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„The Influence of Chronotype and Sleep Behavior on Effort Mobilization"

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Content

Abstract

Social demands like early school timetables or work schedules can conflict with peoples' chronotype resulting in a circadian mismatch. According to the principles of fatigue analysis and the motivational intensity theory (MIT) a circadian mismatch should result in more fatigue and therefore more effort mobilization. To gain insight on how chronotype affects performance and effort mobilization a repeated measure design was used. After prescreening for suitable participants with either a morning or evening chronotype N=36 participants completed a low and a high difficult version of the N-back task during both, a circadian match and mismatch. Effort-related cardiovascular (CV) reactivity as change from baseline in cardiac pre-ejection period (PEP) and systolic blood pressure (SBP) were assessed as key dependent variables. As results showed that performance was the same during a circadian match and mismatch it was expected that participants would need to invest more effort for that same performance during a mismatch. However, results showed the contrary in the way that participants invested less effort, indicated through both PEP and SBP responses, during a mismatch. While Social Jetlag (SJL) and Individual lack of sleep (ILS) were expected to moderate the effect chronotype has on effort mobilization and performance, they did not. Explorative findings showed that both effort and performance improved from the first to second in-lab session, suggesting a training effect. Interestingly the training effect was only significant when completing the task during a circadian match first. Controversial findings emphasize the need for more research on the topic of chronotype and effort mobilization.
Keywords: Chronotype; Circadian Rhythm; Circadian Mismatch; Effort; Cardiovascular measures; Performance; Sleep; Social Jetlag

German Abstract

Gesellschaftliche Anforderungen wie frühe Schul- oder Arbeitszeiten berücksichtigen häufig nicht die individuelle innere Uhr der Menschen, also die Präferenzen verschiedener Chronotypen. Arbeitet oder lernt ein Mensch zu einer Tageszeit, die im Gegensatz zu seiner inneren Uhr (Chronotyp) steht, führt das zu einer zirkadianen Fehlanpassung. Entsprechend den Grundsätzen der Ermüdungsanalyse sowie der Motivationalen Intensitätstheorie (MIT) sollte eine zirkadiane Fehlanpassung zu mehr Erschöpfung und damit zu mehr Anstrengungs-mobilisierung führen. Um Erkenntnisse darüber zu gewinnen, in welcher Weise der Chronotyp die Leistung und die Anstrengungsmobilisierung intraindividuell beeinflusst, wurde ein Messwiederholungsdesign verwendet. Nach Vorauswahl geeigneter Teilnehmer:innen mit morgendlichem oder abendlichem Chronotyp, absolvierten N=36 Teilnehmende eine N-Back-Aufgabe in niedriger und hoher Schwierigkeitsstufe, einmal morgens und einmal abends. Entsprechend absolvierte jede(r) Teilnehmende die Studie einmal zu einer Tageszeit, die mit der inneren Uhr des eigenen Chronotyp übereinstimmte (Match) und einmal dieser entgegengesetzt war (Mismatch). Die anstrengungsbezogene kardiovaskuläre Reaktivität, gemessen als Veränderung der kardialen prä-Ejektionsperiode (PEP) und des systolischen Blutdrucks (SBP), bildeten die abhängigen Variablen. Da die Ergebnisse zeigten, dass die Leistung während eines Chronotyp Match und Mismatch gleich war, wurde erwartet, dass die Teilnehmenden während eines Mismatch mehr Anstrengung für die gleiche Leistung aufwenden müssten. Die Ergebnisse wiesen jedoch das Gegenteil auf. Teilnehmende während eines Mismtach zeigten weniger Anstrengung, sowohl in der Veränderung von PEP als auch SBP. Weiter wurde erwartet, dass sozialer Jetlag (SJL) und individueller Schlafmangel (ILS) als Moderatoren die Auswirkungen des Chronotyps auf die Anstrengungsmobilisierung und die Leistung abschwächen würden, was nicht der Fall war. Explorative Analysen zeigten, dass sich sowohl Anstrengung als auch Leistung von der ersten zur zweiten Laborsitzung verbesserte, was auf einen Trainingseffekt schließen lässt. Interessanterweise war dieser nur dann signifikant, wenn die Aufgabe zuerst während eines Chrontype Match absolviert wurde. Die kontroversen Ergebnisse der Studie unterstreichen, dass weitere Forschung zum Thema Chronotyp und Anstrengungsmobilisierung nötig ist.

Schlüsselwörter: Chronotyp; zirkadianer Rhythmus; zirkadiane Fehlanpassung; Anstrengung; kardiovaskuläre Maße; Leistung; Schlaf; sozialer Jetlag

1. Introduction and theoretical background

Life on earth follows a 24-hour cycle. In addition to animals and plants, humans have also evolutionarily adapted to this rhythm and developed their own internal clock in accordance with light-dark, nutritional and temperature cycles (Persson & Persson, 2018). The human body has a chronobiological (circadian) rhythm that runs circularly over the course of about 24 hours controlling different levels of physiology, from metabolism to behavior (Roenneberg et al., 2019). Roughly speaking, this rhythm determines whether people are active or asleep. The circadian rhythm is endogenous but can be influenced by external Zeitgeber such as sunlight or artificial light and is believed to alter over the lifespan (Roenneberg, & Merrow, 2007). Within puberty most adolescents however shift toward an evening preference (Fischer et al. 2017; Roenneberg et al., 2004). According to this rhythm, it is easier or harder for individuals to get up early and it influences how efficient someone performs at a certain time of day (Schmidt et al., 2007). While most of the population has a neutral chronotype, there is a not inconsiderable proportion of people with moderate or extrem chronotypes whose circadian rhythms do not match the demands of their environment (Roenneberg et al., 2019; Taillard et al., 2004). People whose circadian rhythm is slightly shorter than 24 hours, known as *larks*, find it comparatively easier to get up early, but more difficult to remain awake later at night. On the other end of the continuum are people with an extreme evening preference and a rhythm longer than 24 hours, known as *owls*. In comparison to neutral chronotypes larks and owls experience a shift in their peaks and troughs of physiological circadian markers (e.g., melatonin). Whilst appearing earlier in larks, they occur delayed in owls with respect to the local time (Baehr, Revelle, & Eastman, 2000; Bailey & Heitkemper, 2001; Duffy, Rimmer, & Czeisler, 2001). People tending more towards a morning type are alert early in the morning while being fatigued later in the day. On the contrary, people tending towards an evening type are comparatively fatigued in the morning and alert later in the day. *Circadian mismatch* generally exists when people must perform at times that are sup-optimal regarding their chronobiological (circadian) rhythm.

The impact of chronotype has been researched in various areas. So far studies have shown that chronotype influences athletic (Vitale & Weydahl, 2017) and academic performance (Díaz-Morales & Escribano, 2015; Merikanto et al., 2013), general health (e.g., dietary outcomes; for review, see Mazri et al., 2019) and mental health (Alvaro et al., 2014; Haraden et al., 2019; Melo et al., 2017; Merikanto et al., 2013). Two areas which might be of special relevance within chronotype research are the work and school environment. Whereas trends in the working environment are starting to adjust schedules to individual preferences, other areas such as education lag behind. Studies have illustrated that the biological circadian rhythm of high school students, especially teenagers, is shifted back by one hour compared to adults. While the growth hormone secretion reaches its maximum (and cortisol its minimum) later in the day amongst teenagers, social demands of adolescents are also dominant in evening hours making it more likely for them to go to bed later (Alvaro et al., 2014; Haraden et al., 2017; Roenneberg et al., 2004). This can not only impair their performance at school but also lead to serious health issues. Owls have been associated with poorer sleep quality than neutral or morning chronotypes (Walsh et al., 2021). Sleep disturbance have been linked to mental health issues (for review, see Scott et al., 2021). Adolescents with late chronotypes are more likely to be emotionally affected throughout the day at school and furthermore sleep less than other chronotypes (Díaz-Morales et al., 2015). Recent research shows that most adolescents not only prefer later school starting times, but also see improvement on sleep and other health-related problems when school starting times are being delayed (Werner et al., 2022). Flexible school starting times also increased sleep quality (Winnebeck et al., 2020) and these sleep improvements sustained in a follow up study (Biller et al., 2022). Nevertheless, early school start times have not generally been adjusted.

Since a circadian mismatch affects various aspects of our daily life it is important to better understand the precise pathway it uses to influence everyday behavior. An initial step taken to understand this pathway were Carbajal and colleagues (2019) who found that a circadian mismatch can influence effort mobilization, one major component of goal pursuit (Richter, 2015). Through the utilization of cardiovascular correlates of effort mobilization Carbajal and colleagues (2019) were able to analyze the relationship between effort and circadian mismatch while avoiding the common pitfalls of self-reported effort assessments (e.g., low reliability) (for review, see Obrist, 1981). This master thesis was designed to replicate and extend findings from Carbajal and colleagues (2019) by analyzing the influence of circadian mismatch on effort-related cardiovascular (CV) responses while including social jetlag (SJL) and the individual lack of sleep (ILS) as possible moderators of the model. This thesis provides a deeper understanding on how chronotype and behavioral sleep patterns influence effort mobilization. Insights of this study can help building a case to reconsider early school start times or avoid subjects that require a lot of cognitive effort within the first school hours.

Research question: *How do chronotype, social jetlag and individual lack of sleep influence effort mobilization when completing a low and high difficulty task in the morning or at night?*

1.2. Chronotype and motivational intensity theory

People experience individual differences in their daily sleep patterns and alertness. Some report falling asleep and waking up early, and generally feel most alert during earlier periods of the day (larks), whereas the reverse is true for others experiencing a much later timing (owls) (for review, see Adan et al., 2012; Roenneberg, Wirz-Justice, & Merrow, 2003). A review conducted by Fabbian and colleagues in 2016 found that owls are generally more affected as their chronotype tendency has been associated with impairments in (1) general unhealthy habits (i.e., smoking and alcohol consumption), (2) mental health (i.e., impulsivity and anger, depression, risk taking behavior or psychopathology), (3) sleep and sleep related behavior (i.e., irregular sleep-wake schedule, poor sleep quality or school performance and motivation) and (4) the educational environment (i.e., lower mood). This was supported by more recent work that highlighted that evening chronotypes had significantly more severe symptomology of depression and anxiety, in addition to poorer sleep quality, than morning or neutral chronotypes (Walsh et al., 2022). Adolescence, reporting an evening chronotype had also been linked to attentional deficits (Giannotti et al., 2002). However, few of these studies have focused on the underlying mechanisms that produce these outcomes. While a recent four-year longitudinal study did not find an effect of chronotype on grades at school (Biller et al., 2022), this study might have missed the underlying impact that chronotype had on invested effort, as it was not measured in the study. To better understand these underlying mechanisms my master thesis integrates the well-known motivational intensity theory (MIT) (Brehm & Self, 1989; for review see also Richter et al., 2016) into the previous research concerning circadian mismatch.

1.3. Effort mobilization and cardiovascular response

Previous research concerning MIT has investigated the effects of fatigue on effort mobilization and associated CV response (Wright, 2014; Wright and Mlynski, 2019; Wright et al., 2018, Wright et al., 2019, Wright and Stewart, 2012). These studies have consistently shown three core principles. First, CV responses, especially those related to beta-adrenergic stimulation of the heart, vary with effort in response to a performance challenge. The more effort a person invests, the stronger should be the associated CV response (Obrist, 1976, 1981). Second, as long as success is seen as possible and worthwhile effort should correlate with task difficulty (Brehm & Self, 1989). Thus, effort mobilization should increase with higher task difficulty, but should be low when tasks are perceived as too difficult, given the importance of success, and therefore not worthwhile. This illustrates the energy/resource conversation principle that people seek to avoid investing effort in tasks that seem impossible or not worth the effort and would therefore waste resources (Richter, 2013). Lastly, the perceived difficulty of a performance task increases with fatigue. Accordingly, people who are fatigued perceive a performance challenge of all difficulty levels as more difficult compared their rested counterparts (Ackerman, 2011; Fairclough, 2000; Fairclough & Graham, 1999; Hockey, 1997). Thus, people who are more fatigued need to invest more effort on a similar task compared to those who are less fatigued when both perceive the task to be possible and worthwhile. This is of particular importance when including chronotype and behavioral sleep patterns in this line of research.

1.4. Circadian mismatch and CV response – Study by Carbajal and colleagues (2019)

This study builds up on a recent study that introduced chronotype, specifically circadian mismatch, into the existing fatigue analysis literature (Carbajal et al., 2019). Considering the theoretical framework people who must perform at suboptimal times, hence experience a circadian mismatch should be more fatigued. As displayed in Figure 1, mismatched performers show stronger effort mobilization and associated CV responses compared to matched performers, as long as they see success as possible and worthwhile. Further mismatched performers should withhold effort at a lower (objective) difficulty level than their matched counterparts. However, if a task is difficult enough, both matched and mismatched performers should withhold effort, as the task is too difficult for all performers to be worthwhile given the level of success importance. If both matched and mismatched performers view success as possible, the importance of success should moderate the relationship between chronotype on the one hand and effort and associated CV responses on the other hand. Whilst research concerning the incorporation of circadian mismatch into the fatigue model is limited, the fatigue model itself is well tested and experienced empirical support (for reviews, see Gendolla et al., 2012, Gendolla et al., 2019; Richter et al., 2016; Wright and Stewart, 2012). A person's perceived level of effort and fatigue differs throughout the day in respect to their chronotype (Anderson et al., 2018; Kunorozva et al., 2014; Vitale et al., 2017; Vitale and Weydahl, 2017). Performance peaks differ within the day as individuals have a specific time of day when they are able to perform at their peak efficiency while this timing is influenced by an individual's chronotype (Schmidt et al., 2007). For example, owls feel more fatigued early in the day but feel more energetic in later hours. Therefore, the perceived task difficulty and accordingly effort mobilization should be different when completing the same task at two different times during the same day. Accordingly, when completing the same task twice, once in the morning and once at night an owl will see the same task as more difficult in the morning because of the circadian mismatch. Therefore, an owl should also need to put forth more effort on the very same task in the morning than at night, if they view the task as possible and worthwhile at both time points.

Carbajal and colleagues (2019) were the first to investigate how a circadian mismatch effects effort mobilization, indicated through CV responses. The study followed a between subject design and thereby investigated the topic on an interindividual level. The researchers reported mixed results including several limitations. While systolic blood pressure (SBP) and mean arterial pressure (MAP) responses recorded during the tasks formed the predicted crossover pattern, being positively correspondent to difficulty in the matched condition but negatively to difficulty in the mismatch condition, this effect was only observed amongst women. Furthermore, heart rate (HR) and pre-ejection period (PEP) scores ran parallel in the morning, but not the evening. Supporting expectations, within the matched condition, effort was generally higher in the difficult task compared to the easy task. Equally, in the mismatch condition people put forth more effort on the easy task and less effort on the difficult task (Carbajal et al., 2019).

While Carbajal and colleagues (2019) were able to illustrate the core predictions of the extension many limitations existed, which I address with my thesis. (1) It only examined larks. In my thesis I looked at both, morning, and evening chronotypes enabling the extension of the works to different types of circadian mismatches. (2) It was conducted between participants not allowing for control of person level factors (e.g., ability). I instead conducted a within person repeated measure design making it possible to extend the research to an intraindividual level. (3) Results of the original study showed negative cardiovascular change scores for MAP and SBP in multiple conditions. This is problematic as negative cardiovascular change scores in blood pressure measures represent a high probability of a measurement error. This can be explained by the fact that CV baseline values should measure a state of complete rest. Correspondingly, whenever a person engages in a task the CV response should always be higher than the baseline value, resulting in a positive cardiovascular change score. Accordingly, I have implemented a longer more thorough baseline phase to ensure participants are measured at complete rest.

Theoretical model

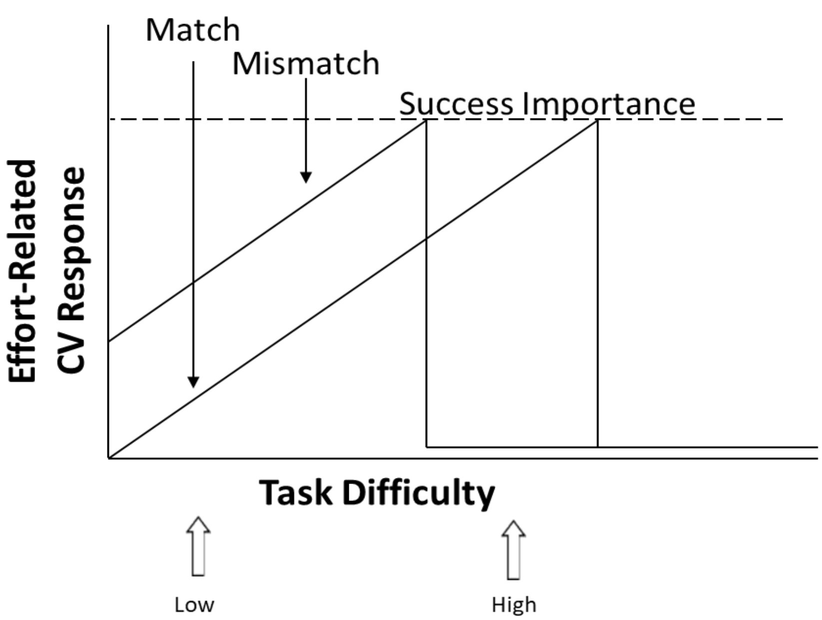

Figure 1. Effort as a function of circadian match/mismatch, difficulty, and success importance, with associated cardiovascular responses following.

1.5. Social Jetlag and Individual Lack of Sleep

The study extends the research by further including SJL and ILS as possible determinants of effort mobilization. Both, to the best of my knowledge, have yet to be considered in this line of research. SJL first introduced in 2006 (Castilhos Beauvalet et al., 2017; for recent review also see Roenneberg et al., 2019) is an additional factor of circadian misalignment. It describes and quantifies the chronic discrepancy between the sleep behavior on work and free days. It could also be understood as the difference between people's biological clock and the social clock (Wittmann et al., 2006). On the one hand, the biological clock depicts the natural sleep pattern according to the individual chronotype. People can follow their biological clock whenever they are not confronted with other environmental demands e.g., on free days. On the other hand, the social clock accounts for general social demands such as work or school starting times. Accordingly, the social clock is especially dominant on work or school days when people align their wake-up times with their social rather than their biological clock. As a result, owls, who are facing a later biological timing whilst exposed to early social demands, are more likely to accumulate a sleep depth throughout work or school days (Wittmann et al., 2006). The strain that goes along with SJL, unlike normal jetlag, is likely to be experienced on a weekly basis. This is of importance as evidence showed that a major component in a variety of cognitive performance tasks, vigilant attention, is impaired in sleep deprived people (Stepan et al., 2021). Adding to this, a recent study on vigilant attention showed that performance deficits rise with consecutive days of sleep restriction, whereas the perceived sleepiness shows an adaptation pattern (Hudson et al., 2020). Considering this, SJL could be seen as a chronic sleep depth that accumulates throughout workdays and that is in consequence compensated for on free days. However, weekend recovery sleep is likely not a sufficient behavioral strategy to compensate for all the deficits caused by insufficient sleep on consecutive working days (Depner et al., 2019). Instead, sufficient sleep should be aimed for daily. Throughout the week especially people with fixed timetables, such as high school students, teachers or workers with obligations in early hours are confronted with early wake up times, that might be conflicted with their chronotype. Considering a person who experiences a SJL of two hours, he/she might adapt and learn to live with it although this person's cognitive performance might be impaired, or the person needs to invest more effort for it. Accordingly, SJL should correlate with a person's objective fatigue level and therefore making tasks seem more difficult. Ultimately this person should need to put more effort in tasks and disengage at a lower difficulty level compared to a person with less SJL.

ILS depicts the difference between the self-reported individual need for sleep and the actual total sleep duration on a daily basis. While there is an agreement that a sleep duration of less than six hours and more than ten hours is not recommended for adults (Hirshkowitz et al., 2015) the exact amount of sleep a person needs to feel rested is likely to differ between people. This study therefore emphasizes the role of individual sleep preferences while integrating it into previous research about the consequences of impaired sleep. Fatigue due to sleep loss has been associated with deficits in cognitive performance, (Jackson & Van Dongen, 2011; Killgore, 2010; Lim & Dinges, 2010) academic performance (Díaz-Morales & Escribano, 2015; Haraszti et al., 2014) and with increased risk of errors and accidents (Dinges, 1995; Philip et al., 2004). Rather than comparing a person's sleep duration to a standardized number, e.g., eight hours which are commonly recommended (Hirshkowitz et al., 2015), this study instead wants to compare the actual sleep duration to the individual need for sleep. Accordingly, a person's fatigue level should increase with their ILS resulting in them viewing all tasks as more difficult. Ultimately this person will need to invest more effort on tasks and disengage from a task at a lower difficulty level.

1.6. Current study and hypotheses

To accomplish the aims of this study individuals, predetermined as either larks or owls, will need to complete an easy and difficult cognitive task during a morning and evening timeslot. This creates a repeated measure, 2 circadian mismatch (match versus mismatch) x 2 task difficulty (high versus low) within subject factorial design. A chronotype match or mismatch results from connecting a person's chronotype with the morning or evening condition. An owl for example experiences a chronotype match in the evening as this is the preferred time of day but faces a circadian mismatch when coming into the lab in the morning.

Based on the original study by Carbajal and colleagues (2019) and considering the additional theoretical framework presented this study assumes the following hypotheses:

H1*: During a chronotype match participants show less effort mobilization on a task of low difficulty, indicated through cardiovascular reactivity than during a circadian mismatch.*
H1a*: SJL and ILS moderate the effect chronotype has on effort mobilization. The more SJL/ ILS participants report the more effort mobilization should be indicated through cardiovascular reactivity, on a task of low difficulty.*
H2*: During a chronotype match participants show more effort mobilization on a task of high difficulty, indicated through cardiovascular reactivity than during a circadian mismatch.*
H2a: *The more SJL / ILS the less effort mobilization should be indicated, through cardiovascular reactivity, on a task of high difficulty.*
H3: *Performance should be worse when participants are asked to complete a task of high difficulty during a circadian mismatch, than at any other measurement point*
H3a*: The more SJL/ ILS participants report, the worse their performance on a task of high difficulty should be in the morning.*

2. Method

All ethical and research guidelines were followed for the study. The study was pre-registered and can be accessed through the following link: https://aspredicted.org/blind.php?x=BC8_MCQ.

2.1. Study Design & Procedure

The study consisted of two parts, an online study and an experimental in-lab study.

2.1.1. Online Procedure

The online study was split up into two sections. The first was used to screen for suitable participants. Scores of the Morningness Eveningness Questionnaire (MEQ) (Horne & Ostberg, 1976) determined whether participants met the requirement of either being a morning or an evening chronotype. For the study's purpose scores ranging from 14-30 (definite evening type) and 31-41 (moderate evening type) were classified as evening type, while scores from 59-69 (moderate morning type) and 70-86 (definite morning type) defined a morning type. People who reported a neutral chronotype (scores: 42-58) were excluded from the study. Further hypertension, existing heart condition and wearing a pacemaker were defined as exclusion criteria and retrieved subsequently. Participants that met all requirements filled out pre task questionnaires including information about their ILS. The first part ended by having participants complete the N1 and N3 version of the N-back task, a commonly used working memory task in research concerning mental effort (Jaeggi et al., 2010). In presenting participants the N-back tasks in the online study they were already familiar with it when completing it in-lab. Doing so I wanted to counteract possible training effects. After each N-back task participants filled out post task questionnaires about the perceived difficulty of the N-back task and how important it was to them to be successful in the previous N-back task. Also, demographic data was queried before they were debriefed from the online study. Afterwards participants received a personal e-mail with a standardized information letter about the further procedure of the study. It included a link through which participants were able to sign-up for the first of two in-lab sessions.

2.1.2. In-lab Procedure

According to the study design, each participant came into the lab twice, once in the morning between 7 -10 a.m. and once in the evening between 7 – 10 p.m. Both times, they were able to choose between two timeslots, one from 7-8.30 am/pm and one from 8.30-10 am/pm. Each lab timeslot required participants to complete an easy (N1) and a difficult (N3) version of the N-back task. Participants were run individually by one of three experimenters, all males. Once in lab, participants were welcomed and guided to a desk featuring a computer monitor with an available mouse, consent form and data protection form. The consent form included detailed information about the procedure of the study, especially about the measurement of cardiovascular data. It was explained that blood pressure, HR and PEP are measured non-invasively using a CNAP arm cuff and four painless electrodes. After reviewing and agreeing to both forms, participants were given a baseline mood checklist, the multidimensional mood questionnaire (MDBF) (Steyer et al.,1997) to assess the fatigue level at baseline and a pre task questionnaire. The latter consisted of questions regarding last night’s sleep behavior both qualitative and quantitative, yesterday’s smartphone usage after 9 p.m. and daily and regular caffeine intake. Participants were additionally asked if they took a nap during the day. Subsequently the assigned individual experimenter provided the participant with an overview of the following procedure, before applying electrodes and the CNAP arm cuff. Four disposable spot electrodes were placed on each side of the participant's neck and torso. The CNAP arm cuff was applied on their non-dominant arm to avoid measurement distortions due to movement during the task. Moreover, participants were asked not to move during the measurement.

When fully equipped the participant started a three-part process that included (1) the CV baseline, (2) the easy or difficult N-back task and (3) a post task questionnaire. To assess the cardiovascular baseline participants listened to relaxing music on YouTube for ten minutes. However, only the last two minutes were used to calculate the CV baseline that should reflect a state of complete rest. The following N-back task was carried out digitally on the computer. While performing the N-back task CV data was recorded. The post task questionnaire was displayed on the screen automatically as soon as the N-back task was completed. It included two questions that assessed the subjective success importance and the perceived task difficulty, both rated on a 10-point likert scale. This process was then repeated in the opposite, either easy or difficult condition depending on the condition that was randomly assigned to the participant in the first round.

Depending on whether the first in-lab session was completed in the morning or evening condition, the participant needed to repeat the in-lab procedure in the other condition. A participant that chose to come into the lab at night for the first in-lab session had then to sign up for a timeslot in the morning. Also, the difficulty of the N-back tasks was presented in the reversed pattern. Accordingly, someone who did the difficult N-back task first in the first in-lab session was than given the opposite, easy N-back task first in their second in-lab session. After completing the study at both times points, the experimenter went over a few general questions pertaining to the study with the participant (e.g., familiarity with the N-back task, aim of the study and a check whether the participant thought the study used deception). Afterwards the participant was fully debriefed.

2.2. Sample Size and Chronotype Assessment

Participants were recruited through the LABS system, an internal database for current studies ran at the University of Vienna. In order to obtain statistically meaningful results a power analysis was carried out beforehand to determine a suitable sample size. Based on guidance from Perugini and colleagues (2014) a power analysis (G*Power 3.1) for a repeated-measures ANOVA for the effect size obtained from Carbajal and colleagues (2019), i.e., partial eta squared = 0.011, an alpha of 0.05 (two-tailed) and a power of $1- \beta = 0.80$ was accomplished. Results revealed a total sample size of 120, to achieve a power of 80% and an effect size of .20.

Chronotype was measured in the online questionnaire using the German version of the Morning Eveningness Questionnaire (MEQ-D) (Griefahn et al., 2001) categorizing participants into one of five chronotype types (definite evening type, moderate evening type, neutral type, moderate morning type, definite morning type). The questionnaire operationalizes chronotype as a trait and consists of 19 self-reporting items covering different aspects of individual preferences for activities at specific times throughout a day (e.g.: *"If you had no commitments the next day, what time would you go to bed compared to your usual bedtime?")* (Horne & Ostberg, 1976, Griefahn et al., 2001).

377 participants completed the online study of which N=140 met the requirement of being either a morning or evening chronotype. N=97 provided their E-mail address which was required to participate in the consecutive in-lab part as participants were invited and instructed by E-mail. The final sample consisted of N=36 participants who completed both in-lab sessions. 80,6% of the participants were women, 16,7% male and 2,8% non-binary. The participants age ranged from 18 to 40 years (M= 23,31; SD=5.28). Regarding the distribution of chronotypes, except one extreme morning type (N = 1, 2.9%) the sample consisted of 38,8% (N = 14) moderate morning and 58% (N = 21) evening chronotypes. Chronotype was assessed as grouping variable with a final distribution of 42% (15) morning chronotypes and 58% (21) evening chronotypes.

2.3. Operationalization

2.3.1. Chronotype and Social Jetlag

The German core version of the Munich Chronotype Questionnaire (MCTQ-Core) (Roenneberg et al., 2003) consisting of 17 items was used to obtain behavioral insights about regular sleep patterns and calculate SJL. The MCTQ served as a complement to also assess chronotype on a behavioral level by asking questions about daily sleep-wake cycles. Items provided information about bedtime, time spent in bed awake before deciding to turn off the lights (prepare for sleep), sleep latency, wake-up time (sleep offset), and get-up time, while each stage was visualized by iconic pictures. The questions were asked separately for workdays and work free days, as the sleep and wake behavior on free days might closer reflect the natural circadian rhythm since it is not confounded by social demands, like early wake up times. Using sleep onset, which is calculated by adding sleep latency to the time of sleep preparation and sleep offset the MCTQ provides the point of mid sleep. The point of mid sleep on work free days (MSF) was used to assess chronotype and had previously shown to be an accurate marker for the circadian rhythm (Kantermann et al., 2015). As a result, chronotype as measured in the study, reflected both the typical timing of the sleep-wake behavior cycles and subjective preferences of daily activities and feelings of alertness.

SJL was measured by computing the difference between MSF and the midsleep on workdays (MSW), both provided by the MCTQ. Negative values of SJL express that a person's MSW is earlier than their MSF, making it more likely that this person slept in longer on their free days but had to get up earlier on working days. The opposite holds true for positive values of SJL.

2.3.2. Individual lack of sleep

ILS was operationalized as the difference between self-reported individual need for sleep and the actual total sleep duration from the previous night. Individual need for sleep was assessed with a single item *"How many hours of sleep do you personally need to be rested before a workday* **?" (**adapted from Hublin et al., 2001; Ursin et al., 2005).

2.3.3. N-back task difficulty and Performance

Task difficulty and performance were determined and measured using a recognition working memory task (N-back task). The N-back task is a commonly used performance task, assessing working memory in psychology and cognitive neuroscience (Jaeggi et al., 2010). Within the task participants had to determine whether a target letter fulfills the previous instructed criteria. The low difficulty condition (N1) required pressing the letter “A” on the keyboard whenever the previous target letter was the same as the presented letter. In the high difficult condition (N3) participants had to press “A” whenever the presented letter was the same as the third to last letter. Each N-back task consisted of 15+ trials (Ragland et al., 2002) in which each letter was presented for 500ms followed by an additional 2000ms gap before the next letter in the sequence was presented. Participants had the total time of 2500ms to respond by pressing “A” whenever they detected the target letter. Performance was measured as the number of incorrect responses, resulting in a percentage score ranging from 0-100%.

2.3.4. Perceived Difficulty and Success Importance

Perceived Difficulty of the N-back tasks and the individual success importance were measured through single items. Both items were answered on a 10-point likert-scale, providing a subjective evaluation.

2.3.5. Cardiovascular Responses

Effort related CV responses were measured using Electrocardiogram (ECG) and thoracic impedance (impedance cardiogram, ICG). Signals were sampled using a Cardioscreen 1000 system (medis, Ilmenau, Germany), allowing for cardiac PEP and HR determination. PEP is an index of cardiac contractility, while lower PEP values indicate stronger heart contractility (Newlin & Levenson, 1979; Kelsey, 2012). HR was quantified in beats per minute (bpm). Furthermore, a Dinamap Carescape V100 monitor (GE, Freiburg, Germany) was used which utilizes one armband to record blood pressure including SBP, dystolic blood pressure (DBP) and MAP. Blood pressure values were quantified in millimeters of mercury (mmHg). For all CV responses reactivity scores were computed by subtracting the average value obtained from the last two minutes of a 10-minute baseline period from the average value obtained during the entirety of the difficult or easy N-back task. This resulted in two distinct reactivity scores being produced for each CV measure from each lab session.

With the expectation that PEP and SBP would be especially correspondent to effort, SBP and PEP are the main variables of interest for the purpose of this study. Therefore HR, DBP and MAP will not be reported in the main text.

2.4. Statistical Analyses

To analyze the data multiple hierarchical linear models (HLM) were computed in the statistic software R. Chronotype was assessed as group variable. Time of day, task difficulty and the interaction of both was nested within participants.

2.4.1. Cardiovascular Measures

CV responses were operationalized as change from baseline (Δ) and are displayed in a separate model for each cardiovascular Δ score in each condition. Cardiovascular Δ scores show how effort changed from when participants did nothing to when they performed a task. To test the hypotheses within the 2 (difficulty, low versus high) x 2 (chronotype, match versus mismatch) repeated measure design, hierarchical linear models within R were accomplished on each CV Δ score individually and equally for the N-back task performance measure. HLM were also used to analyze the effects of SJL and ILS while both were inserted separately as additional independent variables.

2.4.2. Subjective Data

Subjective Data included items from both the pre-task questionnaire and the post task questionnaire. Baseline perceived fatigue levels were assessed within the pre task questionnaire using the mood dimension *awake-sleepy* of the MDBF. Participants answered eight items on a 5-point likert scale and were asked to indicate how they felt right now at that moment from 1 = not at all to 5 = very (e.g., “rested, tired “). Items addressing fatigue were coded reversed. People who score high are believed to feel energetic and lively whereas people who score low feel tired, sleepy, listless (Steyer et al.,1997). For the purpose of the study lower scores indicated that participants experienced fatigue.

3. Results

3.1. Effort mobilization baseline measures

Baseline means are in Table 1.

3.1.1. SBP Baseline

HLM in R was used to investigate whether SBP baseline values differed between the two chronotype groups or the morning and night in-lab session (time period) within participants. Chronotype, time period and the interaction of both were inserted as independent variables while averaged SBP baseline values were the dependent variable. Results revealed neither a difference between both chronotype groups F (1,34.98)=1.90 p=.18, η_p^2=.05 nor between the morning and night timeslots F (1,106)=0.04 p=.84, η_p^2<.001. Also no significant interaction effect was found F (1,106)=0.78 p=.38, η_p^2<.001. Overall participants showed a SBP value of M=108.23 mmHg (SD= 8.38) ranging from 87.33 to 127.75 mmHg.

3.1.2. PEP Baseline

To investigate whether the PEP baseline values differed between the two chronotype groups or between the morning and night in-lab sessions within participants, I computed a HLM in R. Chronotype, time period and the interaction of both were used as independent variables and average PEP values as dependent variable. While there was no difference between the two chronotype groups F (1,34)=1.20, p=<.28 the results showed a significant difference between the morning and night PEP baseline F (1,106)=80.21, p=<.001, η_p^2=0.43. Overall, the average PEP baseline value was lower at night M=122.32 (SD=12.39) than in the morning M=134.15 (SD=12.72), showing that participants were more rested in the morning than at night. This effect, indicated by the mean difference, was greater for larks (M=138.12 – 122.81 = 15.31) than for owls (M=131.32 – 121.97 = 9.35). Looking at the interaction effect, results also showed a significant difference in the PEP baseline values F (1,106)=4.67, p=.03, η_p^2= .04. Moreover, during their circadian match condition PEP baseline mean scores were high among larks (M=138.12) but comparatively low in owls (M=121.97), indicating that larks were generally more rested during their match condition than owls (see Table 1).

3.1.3. Fatigue Level

To check if the fatigue levels of the participant differed in any way between their two in-lab sessions or between the two chronotype groups in general, I conducted an HLM in R. The mean value of the *wakefulness-fatigue* subscale of the MDBF was used as the dependent variable. Again chronotype, time period and the interaction of both were used as independent variables. While the results showed no difference between the morning and night in-lab sessions F (1,106)=1.23, p=.27, $\eta_p{}^2$=.01 there was a significant difference between the two chronotypes F (1,34.52)=12.09, p=.001, $\eta_p{}^2$=.26. Overall evening chronotypes (owls) showed lower energy levels (M=3.00, SD=0.94) than morning chronotypes (larks) (M=3.74, SD=0.82). More importantly there was also a significant difference of baseline fatigue levels within participants between their match and mismatch condition F(1,107.01)=74.32, p<.001, $\eta_p{}^2$=0.41. In general participants reported higher energy levels in their match (M=3.71, SD=0.80) than in their mismatch condition (M=2.92, SD=0.95), thus the perceived fatigue was higher in their mismatch than in the match condition.

Table 1

Baseline Values. Means and 95% CI amongst each condition.

	Larks		Owls	
	Match (Morning)	Mismatch (Night)	Match (Night)	Mismatch (Morning)
SBP	**106.51**	**106.00**	**110.05**	**109.24**
	[102.81, 110.21]	[101.99, 110.00]	[106.67, 113.44]	[106.12, 112.37]
PEP	**138.12**	**122.81**	**121.97**	**131.32**
	[132.51, 143.74]	[117.18, 128.45]	[117.21, 126.73]	[126.57, 136.06]
Fatigue	**4.20**	**3.29**	**3.35**	**2.65**
	[3.87, 4.54]	[2.92, 3.65]	[3.05, 3.66]	[2.37, 2.94]
ILS	**0.89**	**0.68**	**-0.17**	**1.75**
	[0.12, 1.65]	[-0.06, 1.42]	[-0.79, 0.46]	[1.11, 2.40]

Note. SBP = systolic blood pressure in mmHg. PEP = pre-ejection period. Lower PEP values indicate stronger heart contractility. Fatigue = perceived fatigue on a scale from 1-5 (MDBF).

Higher values indicate more energy and lower values more fatigue. ILS = Individual lack of sleep. Higher values indicate a greater lack of sleep, while negative values indicate that participants slept longer than their individual sleep need. For each condition means are followed by 95% CI in parentheses.

3.2 Main Analysis

Mean performance and effort related CV mean Δ scores of the main analysis are depicted in Table 2.

3.2.1. Performance

To investigate whether a circadian mismatch influences performance, I computed an HLM in R. N-back task difficulty (N1 or N3), circadian match and mismatch and the interaction of both were used as independent variables. Results showed a significant difference between the easy (N1) and difficult N-back task (N3) F (1,116.12)=186.69, p<.001, η_p^2=.62 in the way that performance was higher in the easy (M=0.99, SD=0.01) than in the difficult N-back task (M=0.91, SD=0.06). Overall performance was high across both difficulties and did not show much variance with the correct response rate ranging from min=0.78 to max=1.00. While the performance differed between the easy and difficult N-back task, it did not differ between the match and mismatch condition of participants F (1,114.96)=0.01, p=.91, η_p^2<.001 (see Figure 2). Indicating that the performance was the same regardless of whether participants conducted the N-back task during a circadian match or mismatch time.

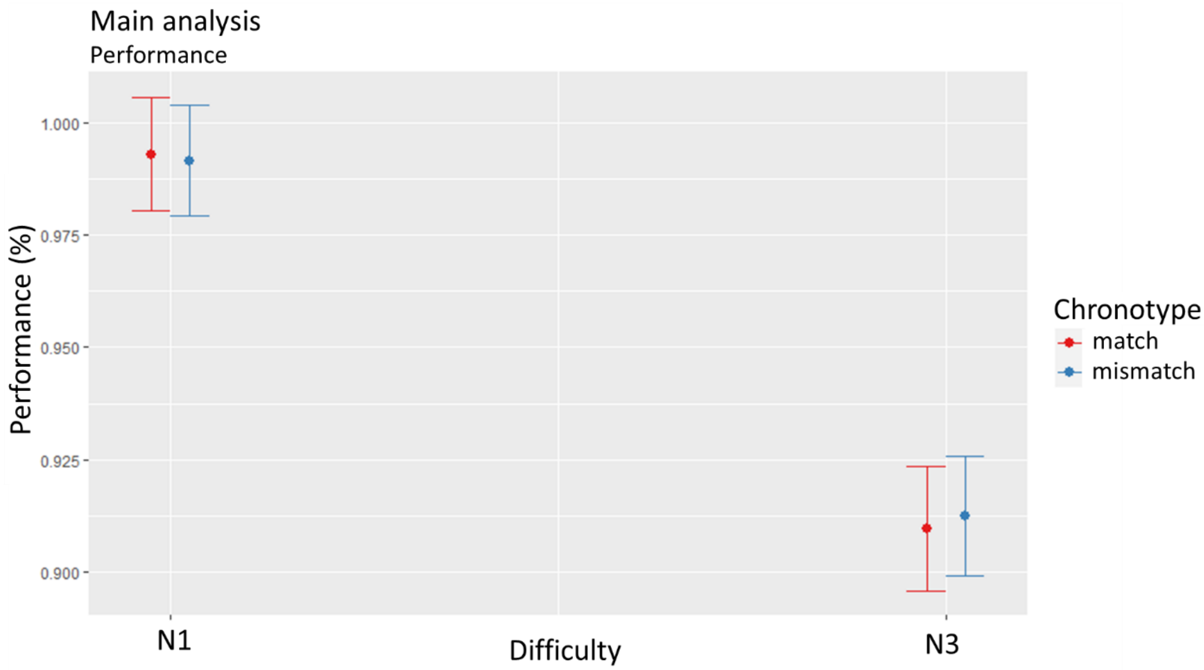

Figure 2. Performance in % in the N1 (easy) and N3 (difficult) N-back task. Comparison of chronotype match and mismatch.

3.2.2. Pre-Ejection Period

To investigate whether participants' effort mobilization differed from their circadian mismatch to their circadian match condition, I used an HLM in R with PEP mean Δ scores as dependent variable and applying both N-back task difficulties, circadian match or mismatch and the interaction of both as independent variables into the model. I expected effort mobilization to be higher during a circadian mismatch than during a circadian match. Results indicated a significant difference in effort mobilization between both, the easy and difficult N-back task F (1,80.74)=18.17, p<.001, $\eta_p{}^2$=.18 and also between a participants circadian match and mismatch F (1,80.55)=12.86, p<.001, $\eta_p{}^2$=.14. As expected, PEP Δ scores were higher in the difficult N-back task (N3) M=-4.72 (SD=5.72) than in the easy N-back task (N1) M=-2.07 (SD=4.50). Noting that negative PEP Δ scores indicate effort mobilization. Contrary to my expectations PEP Δ scores were higher (more negative) when completing the N-back task during a match (M=-4.79, SD= 5.74), than during a circadian mismatch (M=-1.97, SD=4.40) (see Figure 3). Thus, participants showed more effort mobilization during a match than during a circadian mismatch.

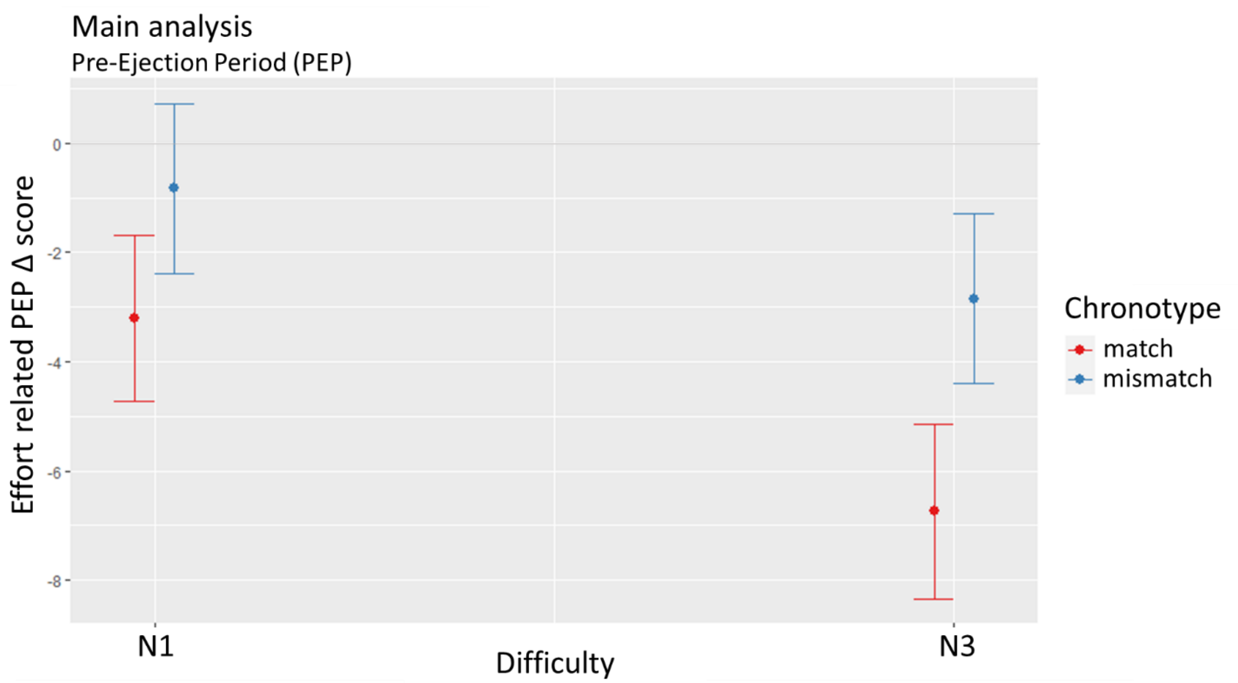

Figure 3. Effort mobilization indicated through PEP change scores. N1 (easy) and N3 (difficult) N-back task. Comparison of chronotype match and mismatch.

3.2.3. Systolic Blood Pressure

The analysis for SBP, as a second indicator for effort mobilization, followed the same principle as PEP. I expected SBP Δ scores to be greater during a circadian mismatch than during a circadian match, while higher SBP Δ scores indicated more effort mobilization. Again, I made use of an HLM in R with SBP mean Δ scores as dependent variable and inserting easy and difficult N-back task difficulty, circadian match and mismatch and the interaction of both as independent variables. The results indicated the same pattern that I found for PEP, in the way that SBP Δ scores differed significantly between the easy and difficult n-back task F (1,78)=11.56, p=.001, $\eta_p{}^2$=.13 and also between when a participant conducted the N-back task during a circadian match or mismatch F (1,88.72)=5.92, p=.02, $\eta_p{}^2$=.06. Again, the results showed the contrary of what was expected, indicating that SBP Δ scores (effort mobilization) were higher during a match (M=1.90, SD=4.81) than during a circadian mismatch (M=0.28, SD=3.97) (see Figure 4).

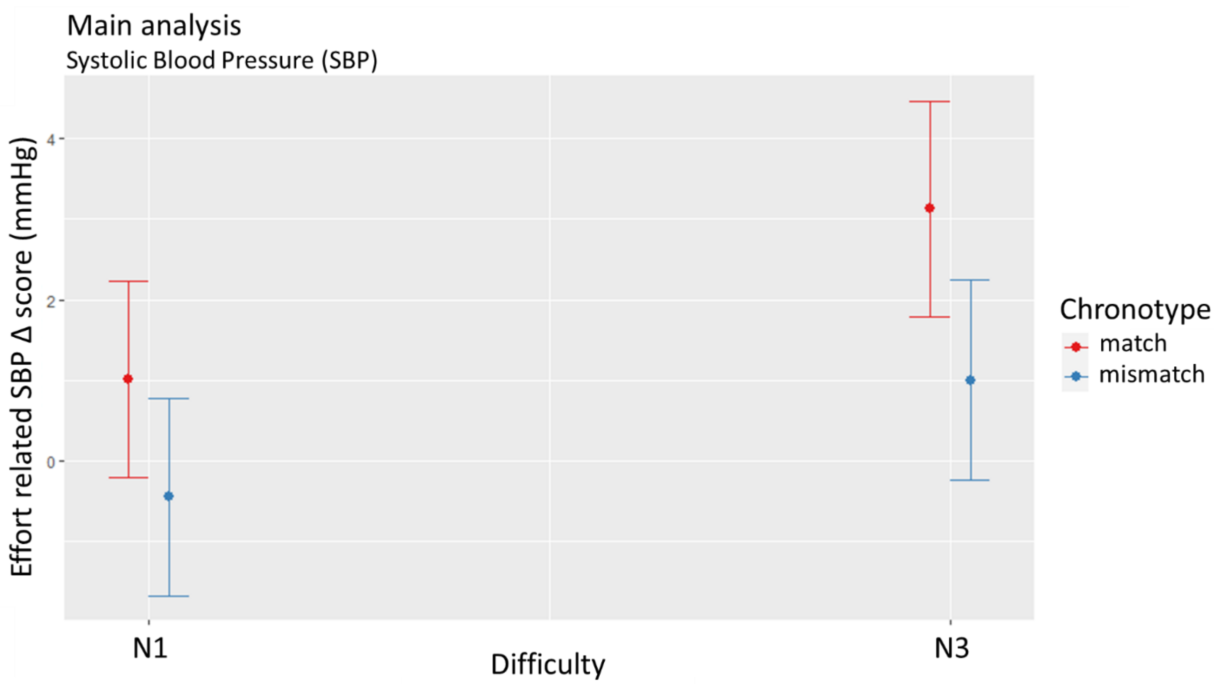

Figure 4. Main analysis. Effort mobilization indicated through SBP change scores in mmHg. N1 (easy) and N3 (difficult) N-back task. Comparison of chronotype match and mismatch.

Table 2
Main analysis. Means and 95% CI amongst each condition.

	N1		N3	
	Match	Mismatch	Match	Mismatch
Performance	**0.99**	**0.99**	**0.91**	**0.91**
	[0.98, 1.00]	[0.98, 1.00]	[0.90, 0.92]	[0.90, 0.93]
SBP	**1.01**	**-0.45**	**3.13**	**1.00**
	[-0.21, 2.24]	[-1.67, 0.78]	[1.79, 4.46]	[-0.24, 2.24]
PEP	**-3.20**	**-0.83**	**-6.74**	**-2.85**
	[-4.71, -1.69]	[-2.39, 0.72]	[-8.34, -5.14]	[-4.40, -1.29]

Note. Performance = N-back task performance. Correct answers in %. SBP = systolic blood pressure in mmHg. PEP = pre-ejection period. Lower PEP values indicate stronger heart contractility. For each condition means are followed by 95% CI in parentheses.

3.3. Moderation

Results for SJL and ILS, that served as moderators are depicted below for both, performance and effort related CV responses. Generally the data showed that evening chronotypes reported more SJL (*M*=1.79, *SD*=0.94) than morning chronotypes (*M*=0.89, *SD*=0.88) F (1,141.61)=33.77, p<.001, η_p^2=.19.

Data for ILS showed that the reported ILS was significantly different between the morning and night in-lab sessions F (1,106)=31.70, p<.001, η_p^2=.23, but was not affected by chronotype F(1,34.10) <.001, p=.98. The interaction effect of both also showed a significant difference F (1,106)=20.38, p<.001, η_p^2=.16,. Overall data showed participants reported more ILS during the morning in-lab session (*M*=1.39, *SD*=1.78) than at night (*M*=0.19, *SD*=1.65) while owls reported more ILS in the morning than larks (see table 1).

3.3.1. Performance and SJL

To investigate whether SJL moderated the effect circadian match and mismatch had on performance, I inserted SJL as an additional factor in the HLM. I expected SJL to moderate this effect in the way that more SJL should have resulted in worse performance. However when including SJL as additional independent variable, results showed that SJL had no significant effect on performance F (1,57.04)=0.63, p=.43.

3.3.2. Performance and ILS

To investigate whether ILS moderated the effect circadian match and mismatch had on performance, ILS was applied as an additional independent variable in the HLM. ILS was expected to moderate this effect in the way that more ILS should have resulted in worse performance. The results showed neither a significant effect of ILS on performance F (1,114.85)=0.004, p=.95 nor a significant interaction effect of ILS and circadian match/mismatch on performance F (1, 123.81)=0.05, p=.83.

3.3.3. PEP and SJL

To investigate whether SJL moderated the effect circadian match and mismatch had on effort mobilization, SJL was included in the HLM as an additional factor. The results showed neither a significant effect of SJL on PEP F (1,33.63)=1.65, p=.21 nor a significant interaction effect of SJL and circadian match/mismatch on PEP F (1,71.52)=2.31, p=.13.

3.3.4. SBP and SJL

The same holds true when looking at SBP as an indicator for effort mobilization. The results did not show a significant effect of either SJL on SBP F (1,35.90)=1.33, p=.26, or SJL and circadian match/mismatch on SBP F (1,82.68)=0.06, p=.81.

3.3.5. PEP and ILS

The same analysis was conducted to investigate whether ILS moderated the effect circadian match and mismatch had on effort mobilization. The results showed neither a significant effect of ILS on PEP F (1,82)=0.35, p=.56. nor a significant interaction effect of ILS and circadian match/mismatch on PEP F (1,104.38)=0.03, p=.87.

3.3.6. SBP and ILS

Again, the results did not show a significant effect of either ILS on SBP F (1,81.31)=0.029, p=.59 or an significant interaction effect of ILS and circadian match/mismatch on SBP F(1,112.20)=0.02, p=.31.

3.4. Post task questionnaire

3.4.1. Perceived Difficulty

Ensuring that the difficult N-back task was also perceived as more difficult than the easy N-back task by participants I analyzed the ratings of perceived difficulty (1-10), answered by participants after completing each N-back task. I used perceived difficulty as a dependent variable while the easy and difficult condition were used as independent variables within the HLM. In line with the expectations results showed that the perceived difficulty was significantly different between the N1 and N3 F (1,112.17)=420.81, p<.001, η_p^2=.79. Participants perceived the N3 as more difficult (*M*=7.32, *SD*=2.3) than the N1 (*M*=2.0, *SD*=1.23). To further check if participants perceived a task as more difficult during a circadian mismatch compared to a circadian match, chronotype match and mismatch were included as additional factors into the HLM. Results showed that the perceived difficulty was not affected by circadian match or mismatch F (1,97.10)=0.38, p=.54.

3.4.2. Success Importance

To verify the effectiveness of the incentive a manipulation check was included in the analysis. Participants were told that they would receive an incentive of 1,50€ if their N-back task performance was equal or superior to 70%. As the incentive was consistent over all conditions, I expected success importance to be the same at any point, regardless of task difficulty or circadian match/mismatch. Generally, I expected success importance to be high. Again, I used an HLM with N-back task difficulty and circadian match/mismatch as independent variables and success importance as dependent variable. In accordance with my expectations success importance did not differ significantly neither between both N-back task difficulties F (1,90.16)=0.06, p=.81 nor between circadian match/mismatch F (1,62.68)=0.08, p=.77. Overall, success importance was high among participants (*M*=6.99, *SD*=2.32).

3.5. Explorative Analyses

Training effects can occur when confronted with same tasks at multiple times. Because of that, participants already completed both N-back tasks in the online part of the study and were therefore already familiar with the task. However, to ensure that no training effect occurred between both in-lab sessions, I investigated if performance and effort mobilization differed between the two in-lab sessions. Further I differentiated between whether the first in-lab part was completed during a circadian match or mismatch. Therefore, I computed an HLM in which I included whether participants completed their first in-lab session at a circadian match or mismatch as an additional independent variable. In terms of effort mobilization, I prioritized PEP over SBP as it represents the first choice to measure effort through beta-adrenergic cardiovascular reactivity (Kelsey, 2012).

3.5.1. Performance and timing of circadian (mis-)match

To investigate whether performance changed between the first and second in-lab session while accounting for if their first session was a circadian match or mismatch, I created a variable that described whether participants completed the first in-lab part at their preferred (=match) or at their non-preferred time (=mismatch). This variable was included as an additional factor into the HLM of the main analysis, presented in chapter 2.1. While there was no difference in performance between participants who completed their first in-lab session at their preferred versus those who completed it at their non-preferred time F (1,40.65)=0.13, p=.23 there was a significant interaction effect within participants showing that performance was higher at the second compared to the first in-lab session F (1,101.66)=1.73, p=.05, η_p^2=.04.

3.5.2. Effort mobilization (PEP) and timing of circadian (mis-)match

The same analyses were used to investigate whether effort mobilization was different between the group who completed their first in-lab session at their preferred time compared to the group who completed it at their non-preferred time. Results indicated that PEP Δ scores were not significantly different between the two groups that either completed their first in lab session during a match or mismatch F (1,34.5)=1.75, p=.19. However, there was a significant interaction effect within participants, showing that PEP Δ scores were lower during the first in-lab session compared to the second in-lab session F (1,70.25)=16.97, p<.001, η_p^2=.19. Again, lower PEP Δ scores indicate more effort mobilization. Lastly, this mean difference in PEP was greater and only significant for those who completed their first in-lab session during a chronotype match (N1: M=-3.78 + 0.42= -4.2; N3: M=-7.32 – (-1.34) = -5.98) than during a mismatch (N1: M= -4.07 – (-1.56) = -2.51; N3: M=-6.83 – (-5.17) = -1.6), illustrated in Figure 5.

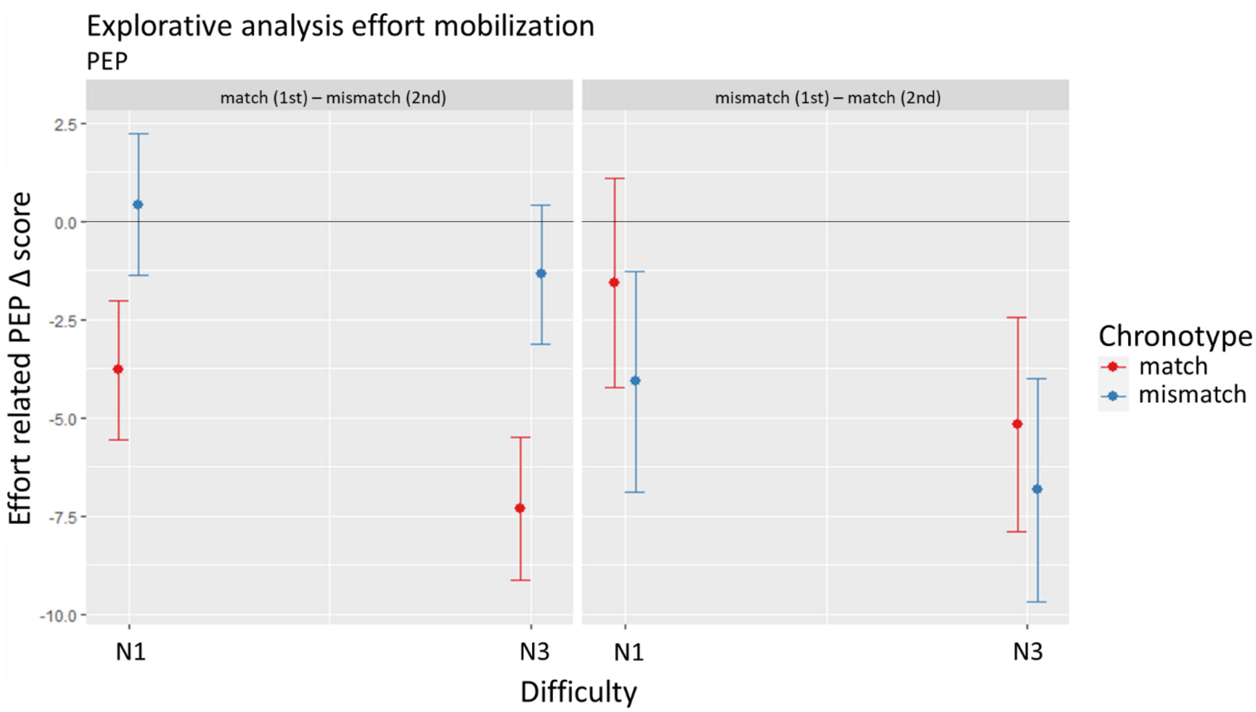

Figure 5. Pre-ejection period change scores. Left part shows the scenario when participant completed the first in-lab session during match, the right graph during a circadian mismatch. Error bars indicate standard errors.

4. Discussion

4.1. Findings for main analysis

This study investigated how chronotype influences effort mobilization when completing a low and a high difficulty task during a circadian match or mismatch. The results of the main analysis for PEP and SBP showed the opposite effect of what I expected. While performance was generally lower in the easy (N1) than in the difficult (N3) task, it did not differ between the match and mismatch conditions. Indicating that participants performed equally well at all time points. However, the average correct response rate was 99% in the easy task and 91% in the difficult task. While I expected participants to disengage from the difficult task during a circadian mismatch, this did not happen and was likely due to ease of the difficult task, as depicted through the high success rate.

N-back task performance was the same regardless of whether a participant completed it during a chronotype match or mismatch. Considering this, I expected that when a person completes the same task, with the same performance result he/she should therefore need to put forth more effort during a circadian mismatch than during a circadian match time to offset their increased level of fatigue. Nevertheless, the results for PEP (& SBP) indicated the opposite effect. Participants invested more effort for the same task at a circadian match compared to completing it at their circadian mismatch. While results were found to support my second hypothesis, participants having a lower effort mobilization on the difficult task during their mismatch time, the overall pattern of findings does not support the theoretical predictions that formulated this hypothesis. Notably, these results should have been observed due to mismatch participants disengaging from the difficult task. Considering the results for the N-back task performance, I feel confident in assuming that disengagement did not occur at any point during the study. Accordingly, as long as the participant engaged on the task, regardless of its difficulty, he/she should need to put forth more effort in the mismatch than in the match condition. Again, the results showed the contrary.

While one could argue that participants could have been more motivated during their circadian match, the data I collected after each N-back task, asking about the individual success importance, did not differ at any point. This means it was unlikely that participants voluntarily invested more effort during a circadian match because of motivational reasons. Another explanation for the contrary findings is depicted in my explorative analysis.

4.2. Findings for explorative analysis

When looking at the data, performance differed between the first and second in-lab session. Participants performed significantly better in their second compared to their first in-lab session. An explanation therefore might be a possible training effect that occurred between both in-lab sessions. While I was aware that a training effect is likely to occur when completing the same task repeatedly, I expected this effect to greatly diminish following the first repetition. Because of that I implemented the N-back task in the online-part of the study, so all participants were already familiar with both N-back tasks when completing it in-lab. Doing so I wanted to control for a possible training effect. However, the data still showed patterns reflecting a training effect that likely occurred between both in-lab sessions and potentially distorted the collected data.

Figure 5 indicates that not only performance, but also effort mobilization was affected. Interestingly, while effort mobilization was generally lower in the second in-lab session it shows that this effect was only relevant for participants who completed their first in-lab session at a time that matched their chronobiological rhythm. In this case participants needed to mobilize less effort in their second in-lab session to achieve the same results in the cognitive task. On the other hand, participants who did their first in-lab session during a circadian mismatch showed marginally more effort mobilization in their second in-lab session. As they invested more effort in the second in-lab session, it is unlikely that those participants experienced a training effect at all. For this scenario, the pattern I found in my main analysis is inverted and pointing into the direction I originally expected. Though not significantly, participants showed slightly more effort mobilization at their circadian mismatch than at their match time, when completing their first in-lab session during a time that conflicts with their natural circadian rhythm. This would then be in line with the fatigue analysis and the core principles of MIT (for review see Richter et al., 2016). Putting it together, the data likely shows a training effect, but only for those who completed their first in-lab session during a time that matches with their chronobiological rhythm whereas others had to invest more effort in their second in-lab session to achieve the same result.

Transferring this into everyday life it would mean that when people must work or study at a time that conflicts with their chronotype, they are likely to not benefit from training to the extend those do who work or study during a time in line with their chronotype. This supports the negative outcomes that arise whenever the circadian rhythm is out of time with environmental demands. Whereas misalignment due to travel across time zones can cause acute disruption, social demands that conflict with the individual chronotype can result in chronic disruption. Both acute and chronic circadian mismatch have been associated with severe (mental) health conditions (Dibner, 2020; Rijo-Ferreira & Takahashi, 2019; Vetter, 2020). Finger and Kramer (2021) highlighted the importance and benefits of a synchronization between the circadian rhythm with exogenous environmental cycles but simultaneously emphasized the challenges that modern life (e.g, artificial lighting) brings. This stressses the importance of adapting timetables to chronobiological preferences, especially relevant for high schools. Adolescents, who's chronobiological rhythm is known to be shifted towards an evening chronotype (Crowley et al., 2007, Hagenauer et al., 2009, Roenneberg et al., 2004), must study at early times that are not in line with their natural chronobiological rhythm. Especially in the first hour(s), they might not be able to perform at their best and also not learn/train as efficient as they would later in the day when the time of day actually matches with their chronobiological rhythm. In addition to the training concerns, health issues also arise for high school students when applying these findings to the school scenario. Specifically, as people need to invest different levels of effort to achieve equal results just because of their natural chronobiological rhythm, high school students with an evening chronotype might consistently have to invest more effort leading to higher probability of negative cardiovascular outcomes. To phrase it positively, performing at times that are in line with one's individual chronobiological rhythm might positively influence better training and learning but also have positive health outcomes. Society should therefore aim to respect chronobiological rhythms more.

As this study only found a possible training effect within explorative analysis more research is reasonable and necessary. Future research should intensify research in connecting training effect and chronobiological rhythm. Do you train/learn better when you work/learn during a time that aligns with your chronotype?

4.3. Findings for moderators

Findings for both, ILS and SJL at baseline support previous research in the way that evening chronotypes suffered more SJL than morning chronotypes (Roenneberg et al., 2019). While larks reported similar levels of ILS in the morning and night in-lab session owls experienced significantly more ILS when coming in for their morning in-lab session compared to their session at night. This indicates that owls are especially affected by early social demands which is congruent to prior research, showing that evening chronotypes suffer disadvantages in various aspects of life (Fabbian et al., 2016).

Considering this it is not surprising that in terms of fatigue, larks felt more rested than owls in the morning. Nevertheless, fatigue levels of owls and larks didn't differ at baseline during the night in-lab session. Interestingly, both subjective (MDBF) and objective (PEP) data consistently found that larks were least fatigued in the morning, while no difference between both chronotypes was found at night. This suggests that owls are not only disadvantaged in the morning, but at the same time do not benefit in times that match their chronotype. An explanation therefore could be that evening chronotypes still have to cope with the consequences of their morning fatigue, which aligns with prior research showing that evening chronotypes, especially amongst adolescents, are inclined to consume more caffeine, nicotine and alcohol (Giannotti et al., 2002; Wittmann et al., 2006).

4.3.1 SJL

SJL, introduced by Ronneberg and colleagues in 2019 was expected to moderate the effect chronotype had on effort mobilization and performance. SJL describes the phenomenon that people tend to have different sleep patterns on their workdays compared to their free days. In the way that most people report sleeping in longer on their free days to compensate for potential chronic sleep depth that was accumulated before throughout workdays. People who report higher levels of SJL should therefore be more fatigued than those with less SJL. When integrating SJL into the research model, it was expected to function as a moderator in the manner that more SJL should result in more effort mobilization and worse performance while engaging on a task and should lead people to disengage from a task at a lower difficulty level. As the latter was not the case in this study, the discussion only focusses on the first scenario. Although the results did not show a significant effect, data did trend in the correct direction. In line with my expectation, more SJL resulted in a worse performance on the difficult N-back task. Considering that even the difficult task had a correct response rate of 91% it is likely that the task was too easy to provide the statistical power needed to identify the effect. As the direction of the results is correct, I believe that with increasing difficulty levels the observed effect could strengthen significantly. Moreover, SJL might be especially relevant for people with late chronotypes, who often have to perform at suboptimal times as they are confronted with early wake up times weekly resulting in a circadian mismatch (Roenneberg et al., 2019). It is important to extend research on SJL to raise the awareness about possible health consequences that go hand in hand with chronic circadian misalignment (Scott et al., 2021; Dibner, 2020; Rijo-Ferreira & Takahashi, 2019). Future studies should therefore extend research on SJL and aim to adapt as well as increase the task difficulty level.

4.3.2. ILS

ILS, as proposed by this study should depict a possible sleep depth more accurately than general recommendations for sleep duration. Considering the individual need for sleep and the actual sleep duration of people, ILS displays the individual sleep depth. Like SJL, ILS was expected to moderate the effect chronotype had on effort mobilization and performance. Higher levels of ILS before the in-lab session, depicting those participants slept less compared to their indicated need for sleep, should lead to higher fatigue among the participants. Accordingly higher ILS should have led to more effort mobilization as long as participants engaged on the N-back task. As the results showed no significant effect, it is possible that the training effect concealed the influence of ILS. Nevertheless, it is also plausible that the effect only occurred within the morning in-lab session but not at night. Previous studies showed that sleep related behavior is predominantly observed in the morning but not later in the day (Bonato et al., 2017). Accordingly, later chronotypes might be more vulnerable to suboptimal times than earlier chronotypes. This aligns with a recent study, which indicated that performance deficits were primarily observed in the morning hours, while performance in the afternoon and evening was comparatively little affected (Hudson et al., 2020). One possible explanation therefore is that short-term ILS can be compensated throughout the day using behavioral strategies e.g., napping or consuming caffein, which has already been shown to counteract impairment in vigilant attention (Krause et al., 2017, Stepan et al., 2021). Overall, early social schedules might additionally increase the probability and the extent of ILS. Future studies should therefore extend research on ILS but focus mainly on the impact it might have in the morning.

4.3.2. Post task questionnaire

Assessing the success importance of participants after each N-back task as well as the perceived difficulty of the previous N-back task were necessary manipulation checks. Results of the success importance were as expected, showing no changes over the course of the study. Success importance was generally high among participants which was relevant as the importance to succeed on a task had shown to be a factor in fatigue analysis (Brehm & Self, 1989) (also see Figure 1). According to previous research the perceived task difficulty should increase with fatigue. Correspondingly, participants should have perceived both N-back tasks as more difficult during their circadian mismatch than in during their circadian match (Ackerman, 2011; Fairclough, 2000; Fairclough & Graham, 1999; Hockey, 1997). Nevertheless, the perceived difficulty of the N-back tasks did not differ between the circadian match and mismatch condition. An explanation therefore could be that even though participants perceived the two versions of N-back tasks as distinct in terms of difficulty levels, this difficulty was perceived as fixed regardless of the time of day when completing the task. Training effects might also have had an impact on the perceived difficulty and counteracted the effect fatigue has on the perceived difficulty of performance tasks.

4.4. Limitations

While the study gives interesting new insights on the topic of chronotype and effort mobilization there are several limitations that come along with this study.

First, and most importantly due to the repeated measure design, the data has likely been distorted by a training effect between both in-lab session which I did not foresee. Therefore, all results, especially those of the main analyses should be interpreted with caution. Future studies should therefore be aware of a training effect when using N-back tasks within a repeated measure design.

Second, the final sample was not ideal to test the proposed hypotheses. Specifically, it only consisted of 36 participants with 80% being female falling well short of the needed number of participants to sufficiently test for interactional patterns. According to the power analysis there was only enough participants to interpret direct effects, as I did in my main analysis. However, the sample size was too low to interpret any interaction effects as they are underpowered. Further, the composition of the sample was not ideal. Besides 80% being female, only one participant stated an extreme chronotype while all other participants were categorized as either moderate morning or evening chronotypes. Considering this, I understand this study as a pilot which justifies doing more research on this topic. While I only assessed students, future studies could also aim for either a sample within the working context or a high school sample. Both, but especially the latter would provide new and much needed insights on how chronobiological rhythm influences effort mobilization and performance.

Third, there might have been differences between the timeslots utilized. Participants were run from either 7:00-8:30 am/pm or 8:30-10:00 am/pm. It could be assumed that, especially in the morning, fatigue levels and the associated sleep behavior of the prior night differ between a person asked to come into the lab at 7:00am or 8:30am. Future studies could try to adjust timeslots to relevant timetables within the population (e.g., school timetables or working schedules). Nevertheless, this is more of a logistical problem and linked to available resources.

4.5. Future studies

I believe the results above indicate two future lines of research to flesh out of the model presented here. First would be to design a study that replicates the training effect seen here. Specifically looking to identify if training is diminished when learning at a circadian mismatch compared to a circadian match. A second line of research would be to use the knowledge gained from this pilot data and adapt the current study design to create a more nuanced test for my predictions. Rather than a repeated measure design, future studies should aim for a between subject design including all types of chronotypes. Participants would only need to complete the N-back task once, while I propose presenting multiple N-back tasks with increasing difficulty. By doing so, I would expect to find significant differences of when participants disengaged depending on their circadian match/mismatch. Rather than categorizing chronotype as a factor, chronotype should be assessed and analyzed as a continuous variable. Furthermore, assessing chronotype in the understanding of a bio-psycho-social model will be possible for future studies thanks to the development of the BodyClock RNA test (Wittenbrink et al., 2018). Developed by the Charité Berlin, it can deliver data of current hormone levels (e.g., before starting the task) and by that provide a biological factor of chronotype. In terms of a bio-psycho-social model, the MEQ can be understood as the psychological factor of chronotype and could be supplemented with data from the MCTQ, whose questions focus on the social part of chronotype.

5. Conclusion

All in all, my research demonstrates the importance of the synchronization of social demands with the chronobiological rhythm, as it can positively influence training and learning. While the results were not as expected, explorational findings do indicate that chronotype influences effort mobilization and performance on a cognitive task. In view of this, chronotype is a factor that needs to be considered in the line of research regarding effort mobilization but also in socio-political terms. Flexible schedules that are adapted to the needs of the different chronotypes can not only contribute to better learning but might also have positive health outcomes. As demonstrated integrating circadian mismatch into the fatigue analysis is promising. As knowledge about the underlying mechanisms can be beneficial for multiple professions, follow-up research is legitimate and needed.

References

Ackerman, P. L. (Hrsg.). (2011). *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications.* American Psychological Association. https://doi.org/10.1037/12343-000

Adan, A., Archer, S. N., Hidalgo, M. P., Di Milia, L., Natale, V., & Randler, C. (2012). Circadian typology: A comprehensive review. *Chronobiology International*, *29*(9), 1153–1175. https://doi.org/10.3109/07420528.2012.719971

Alvaro, P. K., Roberts, R. M., & Harris, J. K. (2014). The independent relationships between insomnia, depression, subtypes of anxiety, and chronotype during adolescence. *Sleep Medicine*, *15*(8), 934–941. https://doi.org/10.1016/j.sleep.2014.03.019

Anderson, A., Murray, G., Herlihy, M., Weiss, C., King, J., Hutchinson, E., Albert, N., & Ingram, K. K. (2018). Circadian Effects on Performance and Effort in Collegiate Swimmers. *Journal of Circadian Rhythms*, *16*(1), 8. https://doi.org/10.5334/jcr.165

Baehr, E. K., Revelle, W., & Eastman, C. I. (2000). Individual differences in the phase and amplitude of the human circadian temperature rhythm: With an emphasis on morningness-eveningness: Phase and amplitude of the temperature rhythm. *Journal of Sleep Research*, *9*(2), 117–127. https://doi.org/10.1046/j.1365-2869.2000.00196.x

Bailey, S. L., & Heitkemper, M. M. (2001). Circadian rhythmicity of cortisol and body temperature: morningness-eveningness effects. *Chronobiology International*, *18*(2), 249–261. https://doi.org/10.1081/CBI-100103189

Biller, A. M., Molenda, C., Obster, F., Zerbini, G., Förtsch, C., Roenneberg, T., & Winnebeck, E. C. (2022). A 4-year longitudinal study investigating the relationship between flexible school starts and grades. *Scientific Reports*, *12*(1), 3178. https://doi.org/10.1038/s41598-022-06804-5

Biller, A. M., Molenda, C., Zerbini, G., Roenneberg, T., & Winnebeck, E. C. (2022). Sleep improvements on days with later school starts persist after 1 year in a flexible start system. *Scientific Reports*, *12*(1), 2787. https://doi.org/10.1038/s41598-022-06209-4

Bonato, M., Agnello, L., Galasso, L., Montaruli, A., Roveda, E., Merati, G., La Torre, A., & Vitale, J. A. (2017). Acute modification of cardiac autonomic function of high-intensity interval training in collegiate male soccer players with different chronotype: A cross-cver study. *Journal of Sports Science & Medicine*, *16*(2), 286–294.

Brehm, J. W., & Self, E. A. (1989). The intensity of motivation. *Annual Review of Psychology*, *40*(1), 109–131. https://doi.org/10.1146/annurev.ps.40.020189.000545

Carbajal, I., Mlynski, C., Willson, K., Gillis, K., & Wright, R. A. (2019). Circadian mismatch and cardiovascular response to a performance challenge: Larks in morning and evening work sessions. *International Journal of Psychophysiology*, *143*, 96–104. https://doi.org/10.1016/j.ijpsycho.2019.05.011

Castilhos Beauvalet, J., Luísa Quiles, C., Alves Braga de Oliveira, M., Vieira Ilgenfritz, C. A., Hidalgo, M. P., & Comiran Tonon, A. (2017). Social jetlag in health and behavioral research: A systematic review. *ChronoPhysiology and Therapy*, *Volume 7*, 19–31. https://doi.org/10.2147/CPT.S108750

Crowley, S. J., Acebo, C., & Carskadon, M. A. (2007). Sleep, circadian rhythms, and delayed phase in adolescence. *Sleep Medicine*, *8*(6), 602–612. https://doi.org/10.1016/j.sleep.2006.12.002

Depner, C. M., Melanson, E. L., Eckel, R. H., Snell-Bergeon, J. K., Perreault, L., Bergman, B. C., Higgins, J. A., Guerin, M. K., Stothard, E. R., Morton, S. J., & Wright, K. P. (2019). Ad libitum weekend recovery sleep fails to prevent metabolic dysregulation during a repeating pattern of insufficient sleep and weekend recovery sleep. *Current Biology*, *29*(6), 957-967.e4. https://doi.org/10.1016/j.cub.2019.01.069

Díaz-Morales, J. F., & Escribano, C. (2015). Social jetlag, academic achievement and cognitive performance: Understanding gender/sex differences. *Chronobiology International*, *32*(6), 822–831. https://doi.org/10.3109/07420528.2015.1041599

Díaz-Morales, J. F., Escribano, C., & Jankowski, K. S. (2015). Chronotype and time-of-day effects on mood during school day. *Chronobiology International*, *32*(1), 37–42. https://doi.org/10.3109/07420528.2014.949736

Dibner, C. (2020). The importance of being rhythmic: Living in harmony with your body clocks. *Acta Physiologica*, *228*(1). https://doi.org/10.1111/apha.13281

Dinges, D. F. (1995). An overview of sleepiness and accidents. *Journal of Sleep Research*, *4*, 4–14. https://doi.org/10.1111/j.1365-2869.1995.tb00220.x

Duffy, J. F., Rimmer, D. W., & Czeisler, C. A. (2001). Association of intrinsic circadian period with morningness–eveningness, usual wake time, and circadian phase. *Behavioral Neuroscience*, *115*(4), 895–899. https://doi.org/10.1037/0735-7044.115.4.895

Fabbian, F., Zucchi, B., De Giorgi, A., Tiseo, R., Boari, B., Salmi, R., Cappadona, R., Gianesini, G., Bassi, E., Signani, F., Raparelli, V., Basili, S., & Manfredini, R. (2016). Chronotype, gender and general health. *Chronobiology International*, *33*(7), 863–882. https://doi.org/10.1080/07420528.2016.1176927

Fairclough, S. H. (2000). Mental effort regulation and the functional impairment of the driver. In P. A. Hancock & P. A. Desmond (Hrsg.), *Stress, Workload, and Fatigue* (0 Aufl., S. 479–502). CRC Press. https://doi.org/10.1201/b12791-3.3

Fairclough, S. H., & Graham, R. (1999). Impairment of driving performance caused by sleep deprivation or alcohol: A comparative study. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *41*(1), 118–128. https://doi.org/10.1518/001872099779577336

Fischer, D., Lombardi, D. A., Marucci-Wellman, H., & Roenneberg, T. (2017). Chronotypes in the US – Influence of age and sex. *PLOS ONE*, *12*(6), e0178782. https://doi.org/10.1371/journal.pone.0178782

Gendolla, G. H. E., Wright, R. A., & Richter, M. (2012). Effort intensity: Some insights from the cardiovascular system. In R. M. Ryan (Ed.), *The Oxford handbook of human motivation* (pp. 420–438). Oxford University Press.

Gendolla, G. H. E., Wright, R. A., & Richter, M. (2019). Advancing issues in motivation intensity research: Updated insights from the cardiovascular system. In R. M. Ryan (Ed.), The Oxford handbook of human motivation (pp. 373–392). Oxford University Press.

Giannotti, F., Cortesi, F., Sebastiani, T., & Ottaviano, S. (2002). Circadian preference, sleep and daytime behaviour in adolescence. Journal of Sleep Research, 11(3), 191–199. https://doi.org/10.1046/j.1365-2869.2002.00302.x

Griefahn, B., Kunemund, C., Brode, P., & Mehnert, P. (2001). Zur Validitat der deutschen Ubersetzung des Morningness-Eveningness-Questionnaires von Horne und Ostberg. The validity of a german version of the Morningness-Eveningness-Questionnaire developed by Horne and Ostberg. *Somnologie*, *5*(2), 71–80. https://doi.org/10.1046/j.1439-054X.2001.01149.x

Hagenauer, M. H., Perryman, J. I., Lee, T. M., & Carskadon, M. A. (2009). Adolescent changes in the homeostatic and circadian regulation of sleep. *Developmental Neuroscience*, *31*(4), 276–284. https://doi.org/10.1159/000216538

Haraden, D. A., Mullin, B. C., & Hankin, B. L. (2017). The relationship between depression and chronotype: A longitudinal assessment during childhood and adolescence. *Depression and Anxiety*, *34*(10), 967–976. https://doi.org/10.1002/da.22682

Haraden, D. A., Mullin, B. C., & Hankin, B. L. (2019). Internalizing symptoms and chronotype in youth: A longitudinal assessment of anxiety, depression and tripartite model. *Psychiatry Research*, *272*, 797–805. https://doi.org/10.1016/j.psychres.2018.12.117

Haraszti, R. Á., Ella, K., Gyöngyösi, N., Roenneberg, T., & Káldi, K. (2014). Social jetlag negatively correlates with academic performance in undergraduates. *Chronobiology International*, *31*(5), 603–612. https://doi.org/10.3109/07420528.2013.879164

Hirshkowitz, M., Whiton, K., Albert, S. M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Katz, E. S., Kheirandish-Gozal, L., Neubauer, D. N., O'Donnell, A. E., Ohayon, M., Peever, J., Rawding, R., Sachdeva, R. C., Setters, B., Vitiello, M. V., Ware, J. C., & Adams Hillard, P. J. (2015). National Sleep Foundation's sleep time duration recommendations: Methodology and results summary. *Sleep Health*, *1*(1), 40–43. https://doi.org/10.1016/j.sleh.2014.12.010

Horne, J. A., & Ostberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, *4*(2), 97–110.

Hublin, C., Kaprio, J., Partinen, M., & Koskenvuo, M. (2001). Insufficient sleep—A population-based study in adults. *Sleep*, *24*(4), 392–400. https://doi.org/10.1093/sleep/24.4.392

Hudson, A. N., Van Dongen, H. P. A., & Honn, K. A. (2020). Sleep deprivation, vigilant attention, and brain function: A review. *Neuropsychopharmacology*, *45*(1), 21–30. https://doi.org/10.1038/s41386-019-0432-6

Jackson, M. L., & Van Dongen, H. P. A. (2011). Cognitive effects of sleepiness. In M. J. Thorpy & M. Billiard (Hrsg.), *Sleepiness* (S. 72–81). Cambridge University Press. https://doi.org/10.1017/CBO9780511762697.009

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the *N* -back task as a working memory measure. *Memory*, *18*(4), 394–412. https://doi.org/10.1080/09658211003702171

Kantermann, T., Sung, H., & Burgess, H. J. (2015). Comparing the morningness-eveningness questionnaire and munich chronotype questionnaire to the dim light melatonin onset.

Journal of Biological Rhythms, *30*(5), 449–453. https://doi.org/10.1177/0748730415597520

Kelsey, R. M. (2012). Beta-adrenergic cardiovascular reactivity and adaptation to stress: The cardiac pre-ejection period as an index of effort. In R. A. Wright & G. H. E. Gendolla (Hrsg.), *How motivation affects cardiovascular response: Mechanisms and applications.* (S. 43–60). American Psychological Association. https://doi.org/10.1037/13090-002

Killgore, W. D. S. (2010). Effects of sleep deprivation on cognition. In *Progress in Brain Research* (Bd. 185, S. 105–129). Elsevier. https://doi.org/10.1016/B978-0-444-53702-7.00007-5

Krause, A. J., Simon, E. B., Mander, B. A., Greer, S. M., Saletin, J. M., Goldstein-Piekarski, A. N., & Walker, M. P. (2017). The sleep-deprived human brain. *Nature Reviews Neuroscience*, *18*(7), 404–418. https://doi.org/10.1038/nrn.2017.55

Kunorozva, L., Roden, L. C., & Rae, D. E. (2014). Perception of effort in morning-type cyclists is lower when exercising in the morning. *Journal of Sports Sciences*, *32*(10), 917–925. https://doi.org/10.1080/02640414.2013.873139

Lim, J., & Dinges, D. F. (2010). A meta-analysis of the impact of short-term sleep deprivation on cognitive variables. *Psychological Bulletin*, *136*(3), 375–389. https://doi.org/10.1037/a0018883

Lowe, C. J., Safati, A., & Hall, P. A. (2017). The neurocognitive consequences of sleep restriction: A meta-analytic review. *Neuroscience & Biobehavioral Reviews, 80,* 586–604. https://doi.org/10.1016/j.neubiorev.2017.07.010

Mazri, F. H., Manaf, Z. A., Shahar, S., & Mat Ludin, A. F. (2019). The association between chronotype and dietary pattern among adults: A scoping review. *International Journal of Environmental Research and Public Health*, *17*(1), 68. https://doi.org/10.3390/ijerph17010068

Melo, M. C. A., Abreu, R. L. C., Linhares Neto, V. B., de Bruin, P. F. C., & de Bruin, V. M. S. (2017). Chronotype and circadian rhythm in bipolar disorder: A systematic review. *Sleep Medicine Reviews*, *34*, 46–58. https://doi.org/10.1016/j.smrv.2016.06.007

Merikanto, I., Lahti, T., Kronholm, E., Peltonen, M., Laatikainen, T., Vartiainen, E., Salomaa, V., & Partonen, T. (2013). Evening types are prone to depression. *Chronobiology International*, *30*(5), 719–725. https://doi.org/10.3109/07420528.2013.784770

Merikanto, I., Lahti, T., Puusniekka, R., & Partonen, T. (2013). Late bedtimes weaken school performance and predispose adolescents to health hazards. *Sleep Medicine*, *14*(11), 1105–1111. https://doi.org/10.1016/j.sleep.2013.06.009

Mlynski, C., Wright, R. A., & Kelly, K. (2020). Ability influence on effort and associated cardiovascular responses: Nocebo-Placebo evidence that perception is key. *Biological Psychology*, *152*, 107867. https://doi.org/10.1016/j.biopsycho.2020.107867

Newlin, D. B., & Levenson, R. W. (1979). Pre-ejection period: Measuring beta-adrenergic influences upon the heart. *Psychophysiology*, *16*(6), 546–552. https://doi.org/10.1111/j.1469-8986.1979.tb01519.x

Obrist, P. A. (1976). The cardiovascular-behavioral interaction? As it appears today. *Psychophysiology*, *13*(2), 95–107. https://doi.org/10.1111/j.1469-8986.1976.tb00081.x

Obrist, P. A. (1981). *Cardiovascular Psychophysiology: A perspective*. Springer US. https://doi.org/10.1007/978-1-4684-8491-5

Patrick, Y., Lee, A., Raha, O., Pillai, K., Gupta, S., Sethi, S., Mukeshimana, F., Gerard, L., Moghal, M. U., Saleh, S. N., Smith, S. F., Morrell, M. J., & Moss, J. (2017). Effects of sleep deprivation on cognitive and physical performance in university students. *Sleep and Biological Rhythms*, *15*(3), 217–225. https://doi.org/10.1007/s41105-017-0099-5

Persson, P. B., & Persson, A. B. (2018). Light and darkness in circadian rhythms. *Acta Physiologica*, *222*(3), e13036. https://doi.org/10.1111/apha.13036

Perugini, M., Gallucci, M., & Costantini, G. (2014). Safeguard power as a protection against imprecise power estimates. *Perspectives on Psychological Science*, *9*(3), 319–332. https://doi.org/10.1177/1745691614528519

Philip, P., Taillard, J., Sagaspe, P., Valtat, C., Sanchez-Ortuno, M., Moore, N., Charles, A., & Bioulac, B. (2004). Age, performance and sleep deprivation. *Journal of Sleep Research*, *13*(2), 105–110. https://doi.org/10.1111/j.1365-2869.2004.00399.x

Ragland, J. D., Turetsky, B. I., Gur, R. C., Gunning-Dixon, F., Turner, T., Schroeder, L., Chan, R., & Gur, R. E. (2002). Working memory for complex figures: An fMRI comparison of letter and fractal n-back tasks. *Neuropsychology*, *16*(3), 370–379. https://doi.org/10.1037/0894-4105.16.3.370

Richter, M. (2013). A closer look into the multi-layer structure of motivational intensity theory: The multi-layer structure of motivational intensity theory. *Social and Personality Psychology Compass*, *7*(1), 1–12. https://doi.org/10.1111/spc3.12007

Richter, M. (2015). Goal pursuit and energy conservation: Energy investment increases with task demand but does not equal it. *Motivation and Emotion*, *39*(1), 25–33. https://doi.org/10.1007/s11031-014-9429-y

Richter, M., Gendolla, G. H. E., & Wright, R. A. (2016). Three decades of research on motivational intensity theory. In *Advances in Motivation Science* (Bd. 3, S. 149–186). Elsevier. https://doi.org/10.1016/bs.adms.2016.02.001

Rijo-Ferreira, F., & Takahashi, J. S. (2019). Genomics of circadian rhythms in health and disease. *Genome Medicine*, *11*(1), 82. https://doi.org/10.1186/s13073-019-0704-0

Robert J. Hockey, G. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology*, *45*(1–3), 73–93. https://doi.org/10.1016/S0301-0511(96)05223-4

Roenneberg, Pilz, Zerbini, & Winnebeck. (2019). Chronotype and Social Jetlag: A (self-) critical review. *Biology*, *8*(3), 54. https://doi.org/10.3390/biology8030054

Roenneberg, T., Kuehnle, T., Pramstaller, P. P., Ricken, J., Havel, M., Guth, A., & Merrow, M. (2004). A marker for the end of adolescence. *Current Biology*, *14*(24), R1038–R1039. https://doi.org/10.1016/j.cub.2004.11.039

Roenneberg, T., & Merrow, M. (2007). Entrainment of the human circadian clock. *Cold Spring Harbor Symposia on Quantitative Biology*, *72*(1), 293–299. https://doi.org/10.1101/sqb.2007.72.043

Roenneberg, T., Wirz-Justice, A., & Merrow, 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

Schmidt, C., Collette, F., Cajochen, C., & Peigneux, P. (2007). A time to think: Circadian rhythms in human cognition. *Cognitive Neuropsychology*, *24*(7), 755–789. https://doi.org/10.1080/02643290701754158

Scott, J., Kallestad, H., Vedaa, O., Sivertsen, B., & Etain, B. (2021). Sleep disturbances and first onset of major mental disorders in adolescence and early adulthood: A systematic review and meta-analysis. *Sleep Medicine Reviews*, *57*, 101429. https://doi.org/10.1016/j.smrv.2021.101429

Stepan, M. E., Altmann, E. M., & Fenn, K. M. (2021). Caffeine selectively mitigates cognitive deficits caused by sleep deprivation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 47*(9), 1371–1382. https://doi.org/10.1037/xlm0001023

Steyer, R., Schwenkmezger, P. & Notz, P., Eid, M. (1997). *Der Mehrdimensionale Befindlichkeitsfragebogen (MDBF)*. Göttingen: Hogrefe.

Taillard, J., Philip, P., Chastang, J.-F., & Bioulac, B. (2004). Validation of Horne and Ostberg morningness-eveningness questionnaire in a middle-aged population of french workers. *Journal of Biological Rhythms*, *19*(1), 76–86. https://doi.org/10.1177/0748730403259849

Ursin, R., Bjorvatn, B., & Holsten, F. (2005). Sleep duration, subjective sleep need, and sleep habits of 40- to 45-year-olds in the Hordaland Health Study. *Sleep*, *28*(10), 1260–1269. https://doi.org/10.1093/sleep/28.10.1260

Vetter, C. (2020). Circadian disruption: What do we actually mean? *European Journal of Neuroscience*, *51*(1), 531–550. https://doi.org/10.1111/ejn.14255

Vitale, J. A., La Torre, A., Baldassarre, R., Piacentini, M. F., & Bonato, M. (2017). Ratings of perceived exertion and self-reported mood state in response to high intensity interval training. A crossover study on the effect of chronotype. *Frontiers in Psychology*, *8*, 1232. https://doi.org/10.3389/fpsyg.2017.01232

Vitale, J. A., & Weydahl, A. (2017). Chronotype, physical activity, and sport performance: A systematic review. *Sports Medicine*, *47*(9), 1859–1868. https://doi.org/10.1007/s40279-017-0741-z

Walsh, N. A., Repa, L. M., & Garland, S. N. (2022). Mindful larks and lonely owls: The relationship between chronotype, mental health, sleep quality, and social support in young adults. *Journal of Sleep Research*, *31*(1). https://doi.org/10.1111/jsr.13442

Werner, H., Albrecht, J. N., Widmer, N., Janisch, D., Huber, R., & Jenni, O. G. (2022). Adolescents' preference for later school start times. *Journal of Sleep Research*, *31*(1). https://doi.org/10.1111/jsr.13401

Winnebeck, E. C., Vuori-Brodowski, M. T., Biller, A. M., Molenda, C., Fischer, D., Zerbini, G., & Roenneberg, T. (2020). Later school start times in a flexible system improve teenage sleep. *Sleep*, *43*(6), zsz307. https://doi.org/10.1093/sleep/zsz307

Wittenbrink, N., Ananthasubramaniam, B., Münch, M., Koller, B., Maier, B., Weschke, C., Bes, F., de Zeeuw, J., Nowozin, C., Wahnschaffe, A., Wisniewski, S., Zaleska, M., Bartok, O., Ashwal-Fluss, R., Lammert, H., Herzel, H., Hummel, M., Kadener, S., Kunz, D., & Kramer, A. (2018). High-accuracy determination of internal circadian time from a single blood sample. *Journal of Clinical Investigation*, *128*(9), 3826–3839. https://doi.org/10.1172/JCI120874

Wittmann, M., Dinich, J., Merrow, M., & Roenneberg, T. (2006). Social Jetlag: misalignment of biological and social time. *Chronobiology International*, *23*(1–2), 497–509. https://doi.org/10.1080/07420520500545979

Wright, R. A. (2014). Presidential address 2013: Fatigue influence on effort—considering implications for self-regulatory restraint. *Motivation and Emotion*, *38*(2), 183–195. https://doi.org/10.1007/s11031-014-9406-5

Wright, R. A., & Mlynski, C. (2019). Fatigue determination of inhibitory strength and control: A babe in a bath. *Motivation Science*, *5*(1), 66–78. https://doi.org/10.1037/mot0000114

Wright, R. A., Mlynski, C., & Carbajal, I. (2018). *Polish Psychological Bulletin*. https://doi.org/10.24425/119475

Wright, R. A., & Stewart, C. C. (2012). Multifaceted effects of fatigue on effort and associated cardiovascular responses. In R. A. Wright & G. H. E. Gendolla (Hrsg.), *How motivation affects cardiovascular response: Mechanisms and applications.* (S. 199–218). American Psychological Association. https://doi.org/10.1037/13090-010

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bpm	Beats per minute
CV	Cardiovascular
DBP	Dystolic blood pressure
HR	Heart rate
ILS	Individual lack of sleep
MAP	Mean artereal pressure
MCTQ	Munich Chronotype Questionnaire
MDBF	Multidimensional Mood Questionnaire
MEQ	Morningness-Eveningness Questionnaire

MIT	Motivational intensity theory
mmHg	Millimeters of mercury
MSF	Midpoint of sleep on free days
MSW	Midpoint of sleep on workdays
PEP	Pre-ejection period
SBP	Systolic blood pressure
SJL	Social Jetlag