the average annual GHI and daylight duration for the nearest March equinox, as well as the June and December solstices, as proxies for latitude, following the methods of Leocadio-Miguel et al. (2017) ( $R_{\text{adj}}^2 = 0.0879205$ ,  $F(8, 65814) = 794.12$ ,  $p\text{-value} < 1e - 05$ ). The second full model (**B**) added only latitude as a predictor ( $R_{\text{adj}}^2 = 0.0856143$ ,  $F(5, 65817) = 1233.588$ ,  $p\text{-value} < 1e - 05$ ). All coefficients were statistically different from zero ( $p\text{-value} < 0.05$ ). Assumption checking and residual diagnostics primarily relied on visual inspection, as formal assumption tests (e.g., Anderson–Darling) are often not recommended for large samples (Shatz, 2024). All validity assumptions were met, and no serious multicollinearity was found among the predictor variables.

Sunrise times for the nearest March and September equinoxes, as well as the June and December solstices, were excluded due to high multicollinearity. Daylight duration for the September equinox was excluded for its multicollinearity with daylight duration during the March equinox.

An ANOVA for nested models revealed a significant reduction in the residual sum of squares in both tests (**A**  $F(4, 65814) = 51.71$ ,  $p\text{-value} < 1e - 05$ ) (**B**  $F(1, 65817) = 37.325$ ,  $p\text{-value} < 1e - 05$ ). However, similarly to Leocadio-Miguel et al. (2017), when estimating Cohen’s  $f^2$  effect size, the results were below the MES (i.e., negligible) (**A**  $f^2 = 0.0030818$ , 95% CI[0, 0.0121371]) (**B**  $f^2 = 0.0005519$ , 95% CI[0, 0.0095239]).

## 5.4 DISCUSSION

We emphasize that the assumption of a causal, linear relationship between latitude and chronotype constitutes an *a priori* hypothesis, which this study seeks to falsify.

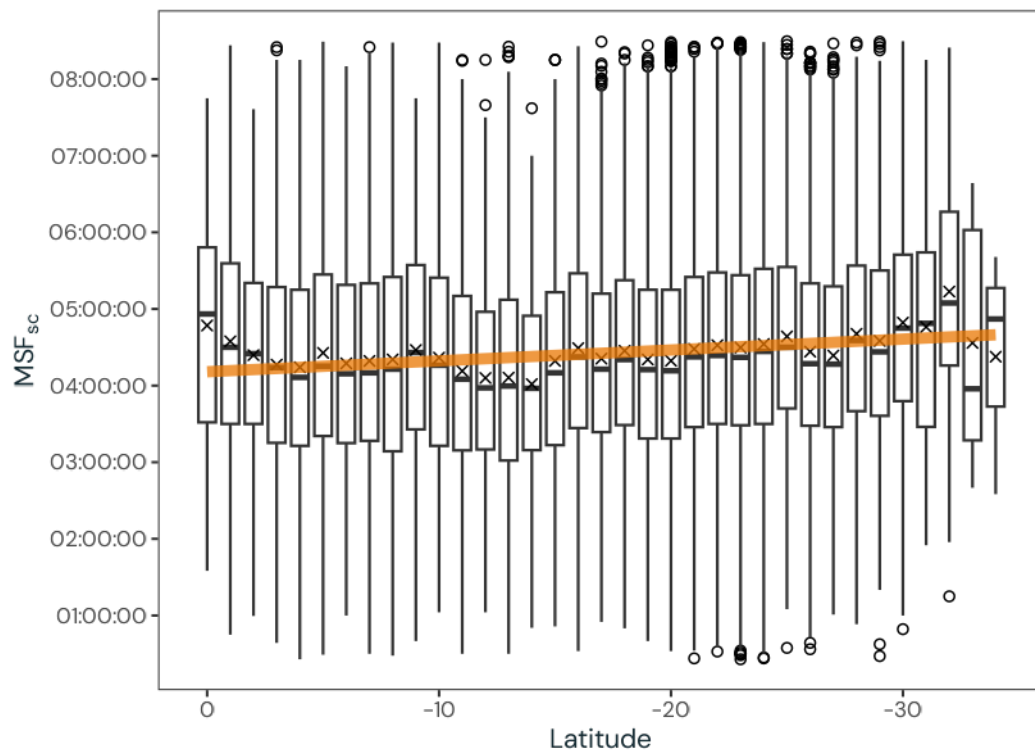
Despite a broad latitudinal range (33.85026 degrees) and a large, balanced sample, our results indicate that the effect of latitude on chronotype is negligible. Indeed, despite suggestions of a potential link in several studies, robust empirical evidence supporting this claim in humans is lacking.

Our results align with those of Leocadio-Miguel et al. (2017), who reported a similar effect size (Cohen's  $f^2 = 0.004143174$ ). However, their analysis did not incorporate a minimum effect size criterion, leading to misleading interpretations. The small and inconsistent nature of the latitude effect is illustrated in Figure 12, while Figure 13 displays the mean chronotype by Brazilian state.



Figure 12 – Boxplots of mean  $MSF_{sc}$  values aggregated by  $1^\circ$  latitude intervals, illustrating the relationship between latitude and chronotype.

$MSF_{sc}$  represents the local time of the sleep-corrected midpoint between sleep onset and sleep end on work-free days, a proxy for chronotype. Higher  $MSF_{sc}$  values indicate later chronotypes. The  $\times$  symbol points to the mean. The orange line represents a linear regression. The differences in mean/median values across latitudes are minimal relative to the Munich ChronoType Questionnaire (MCTQ) scale.

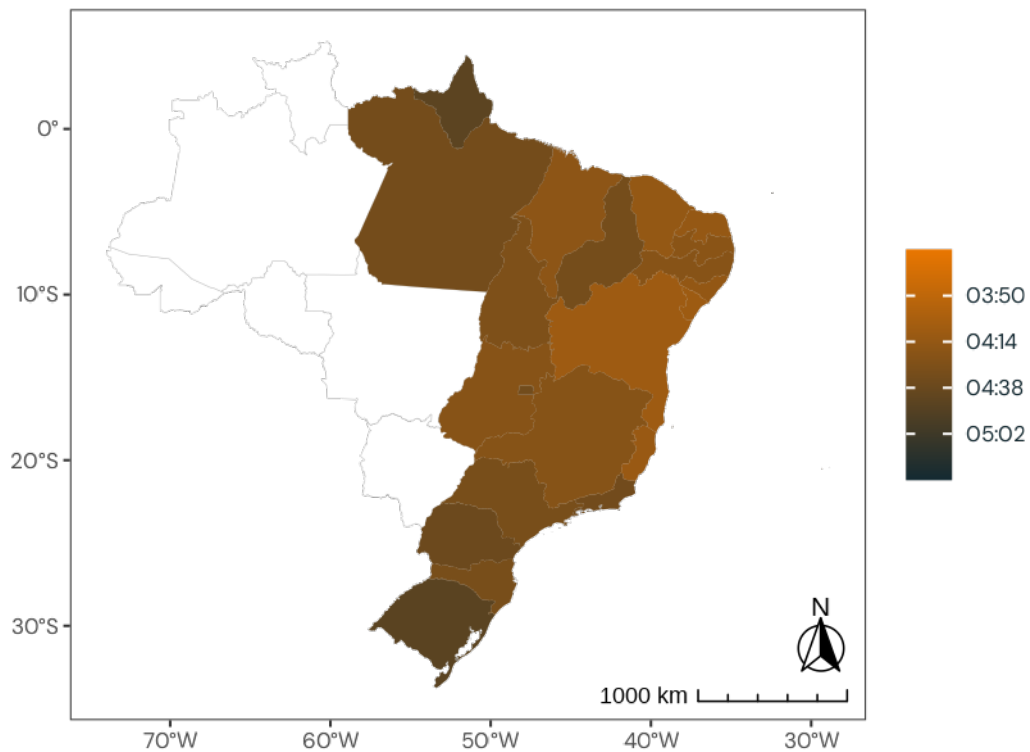


Source: Created by the author.

The absence of a clear relationship between latitude and chronotype can be attributed to multiple factors. As Jürgen Aschoff might have put it, this may reflect a lack of “ecological significance” (Aschoff et al., 1972). Even if latitude does influence circadian rhythms, the effect could be too minor to detect or might be overshadowed by other, more prominent factors like social behaviors, work hours, or the widespread use of artificial lighting. Furthermore, the variations in sunlight exposure between latitudes may not be substantial enough to meaningfully impact the circadian system, which is highly responsive to light. Given that even minor light fluctuations can lead to measurable physiological changes (Khalsa et al., 2003; Minors et al., 1991), latitude alone may not be a decisive factor in determining chronotype.

Figure 13 – Geographical distribution of  $MSF_{sc}$  values by Brazilian state, illustrating how chronotype varies with latitude in Brazil.

$MSF_{sc}$  is a proxy for chronotype, representing the midpoint of sleep on work-free days, adjusted for sleep debt. Higher  $MSF_{sc}$  values correspond to later chronotypes. The color scale was not transformed and it has as limits the first and third quartile (interquartile range). Differences in mean  $MSF_{sc}$  values across states are small and fall within a narrow range relative to the scale of the Munich ChronoType Questionnaire (MCTQ), limiting the significance of these variations.



Source: Created by the author.

This study suggests a more complex relationship between latitude and the circadian system than originally expected. The perceived link between these variables may be a consequence of prioritizing statistical rituals over statistical thinking and a tendency toward confirmation bias, rather than rigorous and unbiased data analysis.

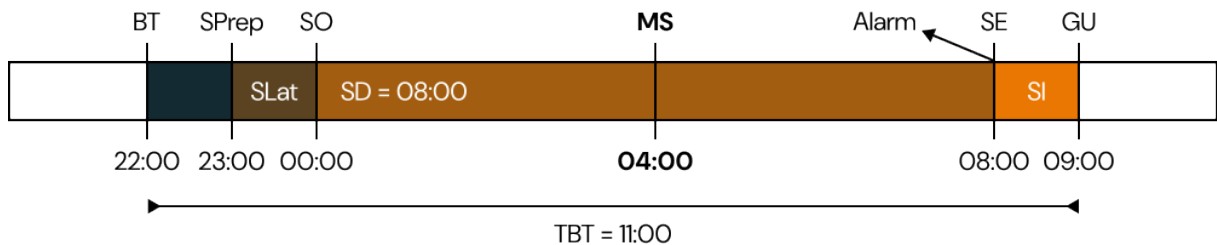
## 5.5 METHODS

### 5.5.1 Measurement Instrument

Chronotypes were assessed using a sleep log based on the core version of the Munich ChronoType Questionnaire (MCTQ) (Roenneberg et al., 2003), a well-validated and widely used self-report tool for measuring sleep-wake behavior and determining chronotype (Roenneberg, Pilz, et al., 2019). The MCTQ derives chronotype from the sleep-corrected midpoint of sleep on free days ( $MSF_{sc}$ ), which compensates for sleep debt incurred during the workweek (Roenneberg, 2012). Figure 14 illustrates the variables collected by the MCTQ.

Figure 14 – Variables measured by the Munich Chronotype Questionnaire (MCTQ). In its standard version, these variables are collected in the context of workdays and work-free days.

BT = Local time of going to bed. SPrep = Local time of preparing to sleep. SLat = Sleep latency (Duration. Time to fall asleep after preparing to sleep). SO = Local time of sleep onset. SD = Sleep duration. **MS** = Local time of mid-sleep. SE = Local time of sleep end. Alarm = Indicates whether the respondent uses an alarm clock. SI = “Sleep inertia” (Duration. Despite the name, this variable represents the time the respondent takes to get up after sleep end). GU = Local time of getting out of bed. TBT = Total time in bed.



Source: Created by the author.

Participants completed an online questionnaire, which included the sleep log as well as sociodemographic (e.g., age, sex), geographic (e.g., full residential address), anthropometric (e.g., weight, height), and data on work and study routines. A version of the questionnaire, stored independently by the Internet Archive organization, can be viewed at <https://web.archive.org/web/20171018043514/each.usp.br/gipso/mctq>.

### 5.5.2 Geographic Parameters

We obtained latitude and longitude data by geocoding participants' residential addresses using two main resources:

- **QualoCEP** (Qual o CEP, 2024): A dataset of Brazilian postal codes with integrated geocoding via the Google Geocoding API. This served as our primary source.
- **Google Geocoding API**: Used for addresses not included in QualoCEP. We employed the **tidygeocoder** R package (Cambon et al., 2021) to facilitate this process.

To ensure consistency, we randomly compared results from QualoCEP and Google Geocoding API. This can be seen in the supplementary materials.

### 5.5.3 Solar Irradiance Data

The solar irradiance data came from the **2017 Solar Energy Atlas** of Brazil's National Institute for Space Research (INPE) (E. B. Pereira et al., 2017). We used the Global Horizontal Irradiance (GHI) data, representing the total amount of irradiance received from above by a surface horizontal to the ground.

### 5.5.4 Astronomical Calculations

The **suntools** R package (Bivand & Luque, n.d.) was employed to calculate sunrise, sunset times, and daylight duration for each participant's location. These calculations are based on equations provided by Meeus (1991) and the National Oceanic and Atmospheric Administration (NOAA).

The dates and times of equinoxes and solstices were acquired from the **Time and Date AS** service (Time and Date AS, n.d.). To verify accuracy, we compared this data with the equations from Meeus (1991) and the results from the National Aeronautics and Space Administration (NASA) **ModelE AR5 Simulations** (National Aeronautics and Space Administration & Goddard Institute for Space Studies, n.d.).

### 5.5.5 Sample Characteristics

The analysis dataset consisted of 65,824 participants aged 18 or older residing in the UTC-3 timezone. These individuals completed the survey during a one-week period from October 15th to 21st, 2017, providing a snapshot of the population at that specific time.

The unfiltered valid sample included 115,166 participants from all Brazilian states. The raw dataset contained 120,265 individuals, with 98.173% of the responses collected between October 15th and 21st, 2017. This data collection period coincided with the promotion of the online questionnaire via a [broadcast](#) on a nationally televised Sunday show in Brazil (Rede Globo, [2017](#)).

Based on 2017 data from the Brazilian Institute of Geography and Statistics's (IBGE) Continuous National Household Sample Survey ([PNAD Contínua](#)) (Instituto Brasileiro de Geografia e Estatística, [n.d.](#)), Brazil had 51.919% of females and 48.081% of males with an age equal to or greater than 18 years old. The sample is skewed for female subjects, with 66.433% of females and 33.567% of male subjects. The mean age was 32.109 (SD = 32.109), ranging from 18 to 58.95 years.

To balance the sample, weights were incorporated into the models. These weights were calculated through cell weighting, using sex, age group, and state of residence as references, based on population estimates from IBGE for the same year as the sample.

A survey conducted in 2019 by IBGE ([2021](#)) found that 82.17% of Brazilian households had access to an internet connection. Therefore, this sample is likely to have a good representation of Brazil's population.

The sample latitudinal range is 33.85026 decimal degrees (Min. = -33.52156, Max. = 0.32869) with a longitudinal span of 22.74063 (Min. = -57.5531, Max. = -34.81247). For comparison, Brazil has a latitudinal range of 39.02299 decimal degrees (Min. = -33.75115; Max. = 5.27184) and a longitudinal span of 45.15451 (Min. = -73.99045; Max. = -28.83594), according to data from IBGE collected via the [geobr](#) R package (R. H. M. Pereira & Goncalves, [n.d.](#)).

Additional details about the sample are available in the supplementary materials.

### 5.5.6 Power Analysis

To assess the adequacy of the sample size for detecting effects reaching the Minimum Effect Size (MES) threshold ( $f^2 = 0.02$ ), we conducted an *a posteriori* power analysis using the `pwrss` R package (Bulus, n.d.). This analysis revealed a minimum sample size of 1,895 observations per variable to achieve a power ( $1 - \beta$ ) of 0.99 with a significance level ( $\alpha$ ) of 0.01. Our large sample size ( $n = 65,824$ ) comfortably surpasses this threshold, ensuring adequate power.

### 5.5.7 Data Wrangling

Data wrangling and analysis followed the data science framework proposed by Hadley Wickham and Garrett Grolemund (Wickham et al., 2023). All processes were conducted using the R programming language (R Core Team, n.d.), the RStudio IDE (Posit Team, n.d.), and several R packages. The `tidyverse` and `rOpenSci` peer-reviewed package ecosystem and other R packages adherents of the tidy tools manifesto (Wickham, 2023) were prioritized.

The MCTQ data was analyzed using the `mctq` R package (Vartanian, n.d.), which is part of the `rOpenSci` peer-reviewed ecosystem. The data pipeline was built using the `rOpenSci` peer-reviewed `targets` R package (Landau, 2021), which provides a reproducible and efficient workflow for data analysis.

All processes were designed to ensure result reproducibility and adherence to the FAIR principles (Findability, Accessibility, Interoperability, and Reusability) (Wilkinson et al., 2016). All analyses are fully reproducible and were conducted using `Quarto` computational notebooks. The `renv` R package (Ushey & Wickham, n.d.) was employed to ensure that the R analysis environment can be reliably restored.

### 5.5.8 Hypothesis Test

To test the study hypothesis, nested multiple linear regression models were compared: a restricted model (excluding latitude) and a full model (including latitude). To ensure practical significance, a Minimum Effect Size (MES) criterion was applied, in line with the original Neyman–Pearson framework for hypothesis testing (Neyman & Pearson, 1928a, 1928b; Perezgonzalez, 2015). The MES was set at a Co-

hen's threshold for small effects ( $f^2 = 0.02$ , equivalent to  $R^2 = 0.01960784$ ) ("just barely escaping triviality" (Cohen, 1988, p. 413)). Consequently, latitude was considered significant only if its inclusion explained at least 1.960784% of the variance in the dependent variable.

The hypothesis test was structured as follows:

- **Null hypothesis** ( $H_0$ ): Adding *latitude* does not meaningfully improve the model's fit, indicated by a negligible change in adjusted  $R^2$  or a non-significant F-test (with a Type I error probability ( $\alpha$ ) of 0.05).
- **Alternative Hypothesis** ( $H_a$ ): Adding *latitude* meaningfully improves the model's fit, indicated by an increase in adjusted  $R^2$  exceeding the MES and a significant F-test (with  $\alpha < 0.05$ ).

Formally:

$$\begin{cases} H_0 : \Delta \text{ Adjusted } R^2 \leq \text{MES} & \text{or} & \text{F-test is not significant } (\alpha \geq 0.05) \\ H_a : \Delta \text{ Adjusted } R^2 > \text{MES} & \text{and} & \text{F-test is significant } (\alpha < 0.05) \end{cases}$$

Where:

$$\Delta \text{ Adjusted } R^2 = \text{Adjusted } R^2_{\text{full}} - \text{Adjusted } R^2_{\text{restricted}}$$

## 5.6 DATA AVAILABILITY

Some restrictions apply to the availability of the main research data, which contain personal and sensitive information. As a result, this data cannot be publicly shared. Data are, however, available from the author upon reasonable request.

The code repository is available on GitHub at <https://github.com/danielvaratan/mastersthesis>, and the research compendium can be accessed via The Open Science Framework at the following link: <https://doi.org/10.17605/OSF.IO/YGKTS>.

## 5.7 ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, Grant number 88887.703720/2022-00.

## 5.8 ETHICS DECLARATIONS

The author declares that the study was carried out without any commercial or financial connections that could be seen as a possible competing interest.

## 5.9 ADDITIONAL INFORMATION

See the supplementary material for more information.

Correspondence can be sent to Daniel Vartanian ([danvartan@gmail.com](mailto:danvartan@gmail.com)).

## 5.10 RIGHTS AND PERMISSIONS

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## 6 CONCLUSION

According to Popper, the aim of science is to provide “satisfactory explanations of whatever strikes us as being in need of explanation” (Popper, 1979, p. 193). This study, using what is arguably the largest dataset on chronotype collected within a single time zone, balanced to reflect population proportions at the time of data collection, found no support for the latitude hypothesis. This result contributes meaningful evidence to the understanding of circadian rhythm regulation, offering a clear and satisfactory answer to the central research question of this thesis regarding human populations: *Is latitude associated with chronotype?* The answer, at present, is **No**.

The development of this work was driven by a commitment to objectivity and scientific rigor, a path that often diverges from the expectations commonly placed on young researchers. The temptation to align with mainstream ideas for easier acceptance within the scientific community — or to increase the likelihood of publication — is ever-present. However, it is crucial to emphasize that this research does not stem from unreasonable skepticism. Instead, it reflects the perspective of a young scientist dedicated to the scientific endeavor and its foundational principles.

### 6.1 LIMITATIONS

While this study provides valuable insights, it is essential to acknowledge certain limitations that may influence the interpretation of the findings.

First, the data collection occurred predominantly during a single week in spring, as summer approached, which limited the photoperiod variability between regions. A better approach would involve data collection across different seasons, particularly during winter, when photoperiod differences are more pronounced between equatorial and polar regions.

Additionally, the use of the Munich Chronotype Questionnaire (MCTQ), while a validated instrument, introduces the potential for recall and social desirability biases inherent to self-reported measures. However, the large sample size likely mitigates these biases, as predicted by the law of large numbers (DeGroot & Schervish,

2012, p. 352). Furthermore, at the time of data collection, the MCTQ had not yet been officially validated in Portuguese (this was only introduced in 2020 by Reis et al. (2020)), which may have introduced minor inconsistencies, though its nature as a sleep log suggests this impact was minimal.

Another factor to consider is the timing of data collection relative to the start of Daylight Saving Time (DST) in Brazil. On the day data collection commenced (October 15th, 2017 – 80.153% of the data used in this analysis were collected on this day), a significant portion of respondents adjusted their clocks forward by one hour. While this could theoretically influence their responses, the questions were specifically designed to capture daily routines, which were not affected by the DST adjustment at that moment. Furthermore, any potential effect of DST would likely strengthen the latitude hypothesis; however, this was not supported by the data.

These limitations, while noteworthy, do not undermine the study's findings but rather highlight areas for refinement in future research.

## 6.2 DIRECTIONS FOR FUTURE RESEARCH

This thesis proposed using a global modeling approach to investigate the latitude–chronotype relationship. However, as demonstrated by the results of this study and others, no significant effect of latitude on chronotype was identified. That said, it remains possible that if such a phenomenon exists, it could be captured through a localized approach, such as agent-based modeling. This approach would simulate an environment where agents are exposed to varying light levels, while accounting for their endogenous rhythms and the circadian clock's phase-response curve to light. The data from this thesis could serve to calibrate and validate this model.

## REFERENCES\*

- Allaire, J. J., Teague, C., Xie, Y., & Dervieux, C. (n.d.). *Quarto*. <https://doi.org/10.5281/ZENODO.5960048>
- Andrade, T. G. de, & Beale, A. D. (2024). Darwin and the biological rhythms. *PNAS Nexus*, 3(8), pgae318. <https://doi.org/10.1093/pnasnexus/pgae318>
- Aschoff, J. (1989a). Circadian temporal adaptation and the perception of time. *International Journal of Psychophysiology*, 7(2), 121–123. [https://doi.org/10.1016/0167-8760\(89\)90071-8](https://doi.org/10.1016/0167-8760(89)90071-8)
- Aschoff, J., Daan, S., Figala, J., & Müller, K. (1972). Precision of entrained circadian activity rhythms under natural photoperiodic conditions. *Naturwissenschaften*, 59(6), 276–277. Retrieved October 25, 2024, from <https://research.rug.nl/files/14698568/1972NaturwissAschoff.pdf>
- Aschoff, J. (1960). Exogenous and endogenous components in circadian rhythms. *Cold Spring Harbor Symposia on Quantitative Biology*, 25, 11–28. <https://doi.org/10.1101/SQB.1960.025.01.004>
- Aschoff, J. (1969). Phasenlage der tagesperiodik in abhängigkeit von jahreszeit und breitengrad. *Oecologia*, 3(2), 125–165. <https://doi.org/10.1007/BF00416979>
- Aschoff, J. (Ed.). (1981). *Biological rhythms* (Vol. 4). Plenum Press. <https://doi.org/10.1007/978-1-4615-6552-9>
- Aschoff, J. (1989b). Temporal orientation: Circadian clocks in animals and humans. *Animal Behaviour*, 37, 881–896. [https://doi.org/10.1016/0003-3472\(89\)90132-2](https://doi.org/10.1016/0003-3472(89)90132-2)
- Bivand, R., & Luque, S. (n.d.). *Suntools: Calculate sun position, sunrise, sunset, solar noon and twilight*. <https://doi.org/10.32614/CRAN.package.suntools>
- Bohlen, J. G., & Simpson. (1973). Latitude and the human circadian system. In J. N. Mills (Ed.), *Biological aspects of circadian rhythms* (pp. 87–120). Plenum Press. <https://doi.org/10.1007/978-1-4613-4565-7>
- Borbély, A. A. (1982). A two process model of sleep regulation. *Human Neurobiology*, 1(3), 195–204. <https://pubmed.ncbi.nlm.nih.gov/7185792/>
- Borbély, A. A., Daan, S., Wirz-Justice, A., & Deboer, T. (2016). The two-process model of sleep regulation: A reappraisal. *Journal of Sleep Research*, 25(2), 131–143. <https://doi.org/10.1111/jsr.12371>
- Brainard, G. C., Hanifin, J. P., Greeson, J. M., Byrne, B., Glickman, G., Gerner, E., & Rollag, M. D. (2001). Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor. *Journal of Neuroscience*, 21(16), 6405–6412. <https://doi.org/10.1523/JNEUROSCI.21-16-06405.2001>
- Buhr, E. D., & Takahashi, J. S. (2013). Molecular components of the mammalian circadian clock. In A. Kramer & M. Mrosovsky (Eds.), *Circadian Clocks* (pp. 3–27, Vol. 217). Springer. [https://doi.org/10.1007/978-3-642-25950-0\\_1](https://doi.org/10.1007/978-3-642-25950-0_1)
- Bulus, M. (n.d.). *{Pwrss}: Statistical Power and Sample Size Calculation*. <https://doi.org/10.32614/CRAN.package.pwrss>
- Cambon, J., Hernangómez, D., Belanger, C., & Posenriede, D. (2021). Tidygeocoder: An R package for geocoding. *Journal of Open Source Software*, 6(65), 3544. <https://doi.org/10.21105/joss.03544>
- Cambridge University Press. (n.d.). *Cambridge dictionary*. Retrieved September 21, 2023, from <https://dictionary.cambridge.org/>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.
- Cohen, J. (1992). A power primer. *Psychological Bulletin*, 112(1), 155–159. <https://doi.org/10.1037/0033-2909.112.1.155>

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\* In accordance with the American Psychological Association (APA) Style, 7th edition.

- Cohen, J. (1994). The earth is round ( $p < .05$ ). *American Psychologist*, 49(12), 997–1003. <https://doi.org/10.1037/0003-066X.49.12.997>
- Cold Spring Harbor Laboratory. (n.d.). 1960: *Biological clocks*, vol. XXV. Retrieved July 17, 2023, from <https://symposium.cshlp.org/site/misc/topic25.xhtml>
- DeGroot, M. H., & Schervish, M. J. (2012). *Probability and statistics* (4th ed.). Addison-Wesley.
- Duffy, J. F., Cain, S. W., Chang, A.-M., Phillips, A. J. K., Münch, M. Y., Gronfier, C., Wyatt, J. K., Dijk, D.-J., Wright, K. P., & Czeisler, C. A. (2011). Sex difference in the near-24-hour intrinsic period of the human circadian timing system. *Proceedings of the National Academy of Sciences*, 108, 15602–15608. <https://doi.org/10.1073/pnas.1010666108>
- Ecochard, R., Stanford, J. B., Fehring, R. J., Schneider, M., Najmabadi, S., & Gronfier, C. (2024). Evidence that the woman's ovarian cycle is driven by an internal circamonthly timing system. *Science Advances*, 10(15), eadg9646. <https://doi.org/10.1126/sciadv.adg9646>
- Ehret, C. F. (1974). The sense of time: Evidence for its molecular basis in the eukaryotic gene-action system. In *Advances in Biological and Medical Physics* (pp. 47–77, Vol. 15). Elsevier. <https://doi.org/10.1016/B978-0-12-005215-8.50009-7>
- Epstein, J. M. (1999). Agent-based computational models and generative social science. *Complexity*, 4(5), 41–60. [https://doi.org/10.1002/\(SICI\)1099-0526\(199905/06\)4:5<41::AID-CPLX9>3.0.CO;2-F](https://doi.org/10.1002/(SICI)1099-0526(199905/06)4:5<41::AID-CPLX9>3.0.CO;2-F)
- Flanagan, A., Bechtold, D. A., Pot, G. K., & Johnston, J. D. (2021). Chrono-nutrition: From molecular and neuronal mechanisms to human epidemiology and timed feeding patterns. *Journal of Neurochemistry*, 157(1), 53–72. <https://doi.org/10.1111/jnc.15246>
- Foster, R. G. (2021). Fundamentals of circadian entrainment by light. *Lighting Research & Technology*, 53(5), 377–393. <https://doi.org/10.1177/14771535211014792>
- Foster, R. G. (2020). Sleep, circadian rhythms and health. *Interface Focus*, 10(3), 20190098. <https://doi.org/10.1098/rsfs.2019.0098>
- Foster, R. G., & Kreitzman, L. (2005). *Rhythms of life: The biological clocks that control the daily lives of every living thing*. Profile Books.
- Frommlet, F., Bogdan, M., & Ramsey, D. (2016). *Phenotype and genotype: The search for influential genes* (Vol. 18). Springer London. <https://doi.org/10.1007/978-1-4471-5310-8>
- Haus, E., & Halberg, F. (1970). Circannual rhythm in level and timing of serum corticosterone in standardized inbred mature C-mice. *Environmental Research*, 3(2), 81–106. [https://doi.org/10.1016/0013-9351\(70\)90008-3](https://doi.org/10.1016/0013-9351(70)90008-3)
- Holland, J. H. (1992). Complex adaptive systems. *Daedalus*, 121(1), 17–30. Retrieved September 15, 2024, from <https://www.jstor.org/stable/20025416>
- Holland, J. H. (2006). Studying complex adaptive systems. *Journal of Systems Science and Complexity*, 19(1), 1–8. <https://doi.org/10.1007/s11424-006-0001-z>
- Holland, J. H. (2014). *Complexity: A very short introduction*. Oxford University Press.
- Horne, J. A., & Östberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, 4(2), 97–110.
- Horzum, M. B., Randler, C., Masal, E., Beşoluk, Ş., Önder, İ., & Vollmer, C. (2015). Morningness-eveningness and the environment hypothesis – a cross-cultural comparison of Turkish and German adolescents. *Chronobiology International*, 32(6), 814–821. <https://doi.org/10.3109/07420528.2015.1041598>
- Hut, R. A., Paolucci, S., Dor, R., Kyriacou, C. P., & Daan, S. (2013). Latitudinal clines: An evolutionary view on biological rhythms. *Proceedings of the Royal Society B: Biological Sciences*, 280(1765), 20130433. <https://doi.org/10.1098/rspb.2013.0433>

- Instituto Brasileiro de Geografia e Estatística. (n.d.). *Tabela 6407: População residente, por sexo e grupos de idade* (Table). Table. SIDRA. Retrieved November 16, 2023, from <https://sidra.ibge.gov.br/tabela/6407>
- Instituto Brasileiro de Geografia e Estatística. (2021). *Pesquisa nacional por amostra de domicílios contínua: Acesso à internet e à televisão e posse de telefone móvel celular para uso pessoal 2019*. Instituto Brasileiro de Geografia e Estatística. Rio de Janeiro, RJ. [https://biblioteca.ibge.gov.br/visualizacao/livros/liv101794\\_informativo.pdf](https://biblioteca.ibge.gov.br/visualizacao/livros/liv101794_informativo.pdf)
- Khalsa, S. B. S., Jewett, M. E., Cajochen, C., & Czeisler, C. A. (2003). A phase response curve to single bright light pulses in human subjects. *The Journal of Physiology*, 549(3), 945–952. <https://doi.org/10.1113/jphysiol.2003.040477>
- Krakauer, D., & Wolpert, D. (2024). The reality ouroboros [magazine]. *Nautilus*. Retrieved October 1, 2024, from <https://nautil.us/the-reality-ouroboros-809153/>
- Kronfeld-Schor, N., Visser, M. E., Salis, L., & van Gils, J. A. (2017). Chronobiology of interspecific interactions in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1734), 20160248. <https://doi.org/10.1098/rstb.2016.0248>
- Kuhlman, S. J., Craig, L. M., & Duffy, J. F. (2018). Introduction to chronobiology. *Cold Spring Harbor Perspectives in Biology*, 10(9), a033613. <https://doi.org/10.1101/cshperspect.a033613>
- Landau, W. (2021). The targets R package: A dynamic Make-like function-oriented pipeline toolkit for reproducibility and high-performance computing. *Journal of Open Source Software*, 6(57), 2959. <https://doi.org/10.21105/joss.02959>
- Latinitium. (n.d.). *Latin dictionaries*. Latinitium. Retrieved September 21, 2023, from <https://latinitium.com/latin-dictionaries/>
- Leocadio-Miguel, M. A., Louzada, F. M., Duarte, L. L., Areas, R. P., Alam, M., Freire, M. V., Fontenele-Araujo, J., Menna-Barreto, L., & Pedrazzoli, M. (2017). Latitudinal cline of chronotype. *Scientific Reports*, 7(1), 5437. <https://doi.org/10.1038/s41598-017-05797-w>
- Leocadio-Miguel, M. A., Oliveira, V. C. D., Pereira, D., & Pedrazzoli, M. (2014). Detecting chronotype differences associated to latitude: A comparison between Horne–Östberg and Munich Chronotype questionnaires. *Annals of Human Biology*, 41(2), 107–110. <https://doi.org/10.3109/03014460.2013.832795>
- Lewin, R. (1993). *Complexity: Life at the edge of chaos*. Collier Books.
- Mairan, J.-J. de. (1729). Observation botanique. *Histoire de l'Académie royale des sciences avec les mémoires de mathématique et de physique tirés des registres de cette Académie*, 35. Retrieved October 17, 2024, from <http://www.bibnum.education.fr/sciencesdelavie/biologie/observation-botanique>
- Maxwell, S. E., Delaney, H. D., & Kelley, K. (2018). *Designing experiments and analyzing data: A model comparison perspective* (3rd ed.). Routledge.
- Meeus, J. (1991). *Astronomical algorithms*. Willmann-Bell.
- Menna-Barreto, L., & Marques, N. (Eds.). (2023, August 16). *História e perspectivas da cronobiologia no brasil e na américa latina*. Editora da Universidade de São Paulo.
- Merrow, M., Spoelstra, K., & Roenneberg, T. (2005). The circadian cycle: Daily rhythms from behaviour to genes. *EMBO reports*, 6(10), 930–935. <https://doi.org/10.1038/sj.embor.7400541>
- Minors, D. S., Waterhouse, J. M., & Wirz-Justice, A. (1991). A human phase-response curve to light. *Neuroscience Letters*, 133(1), 36–40. [https://doi.org/10.1016/0304-3940\(91\)90051-T](https://doi.org/10.1016/0304-3940(91)90051-T)
- Mitchell, M. (2009). *Complexity: A guided tour*. Oxford University Press.
- National Aeronautics and Space Administration & Goddard Institute for Space Studies. (n.d.). *Data.GISS: Time and Date of vernal Equinox*. Retrieved November 24, 2024, from <https://data.giss.nasa.gov/modelE/ar5plots/srvernal.html>
- Neyman, J., & Pearson, E. S. (1928a). On the use and interpretation of certain test criteria for purposes of statistical inference: Part I. *Biometrika*, 20A(1/2), 175–240. <https://doi.org/10.2307/2331945>



- Neyman, J., & Pearson, E. S. (1928b). On the use and interpretation of certain test criteria for purposes of statistical inference: Part II. *Biometrika*, 20A(3/4), 263–294. <https://doi.org/10.2307/2332112>
- Nobel Prize Outreach AB. (n.d.). *Press release*. The Nobel Prize. Retrieved September 28, 2023, from <https://www.nobelprize.org/prizes/medicine/2017/press-release/>
- Paranjpe, D. A., & Sharma, V. K. (2005). Evolution of temporal order in living organisms. *Journal of Circadian Rhythms*, 3. <https://doi.org/10.1186/1740-3391-3-7>
- Partch, C. L., Green, C. B., & Takahashi, J. S. (2014). Molecular architecture of the mammalian circadian clock. *Trends in Cell Biology*, 24(2), 90–99. <https://doi.org/10.1016/j.tcb.2013.07.002>
- Pereira, E. B., Martins, F. R., Gonçalves, A. R., Costa, R., Lima, F. J. L., Rüther, R., Abreu, S. L., Tiepolo, G. M., Pereira, S. V., & Souza, J. G. (2017). *Atlas brasileiro de energia solar* (2nd ed.). Instituto Nacional de Pesquisas Espaciais. <https://doi.org/10.34024/978851700089>
- Pereira, R. H. M., & Goncalves, C. N. (n.d.). *Geobr: Download Official Spatial Data Sets of Brazil*. <https://doi.org/10.32614/CRAN.package.geobr>
- Perezgonzalez, J. D. (2015). Fisher, Neyman–Pearson or NHST? A tutorial for teaching data testing. *Frontiers in Psychology*, 6. <https://doi.org/10.3389/fpsyg.2015.00223>
- Pittendrigh, C. S. (1960). Circadian rhythms and the circadian organization of living systems. *Cold Spring Harbor Symposia on Quantitative Biology*, 25, 159–184. <https://doi.org/10.1101/SQB.1960.025.01.015>
- Pittendrigh, C. S. (1981). Circadian systems: General perspective. In *Biological rhythms* (pp. 57–80, Vol. 4). Plenum Press. <https://doi.org/10.1007/978-1-4615-6552-9>
- Pittendrigh, C. S. (1993). Temporal organization: Reflections of a darwinian clock-watcher. *Annual Review of Physiology*, 55(1), 17–54. <https://doi.org/10.1146/annurev.ph.55.030193.000313>
- Pittendrigh, C. S., Kyner, W. T., & Takamura, T. (1991). The amplitude of circadian oscillations: Temperature dependence, latitudinal clines, and the photoperiodic time measurement. *Journal of Biological Rhythms*, 6(4), 299–313. <https://doi.org/10.1177/074873049100600402>
- Pittendrigh, C. S., & Takamura, T. (1989). Latitudinal clines in the properties of a circadian pacemaker. *Journal of Biological Rhythms*, 4(2), 217–235. <https://doi.org/10.1177/074873048900400209>
- Popper, K. R. (1979). *Objective knowledge: An evolutionary approach*. Oxford University Press.
- Posit Team. (n.d.). *RStudio: Integrated development environment for R*. <http://www.posit.co>
- Qual o CEP. (2024, November). *Banco de cep e código ibge*. <https://www.qualocep.com/>
- R Core Team. (n.d.). *R: A language and environment for statistical computing*. Vienna, Austria. <https://www.R-project.org>
- Raj, A., & van Oudenaarden, A. (2008). Nature, nurture, or chance: Stochastic gene expression and its consequences. *Cell*, 135(2), 216–226. <https://doi.org/10.1016/j.cell.2008.09.050>
- Randler, C. (2008). Morningness–eveningness comparison in adolescents from different countries around the world. *Chronobiology International*, 25(6), 1017–1028. <https://doi.org/10.1080/07420520802551519>
- Randler, C., & Rahafar, A. (2017). Latitude affects morningness–eveningness: Evidence for the environment hypothesis based on a systematic review. *Scientific Reports*, 7(1), 39976. <https://doi.org/10.1038/srep39976>
- Rede Globo (**typedirector**). (2017, October 15). *Metade da população se sente mal no horário de verão, revela pesquisa* [tvbroadcast]. Rio de Janeiro, RJ, Rede Globo. <https://g1.globo.com/fantastico/noticia/2017/10/metade-da-populacao-se-sente-mal-no-horario-de-verao-revela-pesquisa.html>
- Reis, C. (2020). *Sleep patterns in portugal* [Doctoral dissertation, Universidade de Lisboa]. <http://hdl.handle.net/10451/54147>

- Reis, C., Madeira, S. G., Lopes, L. V., Paiva, T., & Roenneberg, T. (2020). Validation of the Portuguese variant of the Munich Chronotype Questionnaire (MCTQ-PT). *Frontiers in Physiology*, 11, 795. <https://doi.org/10.3389/fphys.2020.00795>
- Roenneberg, T. (2012). What is chronotype? *Sleep and Biological Rhythms*, 10(2), 75–76. <https://doi.org/10.1111/j.1479-8425.2012.00541.x>
- Roenneberg, T., Allebrandt, K. V., Mellow, M., & Vetter, C. (2012). Social jetlag and obesity. *Current Biology*, 22(10), 939–943. <https://doi.org/10.1016/j.cub.2012.03.038>
- Roenneberg, T., Kuehnle, T., Juda, M., Kantermann, T., Allebrandt, K., Gordijn, M., & Mellow, M. (2007). Epidemiology of the human circadian clock. *Sleep Medicine Reviews*, 11(6), 429–438. <https://doi.org/10.1016/j.smrv.2007.07.005>
- Roenneberg, T., Kumar, C. J., & Mellow, M. (2007). The human circadian clock entrains to sun time. *Current Biology*, 17(2), R44–R45. <https://doi.org/10.1016/j.cub.2006.12.011>
- Roenneberg, T., & Mellow, M. (2016). The circadian clock and human health. *Current Biology*, 26(10), R432–R443. <https://doi.org/10.1016/j.cub.2016.04.011>
- Roenneberg, T., Pilz, L. K., Zerbini, G., & Winnebeck, E. C. (2019). Chronotype and social jetlag: A (self-) critical review. *Biology*, 8(3), 54. <https://doi.org/10.3390/biology8030054>
- Roenneberg, T., Wirz-Justice, A., & Mellow, M. (2003). Life between clocks: Daily temporal patterns of human chronotypes. *Journal of Biological Rhythms*, 18(1), 80–90. <https://doi.org/10.1177/0748730402239679>
- Roenneberg, T., Wirz-Justice, A., Skene, D. J., Ancoli-Israel, S., Wright, K. P., Dijk, D.-J., Zee, P., Gorman, M. R., Winnebeck, E. C., & Klerman, E. B. (2019). Why should we abolish daylight saving time? *Journal of Biological Rhythms*, 34(3), 227–230. <https://doi.org/10.1177/0748730419854197>
- Sartor, F., Xu, X., Popp, T., Dodd, A. N., Kovács, Á. T., & Mellow, M. (2023). The circadian clock of the bacterium *B. subtilis* evokes properties of complex, multicellular circadian systems. *Science Advances*, 9(31), eadh1308. <https://doi.org/10.1126/sciadv.adh1308>
- Sayama, H. (2015). *Introduction to the modeling and analysis of complex systems*. Open SUNY Text-books.
- Shackelford, J. (2022). *An introduction to the history of chronobiology: Biological rhythms emerge as a subject of scientific research*. University of Pittsburgh Press.
- Shatz, I. (2024). Assumption-checking rather than (just) testing: The importance of visualization and effect size in statistical diagnostics. *Behavior Research Methods*, 56(2), 826–845. <https://doi.org/10.3758/s13428-023-02072-x>
- Silvério, J. T., Tachinardi, P., Langrock, R., Kramer-Sunderbrink, A., Oda, G. A., & Valentinuzzi, V. S. (2024). Changes in daily activity patterns throughout the year in a free-living South American subterranean rodent (*Ctenomys coludo*). *Mammalian Biology*. <https://doi.org/10.1007/s42991-024-00470-y>
- Skeldon, A. C., & Dijk, D.-J. (2021). Weekly and seasonal variation in the circadian melatonin rhythm in humans: Entrained to local clock time, social time, light exposure or sun time? *Journal of Pineal Research*, 71(1), e12746. <https://doi.org/10.1111/jpi.12746>
- Thapan, K., Arendt, J., & Skene, D. J. (2001). An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans. *The Journal of Physiology*, 535(1), 261–267. <https://doi.org/10.1111/j.1469-7793.2001.t01-1-00261.x>
- Time and Date AS. (n.d.). *Solstices & equinoxes for UTC (2000–2049)*. Retrieved November 24, 2024, from <https://www.timeanddate.com/calendar/seasons.html?year=2000&n=1440>
- Ushey, K., & Wickham, H. (n.d.). *Renv: Project environments*. <https://doi.org/10.32614/CRAN.package.renv>
- Vartanian, D. (n.d.). *{Mctq}: Munich ChronoType Questionnaire tools*. <https://docs.ropensci.org/mctq/>

- von Bertalanffy, L. (1968). *General system theory: Foundations, development, applications*. George Braziller.
- Wang, H., Wang, S., Yu, W., & Lei, X. (2023). Consistency of chronotype measurements is affected by sleep quality, gender, longitude, and latitude. *Chronobiology International*, 40(7), 952–960. <https://doi.org/10.1080/07420528.2023.2237118>
- Wasserstein, R. L., & Lazar, N. A. (2016). The ASA statement on p-values: Context, process, and purpose. *The American Statistician*, 70(2). <https://doi.org/10.1080/00031305.2016.1154108>
- Watson, N. F., Badr, M. S., Belenky, G., Bliwise, D. L., Buxton, O. M., Buysse, D., Dinges, D. F., Gangwisch, J., Grandner, M. A., Kushida, C., Malhotra, R. K., Martin, J. L., Patel, S. R., Quan, S. F., & Tasali, E. (2015). Recommended amount of sleep for a healthy adult: A joint consensus statement of the American Academy of Sleep Medicine and Sleep Research Society. *Journal of Clinical Sleep Medicine*, 11(6), 591–592. <https://doi.org/10.5664/jcsm.4758>
- Wickham, H. (2023, February 23). *The tidy tools manifesto*. Tidyverse. Retrieved July 18, 2023, from <https://tidyverse.tidyverse.org/articles/manifesto.html>
- Wickham, H., Çetinkaya-Rundel, M., & Grolemund, G. (2023, July 18). *R for data science: Import, tidy, transform, visualize, and model data* (2nd ed.). O'Reilly Media. <https://r4ds.hadley.nz>
- Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., Da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., ... Mons, B. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data*, 3(1), 160018. <https://doi.org/10.1038/sdata.2016.18>