


Review

The Impact of Physical Activity on the Circadian System: Benefits for Health, Performance and Wellbeing

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Featured Application: This review summarizes current knowledge regarding the effects of physical activity on the robustness of the circadian system and the benefits for health, performance, and wellbeing. We propagate practical implications of circadian activity rhythms for diagnosis and the advantages of scheduled motor activity.

Abstract: Circadian rhythms are an inherent property of all living systems and an essential part of the external and internal temporal order. They enable organisms to be synchronized with their periodic environment and guarantee the optimal functioning of organisms. Any disturbances, so-called circadian disruptions, may have adverse consequences for health, physical and mental performance, and wellbeing. The environmental light–dark cycle is the main zeitgeber for circadian rhythms. Moreover, regular physical activity is most useful. Not only does it have general favorable effects on the cardiovascular system, the energy metabolism and mental health, for example, but it may also stabilize the circadian system via feedback effects on the suprachiasmatic nuclei (SCN), the main circadian pacemaker. Regular physical activity helps to maintain high-amplitude circadian rhythms, particularly of clock gene expression in the SCN. It promotes their entrainment to external periodicities and improves the internal synchronization of various circadian rhythms. This in turn promotes health and wellbeing. In experiments on Djungarian hamsters, voluntary access to a running wheel not only stabilized the circadian activity rhythm, but intensive wheel running even reestablished the rhythm in arrhythmic individuals. Moreover, their cognitive abilities were restored. Djungarian hamsters of the arrhythmic phenotype in which the SCN do not generate a circadian signal not only have a diminished cognitive performance, but their social memory is also compromised. Voluntary wheel running restored these abilities simultaneously with the reestablishment of the circadian activity rhythm. Intensively exercising Syrian hamsters are less anxious, more resilient to social defeat, and show less defensive/submissive behaviors, i.e., voluntary exercise may promote self-confidence. Similar effects were described for humans. The aim of the present paper is to summarize the current knowledge concerning the effects of physical activity on the stability of the circadian system and the corresponding consequences for physical and mental performance.

Keywords: motor activity; circadian rhythms; circadian disruption; health; wellbeing; physical and mental performance



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1. Introduction

Circadian rhythms are an inherent property of all living systems and are generated by an internal clock. In mammals, this is localized in the suprachiasmatic nuclei (SCN) of the hypothalamus [1]. The SCN as central pacemakers are involved in the rhythmic regulation

of sleep–wake behavior [2], locomotor activity [3], metabolism [4], body temperature [5], and other body functions.

Circadian rhythms are an essential part of the external and internal temporal order. They enable organisms to be synchronized with their periodic environment, to be prepared for rather than react to periodic changes and coordinate physiological and behavioral processes. This guarantees an optimal functioning, and any disturbances, or so-called circadian disruptions, may have adverse consequences for health, physical and mental performance, wellbeing, and longevity [6–10]. Such disruptions do occur during aging [11–14], following time-zone transitions [15–17], in shift-workers [18,19], and in subjects suffering from different diseases [20–23]. However, in the latter case, it is not clear if circadian disruptions are a consequence of the disease or a cause.

Therefore, it is highly important to find approaches to synchronize circadian rhythms and, thus, stabilize the entire circadian system. Melatonin, as an effective chronobiotic, is often used [24]. However, the physiological effects of melatonin depend critically on dosing and timing. For chronobiotic purposes, physiologic doses (3 mg or less) are useful, while higher doses (3–10 mg or more) exert antioxidant and immunoregulatory effects [25,26]. Optimal dosing may be different between individuals. Even more important could be a personal adjustment of timing, since physiological responses to melatonin follow phase response curves [27]. When non-physiological doses have to be used, one must consider adverse side effects. Accordingly, non-pharmacological approaches may be preferred, except, for example, in very old people where the use of melatonin might be unavoidable [28,29].

The daily light–dark cycle is the main zeitgeber [30,31]. It synchronizes circadian rhythms with the 24-h environment. In our modern society, however, most people are exposed to only low levels of light in the daytime. On the contrary, the light levels in the evening or at night are often too high. Both have adverse consequences for the synchronization of the circadian rhythms with the 24-h environment and multiple negative effects on physiology, sleep, physical and mental performance, and well-being [19,32–35]. Accordingly, circadian light hygiene and a proper 24-h light regimen in the offices and homes become increasingly important [36–38].

Food can also serve as a synchronizer for the circadian system. Timed feeding may reset the SCN phase via a reinforcement of clock gene expression, entrain peripheral clocks, and facilitate intrinsic synchronization [39–42]. Thus, it can be used to strengthen the circadian system, which in turn promotes healthy aging and longevity [21,43,44].

Robust circadian clocks can also be facilitated by lifestyle, regular physical activity, and timed exercise. Aged people often adopt, although rather intuitively, a regular lifestyle [45,46]. However, a problem of our modern society is a general low level of physical activity [47]. This has adverse consequences for the cardiovascular system and the energy metabolism [48]. Moreover, direct effects on homeostatic physiological mechanisms and disturbances of the circadian system have a considerable impact. Scheduled physical activity is an efficient strategy to maintain circadian rhythms and contribute to healthy ageing [12,13,49]. It upholds feedback coupling with the central brain clock and helps to preserve synchronized circadian rhythms [10,50].

The aim of the present paper is to summarize the current knowledge concerning the effects of physical activity on the stability of the circadian system and the consequences of elevated daily activity for physical and mental health and performance. Most of the data came from experiments on animals. However, as they reflect general biological principles, they are equally true for humans.

2. Physical Activity and the Circadian System

2.1. The Diagnostic Value of Circadian Activity Rhythms

In humans, activity can be monitored easily over many days and at short sampling intervals by means of non-invasive devices worn on the wrist of the non-dominant hand [51]. This method is widely used in field research and in clinical settings, as it is simple, inexpensive, and rather accurate [52–54]. In laboratory animals, motor activity can be monitored by

transmitters that are implanted into the peritoneal cavity and allowing the simultaneous recording of core body temperature [55]. Moreover, most reliable and less expensive are passive infrared motion detectors that are mounted above the cage roof [56]. Both methods record general activity, not just locomotion.

The wide use of actimetry monitoring techniques makes circadian activity rhythm assessment a useful tool to survey circadian rhythm robustness [57,58]. Moreover, rhythm characteristics can be used as indicators of physical and mental fitness and the health status of human beings. Vitale and co-authors [59] used actigraphy to characterize the activity level and the daily activity rhythm of patients following hip and knee joint replacement and designed specific, personalized rehabilitation programs.

The inter-daily rhythm stability and the median level of daytime activity were found to be negatively correlated with cognitive decline and depression in elderly women [53]. Other authors compared the amounts of activity when in bed or out of bed. This can be a preferable option when the 24-h pattern is non-sinusoidal. The estimated dichotomy indices were decreased in diseased individuals, particularly in those suffering from colorectal cancer [54,60]. Together with the mean activity level and autocorrelation coefficients, they are an objective indicator of physical welfare and an appropriate prognostic factor for cancer patients' survival and tumour response [61–63]. According to Hoopes et al., characteristics of the rest–activity rhythm, especially the inter-daily stability and intra-daily variability, can be used as biomarkers of cardiometabolic health [64]. Irregular sleep duration and timing were recognized as novel cardiovascular risk factors, independent of other traditional factors and sleep quantity or quality [65]. An increased fragmentation of the 24-h activity rhythm is also positively associated with symptoms of food addiction [66]. Differences in the period length of the free-running activity rhythm were found in spontaneous hypertensive rats as compared to healthy controls [23]. Remarkably, changes occurred in the pre-hypertensive state already and not after the surgical induction of hypertension. In glaucoma patients, the sleep–wake rhythm was found to be compromised [67].

In laboratory animals, the onset of their main activity period is a convenient phase marker. It characterizes the strength of photic entrainment and undergoes predictable changes, for example, following a phase shift of the light–dark cycle [55,68] or during aging [69,70]. In old mice, a phase advance and a decreased phase stability of the activity onset were observed together with an increased inter-daily rhythm variability. These changes were found to happen earlier than the decrease in total activity per day and can be used to characterize the biological age [71,72]. Interestingly, similar changes were observed for the sleep–wake rhythm of aged people, particularly those suffering from Alzheimer's disease (AD) and Parkinson's disease [53,73–75]. In mild-to-moderate AD, increased fragmentation of the activity pattern predicted cognitive decline that was independent of age, sex, educational level, and season [76]. Interestingly, this work also reported an increased circadian amplitude, illustrating that rhythm stability, amplitude, and phase should be considered altogether to examine the distinctive types of circadian disruption, e.g., “extra-circadian dissemination” [57].

2.2. Beneficial Effects of Increasing the Daily Activity Level

Worldwide, a high percentage of people is physically inactive, especially in high-income countries, and this percentage increases with age [47,77]. The scarce physical activity of elderly people is at least partly caused by sarcopenia, though its progression can be reduced by regular exercise [78,79].

Physical inactivity is one of the most important factors causing lifestyle diseases. It substantially increases the risk of adverse health conditions and shortens life expectancy. Particularly, the incidence of coronary heart disease, metabolic diseases such as obesity and type 2 diabetes, and also breast and colon cancers has been shown to be elevated. Accordingly, a physically active behavior could improve health and has a protective effect on the development of diseases [48,80,81]. The improvement of methods to record physical

activity might help to develop programs to enhance activity levels and, thus, reduce the risk of non-communicable diseases.

Regular exercise helps to prevent cardiovascular disease [82], stroke [83], cancer [84], diabetes, and obesity [85]. It also has positive effects in patients suffering from neuropsychiatric disturbances. Aside from psychological mechanisms such as improved sleep and stress reduction, neurobiological mechanisms such as changes in neurotransmitter concentrations are also involved [86,87]. Exercise can prevent the development of stress-related mood disorders such as depression and anxiety and promote self-confidence. Animal models were used to elucidate the underlying mechanisms [88]. In Syrian hamsters, voluntary exercise promotes resilience to social defeat; animals are less anxious and show less defensive/submissive behaviors [89].

Physical activity positively influences cognitive function in patients with dementia, i.e., it decelerates the cognitive decline [90,91]. Experiments in rodents revealed that physical exercise regulates hippocampal neurogenesis, especially if it is performed in the context of cognitive challenges, and reduces learning deficits [92–96].

2.3. Effects of Motor Activity on the Circadian System

The above-mentioned effects of physical activity are at last in part mediated via the circadian system. It has been well known for many years that motor activity has a considerable impact on circadian rhythms, via a feedback effect on the central pacemaker, the SCN. A correlation between activity level and the period length of the rhythm generated in the SCN was found [56,97,98]. Intensive running wheel use also affects photic phase responses [99–101]. Bouts of physical activity may cause phase changes—so-called non-photic phase responses. Depending on the circadian time, activity bouts may cause a phase advance or a phase delay. Mrosovsky first published a non-photic phase response curve [102]. In Golden hamsters for example, a bout of motor activity in the middle of the light time, i.e., during the subjective day, causes a phase advance. The animals' next activity period starts earlier, i.e., the animals “wake up” and “go to sleep” earlier. Similar effects were described for humans [103]. One hour of moderate treadmill exercise for three consecutive days caused significant phase changes of the urinary aMT6s rhythm, the metabolic end-product of melatonin.

Motor activity and behavioral states may directly influence the neurophysiological properties of the SCN and affect clock genes expression [104–107]. This may be the causal reason for the above-mentioned changes in photic phase responses and free-running periods.

Steinlechner and co-authors [101] argued that the circadian rhythms of Djungarian hamsters can be stabilized by enhanced motor activity. Indeed, Ortega and coworkers demonstrated that wheel running rendered the synchronization of the circadian body temperature rhythm in the golden hamsters [108]. This hypothesis was further supported by studies on aging mice. When animals had access to running wheels, the activity onsets, which were highly variable and phase advanced, became stronger coupled to “lights-off” [14,109].

In Djungarian hamsters with a delayed activity onset, photic entrainment was stabilized by means of elevated motor activity [98,110]. Like many other rodent species, Djungarian hamsters use running wheels voluntarily, regularly, and intensively [111,112]. Some of them eventually developed a wild-type activity pattern with its onset being tightly coupled to “lights-off”; however, this phenomenon could not be explained by the observed changes of endogenous period lengths and photic phase responses. Obviously, mechanisms downstream from the suprachiasmatic nuclei are involved.

Circadian rhythms are reinstated, and cognitive performance is improved in arrhythmic (AR) Djungarian hamsters when they intensively use running wheels [10]. The underlying mechanisms of the AR phenomenon are not yet known. The loss of synchronization between single SCN neurons, similar to what was found in aged mice, is a putative factor [113]. In SCN slices of AR Djungarian hamsters a broad range of firing frequencies in the electrical activity was found [114]. The authors argued that this indicates a loss of

synchrony among SCN neurons. Our study showed that resynchronization and a proper phase relationship between SCN neurons can be achieved by motor activity. Regardless, a more robust output signal downstream from the SCN should foster consistent overt circadian rhythms such as activity.

The observed phenomenon might also be caused by another mechanism. In vivo studies demonstrated that behavioral activity may suppress the firing rate in the SCN of freely moving rodents, e.g., rats and hamsters [106,115], and mice [116]. Since behavioral activity can modulate the SCN firing rate, it may also boost circadian rhythms when activity occurs at the specific time (at night in the case of nocturnal species). These findings are supported by a study which showed that scheduled daily activity can improve behavioral circadian rhythms in mice with compromised SCN function [117]. The 24-h pattern of wheel-running activity observed in our study on AR Djungarian hamsters can also be recognized as some type of scheduled activity, since hamsters utilize the wheels only during the dark phase [10].

The enhancement of circadian rhythm amplitude in the SCN is beneficial for other rhythms controlled by the central pacemaker [116]. Interestingly, only voluntary exercise functions, as it is the arousal and namely the positive arousal that has an effect [118]. Aschoff called this “feedback for fun” (personal communication). This is also important for the beneficial effects, which are discussed in the next section. Physical exercise must be voluntary and fun, otherwise it is much less effective, if at all.

In humans, personalized timing, duration, and the type of exercise should enhance its benefits, particularly for cardiovascular health [119]. Evening exercise might be less beneficial [120]. Moreover, benefits may vary depending on chronotype [121,122], or when metabolic circadian rhythms are compromised in diseases such as diabetes [123]. Overall, considering the timing of exercise can be important in performance and disease contexts to improve circadian alignment and health status as a therapeutic and preventative strategy [124].

In humans, physical activity closely associates with time spent outdoors [125]. Time outdoors was a factor of higher physical activity during COVID-19 mandated lockdown [126]. It was also linked with better sleep, a higher quality of life, and less pronounced phase delay, which was common during lockdown for the majority of the population [126]. In this context, it should be outlined that outdoor activity is related to outdoor light exposure, and these factors act together in facilitating circadian alignment and robustness. Overall, more outdoor time can be linked with a more active lifestyle and lower chronic disease risks [125,126].

This review is mainly based on animal studies, limiting the immediate translation and application of the findings to humans. Therefore, future research aimed at clarifying the benefits of timed physical activity in men and women depending on age, chronotype, and relevant genetic polymorphisms are prompted.

2.4. Beneficial Effects of Stabilized Circadian Rhythms

As described above, physical activity has a strong impact on circadian rhythms, Figure 1. In rodents, it has been shown that voluntary access to a running wheel helps to maintain the high-amplitude circadian rhythms of clock and clock-controlled genes in the SCN. Similar effects can also be expected to occur in humans. As a consequence of high-amplitude circadian rhythms in the SCN, their rhythmic output that controls overt rhythms and peripheral oscillators is strengthened. Proper internal and external phase relationships can be established, and a circadian disruption be abolished [109,117]. This reduces the risk of diseases.

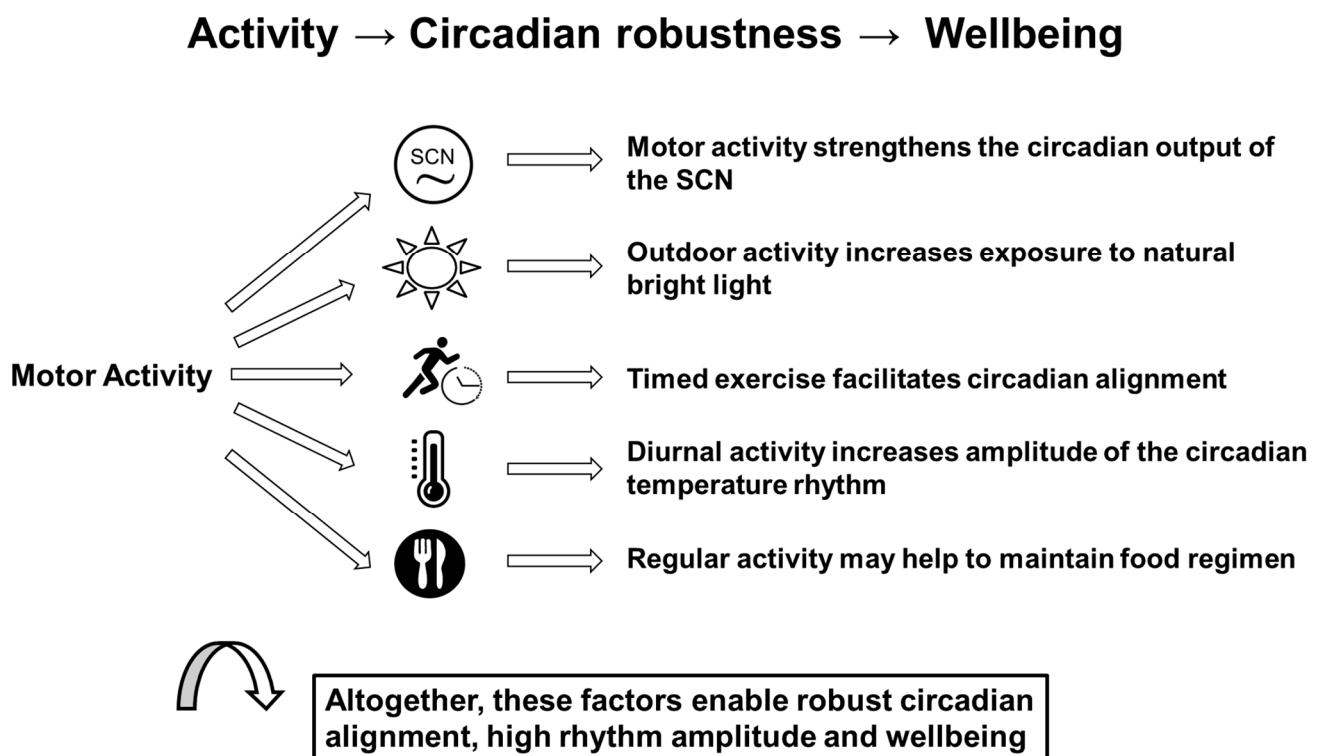


Figure 1. Daytime activity facilitates robust circadian rhythms and promotes health and well-being: schematic overview.

Voluntary exercise also strengthens the circadian system in elderly people. Thus, it can attenuate some age-related changes and improve their health and wellbeing. Higher levels of physical activity in older individuals correlates with a high circadian amplitude of clock gene *Per3* expression [127]. Moreover, the rhythmic expression of *PER3* is associated with physical fitness in older adults. Dupon Rocher et al. have shown that the amplitude of the circadian temperature rhythm is correlated with a higher level of physical activity in older adults [128].

The resynchronization time, e.g., following a time-zone transition, can be shortened, and the adaptation to shift work be improved by means of physical exercise. This has been shown particularly in experiments with induced jet lag [129,130]. Moreover, physical exercise is generally useful to adjust human circadian rhythms to external time cues [131,132] and to synchronize the whole circadian system [133].

As a consequence of stabilized circadian rhythms by means of enhanced physical activity, the cognitive performance can be improved. The SCN are involved in cognitive processes, and stable circadian rhythms are essential for cognitive abilities [134]. Disruption of the circadian sleep–wake cycle may have adverse consequences for neurobehavioral performance [135], because sleep is one of the most critical factors, which may affect cognitive abilities by improving the consolidation of information [136–138]. Moreover, processes such as learning and memory are modulated in a circadian manner.

The importance of the circadian system for cognitive processes has been shown particularly in animal experiments. First, the best cognitive performance was demonstrated in studies where the temporal sequence of tests was in harmony with the 24-h rhythm [139]. Second, cognitive performance differs over the 24-h scale, or in a circadian manner [140,141]. Third, the disruption of the circadian rhythms compromises cognitive abilities. In rats exposed to repeated phase shifts of the light–dark cycle, the learning in the Morris water-maze—particularly the long-term retention—was impaired [142]. Studies of Ruby et al. on arrhythmic Djungarian hamsters revealed substantial deficits in object recognition and spatial working memory [143–145]. These hamsters were rendered arrhythmic by light treatment [146]. In our colony of Djungarian hamsters, the arrhythmic phenotype emerges

spontaneously [98]. Djungarian hamsters with a well-functioning circadian system show a pronounced daily rhythm of cognitive abilities, with the best performance during the activity period. On the other hand, animals of the arrhythmic phenotype, in which the SCN do not generate a circadian signal, not only have no rhythm in their cognitive abilities, but they also fail to perform a novel object recognition task, and show an impaired individual recognition and social memory performance [7,141]. When the animals had access to a running wheel, part of them reestablished a circadian activity rhythm, namely those who used the wheel most intensively. In these animals, cognitive abilities were also restored [10].

Daytime activity associates with exposure to more bright ambient light, temperature circadian amplitude increase—factors that altogether foster circadian alignment and may help to maintain a healthy circadian diet.

3. Conclusions

In the modern world, lifestyle is responsible for almost two-thirds of all cases of disease globally. The World Health Organization has pinpointed the lack of exercise as one of the most important factors causing lifestyle diseases. Not only the amount of activity, but also the time of exercise is important, since time-scheduled activity can be a circadian zeitgeber.

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References

1. Reppert, S.M.; Weaver, D.R. Coordination of circadian timing in mammals. *Nature* **2002**, *418*, 935–941. [[CrossRef](#)]
2. Dijk, D.J.; Lockley, S.W. Integration of human sleep-wake regulation and circadian rhythmicity. *J. Appl. Physiol.* **2002**, *92*, 852–862. [[CrossRef](#)]
3. Wollnik, F.; Turek, F.W. SCN lesions abolish ultradian and circadian components of activity rhythms in LEW/Ztm rats. *Am. J. Physiol.* **1989**, *256*, R1027–R1039. [[CrossRef](#)]
4. Kalsbeek, A.; Scheer, F.A.; Perreau-Lenz, S.; La Fleur, S.E.; Yi, C.X.; Fliers, E.; Buijs, R.M. Circadian disruption and SCN control of energy metabolism. *FEBS Lett.* **2011**, *585*, 1412–1426. [[CrossRef](#)]
5. Waterhouse, J.; Drust, B.; Weinert, D.; Edwards, B.; Gregson, W.; Atkinson, G.; Kao, S.; Aizawa, S.; Reilly, T. The circadian rhythm of core temperature: Origin and some implications for exercise performance. *Chronobiol. Int.* **2005**, *22*, 207–225. [[CrossRef](#)]
6. Hurd, M.W.; Ralph, M.R. The significance of circadian organization for longevity in the golden hamster. *J. Biol. Rhythm.* **1998**, *13*, 430–436. [[CrossRef](#)]
7. Müller, L.; Weinert, D. Individual recognition of social rank and social memory performance depends on a functional circadian system. *Behav Process.* **2016**, *132*, 85–93. [[CrossRef](#)]
8. Sharma, A.; Tiwari, S.; Singaravel, M. Circadian rhythm disruption: Health consequences. *Biol. Rhythm Res.* **2015**, *47*, 191–213. [[CrossRef](#)]
9. Smolensky, M.H.; Hermida, R.C.; Reinberg, A.; Sackett-Lundeen, L.; Portaluppi, F. Circadian disruption: New clinical perspective of disease pathology and basis for chronotherapeutic intervention. *Chronobiol. Int.* **2016**, *33*, 1101–1119. [[CrossRef](#)]
10. Weinert, D.; Schöttner, K.; Müller, L.; Wienke, A. Intensive voluntary wheel running may restore circadian activity rhythms and improves the impaired cognitive performance of arrhythmic Djungarian hamsters. *Chronobiol. Int.* **2016**, *33*, 1161–1170. [[CrossRef](#)]
11. Gubin, D.G.; Weinert, D. Temporal order deterioration and circadian disruption with age. 1. Central and peripheral mechanisms. *Adv. Gerontol.* **2015**, *5*, 209–218. [[CrossRef](#)]
12. Gubin, D.G.; Weinert, D. Deterioration of Temporal Order and Circadian Disruption with Age 2: Systemic Mechanisms of Aging Related Circadian Disruption and Approaches to Its Correction. *Adv. Gerontol.* **2016**, *6*, 10–20. [[CrossRef](#)]
13. Gubin, D.G.; Weinert, D.; Bolotnova, T.V. Age-Dependent Changes of the Temporal Order—Causes and Treatment. *Curr. Aging Sci.* **2016**, *9*, 14–25. [[CrossRef](#)]
14. Weinert, D. Age-dependent changes of the circadian system. *Chronobiol. Int.* **2000**, *17*, 261–283. [[CrossRef](#)]

15. Casiraghi, L.P.; Oda, G.A.; Chiesa, J.J.; Friesen, W.O.; Golombek, D.A. Forced Desynchronization of Activity Rhythms in a Model of Chronic Jet Lag in Mice. *J. Biol. Rhythm.* **2012**, *27*, 59–69. [[CrossRef](#)]
16. Waterhouse, J.; Kao, S.; Edwards, B.; Weinert, D.; Atkinson, G.; Reilly, T. Transient changes in the pattern of food intake following a simulated time-zone transition to the east across eight time zones. *Chronobiol. Int.* **2005**, *22*, 299–319. [[CrossRef](#)]
17. Waterhouse, J.; Reilly, T.; Atkinson, G.; Edwards, B. Jet lag: Trends and coping strategies. *Lancet* **2007**, *369*, 1117–1129. [[CrossRef](#)]
18. Shurkevich, N.P.; Vetoshkin, A.S.; Gapon, L.I.; Dyachkov, S.M.; Gubin, D.G. Prognostic value of blood pressure circadian rhythm disturbances in normotensive shift workers of the Arctic polar region. *Arter. Hypertens.* **2017**, *23*, 36–46. (In Russian)
19. Touitou, Y.; Reinberg, A.; Touitou, D. Association between light at night, melatonin secretion, sleep deprivation, and the internal clock: Health impacts and mechanisms of circadian disruption. *Life Sci.* **2017**, *173*, 94–106. [[CrossRef](#)]
20. Gubin, D.G.; Nelaeva, A.A.; Uzhakova, A.E.; Hasanova, Y.V.; Cornelissen, G.; Weinert, D. Disrupted circadian rhythms of body temperature, heart rate and fasting blood glucose in prediabetes and type 2 diabetes mellitus. *Chronobiol. Int.* **2017**, *34*, 1136–1148. [[CrossRef](#)]
21. Kent, B.A. Synchronizing an aging brain: Can entraining circadian clocks by food slow Alzheimer’s disease? *Front. Aging Neurosci.* **2014**, *6*, 234. [[CrossRef](#)] [[PubMed](#)]
22. Neroev, V.; Malishevskaya, T.; Weinert, D.; Astakhov, S.; Kolomeichuk, S.; Cornelissen, G.; Kabitskaya, Y.; Boiko, E.; Nemtsova, I.; Gubin, D. Disruption of 24-Hour Rhythm in Intraocular Pressure Correlates with Retinal Ganglion Cell Loss in Glaucoma. *Int. J. Mol. Sci.* **2021**, *22*, 359. [[CrossRef](#)] [[PubMed](#)]
23. Yilmaz, A.; Kalsbeek, A.; Buijs, R.M. Functional changes of the SCN in spontaneous hypertension but not after the induction of hypertension. *Chronobiol. Int.* **2018**, *35*, 1221–1235. [[CrossRef](#)]
24. Cardinali, D.P. Melatonin as a chronobiotic/cytoprotector: Its role in healthy aging. *Biol. Rhythm Res.* **2019**, *50*, 28–45. [[CrossRef](#)]
25. Cardinali, D.P.; Brown, G.M.; Pandi-Perumal, S.R. Can Melatonin Be a Potential “Silver Bullet” in Treating COVID-19 Patients? *Diseases* **2020**, *8*, 44. [[CrossRef](#)]
26. Hardeland, R. Divergent Importance of Chronobiological Considerations in High- and Low-dose Melatonin Therapies. *Diseases* **2021**, *9*, 18. [[CrossRef](#)]
27. Lewy, A.J.; Ahmed, S.; Jackson, J.M.; Sack, R.L. Melatonin shifts human circadian rhythms according to a phase-response curve. *Chronobiol. Int.* **1992**, *9*, 380–392. [[CrossRef](#)]
28. Gubin, D.G.; Gubin, G.D.; Gapon, L.I.; Weinert, D. Daily Melatonin Administration Attenuates Age-Dependent Disturbances of Cardiovascular Rhythms. *Curr. Aging Sci.* **2016**, *9*, 5–13. [[CrossRef](#)]
29. Gubin, D.G.; Gubin, G.D.; Waterhouse, J.; Weinert, D. The circadian body temperature rhythm in the elderly: Effect of single daily melatonin dosing. *Chronobiol. Int.* **2006**, *23*, 639–658. [[CrossRef](#)]
30. Daan, S. The Colin S. Pittendrigh Lecture. Colin Pittendrigh, Jürgen Aschoff, and the natural entrainment of circadian systems. *J. Biol. Rhythm.* **2000**, *15*, 195–207. [[CrossRef](#)]
31. Golombek, D.A.; Rosenstein, R.E. Physiology of circadian entrainment. *Physiol. Rev.* **2010**, *90*, 1063–1102. [[CrossRef](#)] [[PubMed](#)]
32. Cho, Y.; Ryu, S.-H.; Lee, B.R.; Kim, K.H.; Lee, E.; Choi, J. Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment. *Chronobiol. Int.* **2015**, *32*, 1294–1310. [[CrossRef](#)] [[PubMed](#)]
33. Green, A.; Cohen-Zion, M.; Haim, A.; Dagan, Y. Evening light exposure to computer screens disrupts human sleep, biological rhythms, and attention abilities. *Chronobiol. Int.* **2017**, *34*, 855–865. [[CrossRef](#)] [[PubMed](#)]
34. Gubin, D.G.; Weinert, D.; Rybina, S.V.; Danilova, L.A.; Solovieva, S.V.; Durov, A.M.; Prokopiev, N.Y.; Ushakov, P.A. Activity, sleep and ambient light have a different impact on circadian blood pressure, heart rate and body temperature rhythms. *Chronobiol. Int.* **2017**, *34*, 632–649. [[CrossRef](#)] [[PubMed](#)]
35. Smolensky, M.H.; Sackett-Lundeen, L.L.; Portaluppi, F. Nocturnal light pollution and underexposure to daytime sunlight: Complementary mechanisms of circadian disruption and related diseases. *Chronobiol. Int.* **2015**, *32*, 1029–1048. [[CrossRef](#)]
36. Cajochen, C.; Freyburger, M.; Basishvili, T.; Garbazza, C.; Rudzik, F.; Renz, C.; Kobayashi, K.; Shirakawa, Y.; Stefani, O.; Weibel, J. Effect of daylight LED on visual comfort, melatonin, mood, waking performance and sleep. *Light. Res. Technol.* **2019**, *51*, 1044–1062. [[CrossRef](#)]
37. Lowden, A.; Ozturk, G.; Reynolds, A.; Bjorvatn, B. Working Time Society consensus statements: Evidence based interventions using light to improve circadian adaptation to working hours. *Ind. Health* **2019**, *57*, 213–227. [[CrossRef](#)]
38. Soltic, S.; Chalmers, A. Optimization of LED Lighting for Clinical Settings. *J. Healthc. Eng.* **2019**, *2019*, 5016013. [[CrossRef](#)]
39. Castillo, M.R.; Hochstetler, K.J.; Tavernier, R.J., Jr.; Greene, D.M.; Bult-Ito, A. Entrainment of the master circadian clock by scheduled feeding. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **2004**, *287*, R551–R555. [[CrossRef](#)]
40. Froy, O.; Miskin, R. Effect of feeding regimens on circadian rhythms: Implications for aging and longevity. *Aging* **2010**, *2*, 7–27. [[CrossRef](#)]
41. Lamont, E.W.; Diaz, L.R.; Barry-Shaw, J.; Stewart, J.; Amir, S. Daily restricted feeding rescues a rhythm of period2 expression in the arrhythmic suprachiasmatic nucleus. *Neuroscience* **2005**, *132*, 245–248. [[CrossRef](#)] [[PubMed](#)]
42. Stokkan, K.A.; Yamazaki, S.; Tei, H.; Sakaki, Y.; Menaker, M. Entrainment of the circadian clock in the liver by feeding. *Science* **2001**, *291*, 490–493. [[CrossRef](#)]
43. Acosta-Rodriguez, V.A.; Rijo-Ferreira, F.; Green, C.B.; Takahashi, J.S. Importance of circadian timing for aging and longevity. *Nat. Commun.* **2021**, *12*, 2862. [[CrossRef](#)] [[PubMed](#)]

44. Mistlberger, R.E.; Antle, M.C. Entrainment of circadian clocks in mammals by arousal and food. *Essays Biochem.* **2011**, *49*, 119–136.
45. Minors, D.; Atkinson, G.; Bent, N.; Rabbitt, P.; Waterhouse, J. The effects of age upon some aspects of lifestyle and implications for studies on circadian rhythmicity. *Age Ageing* **1998**, *27*, 67–72. [[CrossRef](#)]
46. Monk, T.H.; Reynolds, C.F., III; Kupfer, D.J.; Hoch, C.C.; Carrier, J.; Houck, P.R. Differences over the life span in daily life-style regularity. *Chronobiol. Int.* **1997**, *14*, 295–306. [[CrossRef](#)] [[PubMed](#)]
47. Hallal, P.C.; Andersen, L.B.; Bull, F.C.; Guthold, R.; Haskell, W.; Ekelund, U. Lancet Physical Activity Series Working G. Global physical activity levels: Surveillance progress, pitfalls, and prospects. *Lancet* **2012**, *380*, 247–257. [[CrossRef](#)]
48. Lee, I.M.; Shiroma, E.J.; Lobelo, F.; Puska, P.; Blair, S.N.; Katzmarzyk, P.T. Effect of physical inactivity on major non-communicable diseases worldwide: An analysis of burden of disease and life expectancy. *Lancet* **2012**, *380*, 219–229. [[CrossRef](#)]
49. de Souza Teixeira, A.A.; Lira, F.S.; Rosa-Neto, J.C. Aging with rhythmicity. Is it possible? Physical exercise as a pacemaker. *Life Sci.* **2020**, *261*, 118453. [[CrossRef](#)]
50. Weinert, D.; Waterhouse, J. The circadian rhythm of core temperature: Effects of physical activity and aging. *Physiol. Behav.* **2007**, *90*, 246–256. [[CrossRef](#)]
51. Bellone, G.J.; Plano, S.A.; Cardinali, D.P.; Chada, D.P.; Vigo, D.E.; Golombek, D.A. Comparative analysis of actigraphy performance in healthy young subjects. *Sleep Sci.* **2016**, *9*, 272–279. [[CrossRef](#)]
52. Ancoli-Israel, S.; Cole, R.; Alessi, C.; Chambers, M.; Moorcroft, W.; Pollak, C.P. The role of actigraphy in the study of sleep and circadian rhythms. *Sleep* **2003**, *26*, 342–392. [[CrossRef](#)]
53. Carvalho-Bos, S.S.; Riemersma-van der Lek, R.F.; Waterhouse, J.; Reilly, T.; Van Someren, E.J. Strong association of the rest-activity rhythm with well-being in demented elderly women. *Am. J. Geriatr. Psychiatry* **2007**, *15*, 92–100. [[CrossRef](#)]
54. Chevalier, V.; Mormont, M.C.; Cure, H.; Chollet, P. Assessment of circadian rhythms by actimetry in healthy subjects and patients with advanced colorectal cancer. *Oncol. Rep.* **2003**, *10*, 733–737. [[PubMed](#)]
55. Weinert, D.; Sturm, J.; Waterhouse, J. Different behavior of the circadian rhythms of activity and body temperature during resynchronization following an advance of the LD cycle. *Biol. Rhythm Res.* **2002**, *33*, 187–197. [[CrossRef](#)]
56. Weinert, D.; Weiss, T. A nonlinear interrelationship between period length and the amount of activity—Age-dependent changes. *Biol. Rhythm Res.* **1997**, *28*, 105–120. [[CrossRef](#)]
57. Gubin, D.; Weinert, D.; Cornelissen, G. Chronotherapeutics and chronotherapy—Frontiers for personalized medicine. *J. Chronomed.* **2020**, *22*, 3–23. [[CrossRef](#)]
58. Martinez-Nicolas, A.; Madrid, J.A.; García, F.J.; Campos, M.; Moreno-Casbas, M.T.; Almáida-Pagán, P.F.; Lucas-Sánchez, A.; Rol, M.A. Circadian monitoring as an aging predictor. *Sci. Rep.* **2018**, *8*, 15027. [[CrossRef](#)]
59. Vitale, J.A.; Banfi, G.; Tivolesi, V.; Pelosi, C.; Borghi, S.; Negrini, F. Rest-activity daily rhythm and physical activity levels after hip and knee joint replacement: The role of actigraphy in orthopedic clinical practice. *Chronobiol. Int.* **2021**, *38*, 1692–1701. [[CrossRef](#)]
60. Minors, D.; Akerstedt, T.; Atkinson, G.; Dahlitz, M.; Folkard, S.; Levi, F.; Mormont, C.; Parkes, D.; Waterhouse, J. The difference between activity when in bed and out of bed. I. Healthy subjects and selected patients. *Chronobiol. Int.* **1996**, *13*, 27–34. [[CrossRef](#)]
61. Mormont, M.C.; Langouet, A.M.; Claustrat, B.; Bogdan, A.; Marion, S.; Waterhouse, J.; Touitou, Y.; Levi, F. Marker rhythms of circadian system function: A study of patients with metastatic colorectal cancer and good performance status. *Chronobiol. Int.* **2002**, *19*, 141–155. [[CrossRef](#)] [[PubMed](#)]
62. Mormont, M.C.; Waterhouse, J. Contribution of the rest-activity circadian rhythm to quality of life in cancer patients. *Chronobiol. Int.* **2002**, *19*, 313–323. [[CrossRef](#)]
63. Mormont, M.C.; Waterhouse, J.; Bleuzen, P.; Giacchetti, S.; Jami, A.; Bogdan, A.; Lellouch, J.; Misset, J.L.; Touitou, Y.; Levi, F. Marked 24-h rest/activity rhythms are associated with better quality of life, better response, and longer survival in patients with metastatic colorectal cancer and good performance status. *Clin. Cancer Res.* **2000**, *6*, 3038–3045.
64. Hoopes, E.K.; Witman, M.A.; D’Agata, M.N.; Berube, F.R.; Brewer, B.; Malone, S.K.; Grandner, M.A.; Patterson, F. Rest-activity rhythms in emerging adults: Implications for cardiometabolic health. *Chronobiol. Int.* **2021**, *38*, 543–556. [[CrossRef](#)]
65. Huang, T.; Mariani, S.; Redline, S. Sleep Irregularity and Risk of Cardiovascular Events. *J. Am. Coll. Cardiol.* **2020**, *75*, 991–999. [[CrossRef](#)]
66. Borisenkov, M.; Tserne, T.; Bakutova, L.; Gubin, D. Food Addiction and Emotional Eating Are Associated with Intradaily Rest–Activity Rhythm Variability. *Eat Weight Disord.* **2022**. [[CrossRef](#)]
67. Gubin, D.G.; Malishevskaya, T.N.; Astakhov, Y.S.; Astakhov, S.Y.; Cornelissen, G.; Kuznetsov, V.A.; Weinert, D. Progressive retinal ganglion cell loss in primary open-angle glaucoma is associated with temperature circadian rhythm phase delay and compromised sleep. *Chronobiol. Int.* **2019**, *36*, 564–577. [[CrossRef](#)]
68. Schöttner, K.; Limbach, A.; Weinert, D. Re-entrainment behavior of Djungarian hamsters (*Phodopus sungorus*) with different rhythmic phenotype following light-dark shifts. *Chronobiol. Int.* **2011**, *28*, 58–69. [[CrossRef](#)]
69. Weinert, H.; Weinert, D. Circadian activity rhythms of laboratory mice during the last weeks of their life. *Biol. Rhythm Res.* **1998**, *29*, 159–178. [[CrossRef](#)]
70. Weinert, H.; Weinert, D.; Waterhouse, J. The circadian activity and body temperature rhythms of mice during their last days of life. *Biol. Rhythm Res.* **2002**, *33*, 199–212. [[CrossRef](#)]
71. Sturm, J.; Weinert, H.; Weinert, D. Age-dependent changes in the stability of the daily activity rhythms of laboratory mice. *Z. Saugetierkd. Int. J. Mamm. Biol.* **2000**, *65*, 21–32.

72. Weinert, H.; Weinert, D.; Schurov, I.; Maywood, E.S.; Hastings, M.H. Impaired expression of the mPer2 circadian clock gene in the suprachiasmatic nuclei of aging mice. *Chronobiol. Int.* **2001**, *18*, 559–565. [[CrossRef](#)] [[PubMed](#)]
73. Li, P.; Gao, L.; Gaba, A.; Yu, L.; Cui, L.; Fan, W.; Lim, A.S.P.; Bennett, D.A.; Buchman, A.S.; Hu, K. Circadian disturbances in Alzheimer’s disease progression: A prospective observational cohort study of community-based older adults. *Lancet Healthy Longev.* **2020**, *1*, e96–e105. [[CrossRef](#)]
74. Werth, E.; Savaskan, E.; Knoblauch, V.; Gasio, P.F.; van Someren, E.J.; Hock, C.; Wirz-Justice, A. Decline in long-term circadian rest-activity cycle organization in a patient with dementia. *J. Geriatr. Psychiatry Neurol.* **2002**, *15*, 55–59. [[CrossRef](#)] [[PubMed](#)]
75. Zampogna, A.; Manoni, A.; Asci, F.; Liguori, C.; Irrera, F.; Suppa, A. Shedding Light on Nocturnal Movements in Parkinson’s Disease: Evidence from Wearable Technologies. *Sensors* **2020**, *20*, 5171. [[CrossRef](#)] [[PubMed](#)]
76. Targa, A.D.S.; Benítez, I.D.; Dakterzada, F.; Fontenele-Araujo, J.; Minguez, O.; Zetterberg, H.; Blennow, K.; Barbé, F.; Piñol-Ripoll, G. The circadian rest-activity pattern predicts cognitive decline among mild-moderate Alzheimer’s disease patients. *Alzheimers Res. Ther.* **2021**, *13*, 161. [[CrossRef](#)]
77. Charansonney, O.L. Physical activity and aging: A life-long story. *Discov. Med.* **2011**, *12*, 177–185.
78. Choi, Y.; Cho, J.; No, M.-H.; Heo, J.-W.; Cho, E.-J.; Chang, E.; Park, D.-H.; Kang, J.-H.; Kwak, H.-B. Re-Setting the Circadian Clock Using Exercise against Sarcopenia. *Int. J. Mol. Sci.* **2020**, *21*, 3106. [[CrossRef](#)]
79. Kume, Y.; Kodama, A.; Maekawa, H. Preliminary report; Comparison of the circadian rest-activity rhythm of elderly Japanese community-dwellers according to sarcopenia status. *Chronobiol. Int.* **2020**, *37*, 1099–1105. [[CrossRef](#)]
80. Balbus, J.M.; Barouki, R.; Birnbaum, L.S.; Etzel, R.A.; Gluckman, P.D.; Grandjean, P.; Hancock, C.; Hanson, M.A.; Heindel, J.J.; Hoffman, K.; et al. Early-life prevention of non-communicable diseases. *Lancet* **2013**, *38*, 3–4. [[CrossRef](#)]
81. Kelly, S.A.; Pomp, D. Genetic determinants of voluntary exercise. *Trends Genet.* **2013**, *29*, 348–357. [[CrossRef](#)] [[PubMed](#)]
82. Stensel, D. Primary prevention of CVD: Physical activity. *BMJ Clin. Evid.* **2009**, *2009*, 0218. [[PubMed](#)]
83. Gallanagh, S.; Quinn, T.J.; Alexander, J.; Walters, M.R. Physical activity in the prevention and treatment of stroke. *ISRN Neurol.* **2011**, *2011*, 953818. [[CrossRef](#)] [[PubMed](#)]
84. Denlinger, C.S.; Engstrom, P.F. Colorectal cancer survivorship: Movement matters. *Cancer Prev. Res.* **2011**, *4*, 502–511. [[CrossRef](#)]
85. Wadden, T.A.; Webb, V.L.; Moran, C.H.; Bailer, B.A. Lifestyle modification for obesity: New developments in diet, physical activity, and behavior therapy. *Circulation* **2012**, *125*, 1157–1170. [[CrossRef](#)]
86. Matura, S.; Carvalho, A.F.; Alves, G.S.; Pantel, J. Physical Exercise for the Treatment of Neuropsychiatric Disturbances in Alzheimer’s Dementia: Possible Mechanisms, Current Evidence and Future Directions. *Curr. Alzheimer Res.* **2016**, *13*, 1112–1123. [[CrossRef](#)]
87. Vyazovskiy, V.V.; Ruijgrok, G.; Deboer, T.; Tobler, I. Running wheel accessibility affects the regional electroencephalogram during sleep in mice. *Cereb. Cortex.* **2006**, *16*, 328–336. [[CrossRef](#)]
88. Greenwood, B.N.; Fleshner, M. Exercise, learned helplessness, and the stress-resistant brain. *Neuromol. Med.* **2008**, *10*, 81–98. [[CrossRef](#)]
89. Kingston, R.C.; Smith, M.; Lacey, T.; Edwards, M.; Best, J.N.; Markham, C.M. Voluntary exercise increases resilience to social defeat stress in Syrian hamsters. *Physiol. Behav.* **2018**, *188*, 194–198. [[CrossRef](#)]
90. Groot, C.; Hooghiemstra, A.M.; Raijmakers, P.G.H.M.; van Berckel, B.N.M.; Scheltens, P.; Scherder, E.J.A.; van der Flier, W.M.; Ossenkoppele, R. The effect of physical activity on cognitive function in patients with dementia: A meta-analysis of randomized control trials. *Ageing Res. Rev.* **2016**, *25*, 13–23. [[CrossRef](#)]
91. Winchester, J.; Dick, M.B.; Gillen, D.; Reed, B.; Miller, B.; Tinklenberg, J.; Mungas, D.; Chui, H.; Galasko, D.; Hewett, L.; et al. Walking stabilizes cognitive functioning in Alzheimer’s disease (AD) across one year. *Arch. Gerontol. Geriatr.* **2013**, *56*, 96–103. [[CrossRef](#)] [[PubMed](#)]
92. Fabel, K.; Kempermann, G. Physical activity and the regulation of neurogenesis in the adult and aging brain. *Neuromol. Med.* **2008**, *10*, 59–66. [[CrossRef](#)]
93. Feter, N.; Spanevello, R.M.; Soares, M.S.P.; Spohr, L.; Pedra, N.S.; Bona, N.P.; Freitas, M.P.; Gonzales, N.G.; Ito, L.G.M.S.; Stefanello, F.M.; et al. How does physical activity and different models of exercise training affect oxidative parameters and memory? *Physiol. Behav.* **2019**, *201*, 42–52. [[CrossRef](#)] [[PubMed](#)]
94. Mustrup, M.L.; Chen, S.; Desai, S.C.; Cay, E.B.; DeYoung, E.K.; Rhodes, J.S. Aerobic exercise is the critical variable in an enriched environment that increases hippocampal neurogenesis and water maze learning in male C57BL/6J mice. *Neuroscience* **2012**, *219*, 62–71. [[CrossRef](#)] [[PubMed](#)]
95. Rajizadeh, M.A.; Esmailpour, K.; Masoumi-Ardakani, Y.; Bejeshk, M.A.; Shabani, M.; Nakhaee, N.; Ranjbar, M.P.; Borzadaran, F.M.; Sheibani, V. Voluntary exercise impact on cognitive impairments in sleep-deprived intact female rats. *Physiol. Behav.* **2018**, *188*, 58–66. [[CrossRef](#)]
96. van Praag, H.; Christie, B.R.; Sejnowski, T.J.; Gage, F.H. Running enhances neurogenesis, learning, and long-term potentiation in mice. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 13427–13431. [[CrossRef](#)]
97. Edgar, D.M.; Kilduff, T.S.; Martin, C.E.; Dement, W.C. Influence of running wheel activity on free-running sleep/wake and drinking circadian rhythms in mice. *Physiol. Behav.* **1991**, *50*, 373–378. [[CrossRef](#)]
98. Weinert, D.; Schöttner, K. An inbred lineage of Djungarian hamsters with a strongly attenuated ability to synchronize. *Chronobiol. Int.* **2007**, *24*, 1065–1079. [[CrossRef](#)]

99. Antle, M.C.; Sterniczuk, R.; Smith, V.M.; Hagel, K. Non-photic modulation of phase shifts to long light pulses. *J. Biol. Rhythm.* **2007**, *22*, 524–533. [[CrossRef](#)]
100. Ralph, M.R.; Mrosovsky, N. Behavioral inhibition of circadian responses to light. *J. Biol. Rhythm.* **1992**, *7*, 353–359. [[CrossRef](#)]
101. Steinlechner, S.; Stieglitz, A.; Ruf, T. Djungarian hamsters: A species with a labile circadian pacemaker? Arrhythmicity under a light-dark cycle induced by short light pulses. *J. Biol. Rhythm.* **2002**, *17*, 248–258. [[CrossRef](#)] [[PubMed](#)]
102. Mrosovsky, N.; Salmon, P.A.; Menaker, M.; Ralph, M.R. Nonphotic phase shifting in hamster clock mutants. *J. Biol. Rhythm.* **1992**, *7*, 41–49. [[CrossRef](#)]
103. Youngstedt, S.D.; Elliott, J.A.; Kripke, D.F. Human circadian phase-response curves for exercise. *J. Physiol.* **2019**, *597*, 2253–2268. [[CrossRef](#)] [[PubMed](#)]
104. Deboer, T.; Vansteensel, M.J.; Detari, L.; Meijer, J.H. Sleep states alter activity of suprachiasmatic nucleus neurons. *Nat. Neurosci.* **2003**, *6*, 1086–1090. [[CrossRef](#)]
105. Maywood, E.S.; Okamura, H.; Hastings, M.H. Opposing actions of neuropeptide Y and light on the expression of circadian clock genes in the mouse suprachiasmatic nuclei. *Eur. J. Neurosci.* **2002**, *15*, 216–220. [[CrossRef](#)] [[PubMed](#)]
106. Schaap, J.; Meijer, J.H. Opposing effects of behavioural activity and light on neurons of the suprachiasmatic nucleus. *Eur. J. Neurosci.* **2001**, *13*, 1955–1962. [[CrossRef](#)]
107. Song, Y.; Choi, G.; Jang, L.; Kim, S.-W.; Jung, K.-H.; Park, H. Circadian rhythm gene expression and daily melatonin levels vary in athletes and sedentary males. *Biol. Rhythm Res.* **2018**, *49*, 237–245. [[CrossRef](#)]
108. Ortega, G.J.; Romanelli, L.; Golombek, D.A. Statistical and dynamical analysis of circadian rhythms. *J. Theor. Biol.* **1994**, *169*, 15–21. [[CrossRef](#)]
109. Leise, T.L.; Harrington, M.E.; Molyneux, P.C.; Song, I.; Queenan, H.; Zimmerman, E.; Lall, G.S.; Biello, S.M. Voluntary exercise can strengthen the circadian system in aged mice. *Age* **2013**, *35*, 2137–2152. [[CrossRef](#)]
110. Weinert, D.; Schottner, K.; Meinecke, A.C.; Hauer, J. Voluntary exercise stabilizes photic entrainment of djungarian hamsters (*Phodopus sungorus*) with a delayed activity onset. *Chronobiol. Int.* **2018**, *35*, 1435–1444. [[CrossRef](#)]
111. Meijer, J.H.; Robbers, Y. Wheel running in the wild. *Proc. R. Soc. B Biol. Sci.* **2014**, *281*, 20140210. [[CrossRef](#)] [[PubMed](#)]
112. Mrosovsky, N.; Salmon, P.A.; Vrang, N. Revolutionary science: An improved running wheel for hamsters. *Chronobiol. Int.* **1998**, *15*, 147–158. [[CrossRef](#)] [[PubMed](#)]
113. Farajnia, S.; Michel, S.; Deboer, T.; van der Leest, H.T.; Houben, T.; Rohling, J.H.; Ramkisoensing, A.; Yassenkov, R.; Meijer, J.H. Evidence for neuronal desynchrony in the aged suprachiasmatic nucleus clock. *J. Neurosci.* **2012**, *32*, 5891–5899. [[CrossRef](#)] [[PubMed](#)]
114. Margraf, R.R.; Puchalski, W.; Lynch, G.R. Absence of a daily neuronal rhythm in the suprachiasmatic nuclei of acircadian Djungarian hamsters. *Neurosci. Lett.* **1992**, *142*, 175–178. [[CrossRef](#)]
115. Yamazaki, S.; Kerbeshian, M.C.; Hocker, C.G.; Block, G.D.; Menaker, M. Rhythmic properties of the hamster suprachiasmatic nucleus in vivo. *J. Neurosci.* **1998**, *18*, 10709–10723. [[CrossRef](#)]
116. van Oosterhout, F.; Lucassen, E.A.; Houben, T.; van der Leest, H.T.; Antle, M.C.; Meijer, J.H. Amplitude of the SCN clock enhanced by the behavioral activity rhythm. *PLoS ONE* **2012**, *7*, e39693.
117. Power, A.; Hughes, A.T.; Samuels, R.E.; Piggins, H.D. Rhythm-promoting actions of exercise in mice with deficient neuropeptide signaling. *J. Biol. Rhythm.* **2010**, *25*, 235–246. [[CrossRef](#)]
118. Mrosovsky, N.; Biello, S.M. Nonphotic phase shifting in the old and the cold. *Chronobiol. Int.* **1994**, *11*, 232–252. [[CrossRef](#)]
119. Hower, I.M.; Harper, S.A.; Buford, T.W. Circadian Rhythms, Exercise, and Cardiovascular Health. *J. Circadian Rhythm.* **2018**, *16*, 7. [[CrossRef](#)]
120. Rubio-Sastre, P.; Gómez-Abellán, P.; Martínez-Nicolas, A.; Ordovás, J.M.; Madrid, J.A.; Garaulet, M. Evening physical activity alters wrist temperature circadian rhythmicity. *Chronobiol. Int.* **2014**, *31*, 276–282. [[CrossRef](#)]
121. Duglan, D.; Lamia, K.A. Clocking In, Working Out: Circadian Regulation of Exercise Physiology. *Trends Endocrinol. Metab.* **2019**, *30*, 347–356. [[CrossRef](#)] [[PubMed](#)]
122. Thomas, J.M.; Kern, P.A.; Bush, H.M.; McQuerry, K.J.; Black, W.S.; Clasey, J.L.; Pendergast, J.S. Circadian rhythm phase shifts caused by timed exercise vary with chronotype. *JCI Insight* **2020**, *5*, e134270. [[CrossRef](#)] [[PubMed](#)]
123. Heden, T.D.; Kanaley, J.A. Syncing Exercise with Meals and Circadian Clocks. *Exerc. Sport Sci. Rev.* **2019**, *47*, 22–28. [[CrossRef](#)] [[PubMed](#)]
124. Lewis, P.; Korf, H.W.; Kuffer, L.; Groß, J.V.; Erren, T.C. Exercise time cues (zeitgebers) for human circadian systems can foster health and improve performance: A systematic review. *BMJ Open Sport Exerc. Med.* **2018**, *4*, e000443. [[CrossRef](#)] [[PubMed](#)]
125. Beyer, K.M.M.; Szabo, A.; Hoormann, K.; Stolley, M. Time spent outdoors, activity levels, and chronic disease among American adults. *J. Behav. Med.* **2018**, *41*, 494–503. [[CrossRef](#)]
126. Korman, M.; Tkachev, V.; Reis, C.; Komada, Y.; Kitamura, S.; Gubin, D.; Kumar, V.; Roenneberg, T. Outdoor daylight exposure and longer sleep promote wellbeing under COVID-19 mandated restrictions. *J. Sleep Res.* **2022**, *31*, e13471. [[CrossRef](#)]
127. Takahashi, M.; Haraguchi, A.; Tahara, Y.; Aoki, N.; Fukazawa, M.; Tanisawa, K.; Ito, T.; Nakaoka, T.; Higuchi, M.; Shibata, S. Positive association between physical activity and PER3 expression in older adults. *Sci. Rep.* **2017**, *7*, 39771. [[CrossRef](#)]
128. Dupont Rocher, S.; Bessot, N.; Sesboué, B.; Bulla, J.; Davenne, D. Circadian Characteristics of Older Adults and Aerobic Capacity. *J. Gerontol. A Biol. Sci. Med. Sci.* **2016**, *71*, 817–822. [[CrossRef](#)]

129. Dallmann, R.; Mrosovsky, N. Scheduled wheel access during daytime: A method for studying conflicting zeitgebers. *Physiol. Behav.* **2006**, *88*, 459–465. [[CrossRef](#)]
130. Yamanaka, Y.; Honma, S.; Honma, K.-I. Two Coupled Circadian Oscillators Are Involved in Nonphotic Acceleration of Reentrainment to Shifted Light Cycles in Mice. *J. Biol. Rhythm.* **2018**, *33*, 614–625. [[CrossRef](#)]
131. Barger, L.K.; Kenneth, P.; Wright, J.; Hughes, R.J.; Czeisler, C.A. Daily exercise facilitates phase delays of circadian melatonin rhythm in very dim light. *Am. J. Physiol. -Regul. Integr. Comp. Physiol.* **2004**, *286*, R1077–R1084. [[CrossRef](#)] [[PubMed](#)]
132. Yamanaka, Y.; Honma, K.-i.; Hashimoto, S.; Takasu, N.; Miyazaki, T.; Honma, S. Effects of physical exercise on human circadian rhythms. *Sleep Biol. Rhythm.* **2006**, *4*, 199–206. [[CrossRef](#)]
133. Vitale, J.A.; Lombardi, G.; Weydahl, A.; Banfi, G. Biological rhythms, chronodisruption and chrono-enhancement: The role of physical activity as synchronizer in correcting steroids circadian rhythm in metabolic dysfunctions and cancer. *Chronobiol. Int.* **2018**, *35*, 1185–1197. [[CrossRef](#)] [[PubMed](#)]
134. Smarr, B.L.; Jennings, K.J.; Driscoll, J.R.; Kriegsfeld, L.J. A time to remember: The role of circadian clocks in learning and memory. *Behav. Neurosci.* **2014**, *128*, 283–303. [[CrossRef](#)]
135. Dijk, D.J.; Neri, D.F.; Wyatt, J.K.; Ronda, J.M.; Riel, E.; Ritz-De Cecco, A.; Hughes, R.J.; Elliott, A.R.; Prisk, G.K.; West, J.B.; et al. Sleep, performance, circadian rhythms, and light-dark cycles during two space shuttle flights. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **2001**, *281*, R1647–R1664. [[CrossRef](#)] [[PubMed](#)]
136. Diekelmann, S.; Born, J. The memory function of sleep. *Nat. Rev. Neurosci.* **2010**, *11*, 114–126. [[CrossRef](#)]
137. Walker, M.P. The role of slow wave sleep in memory processing. *J. Clin. Sleep Med.* **2009**, *5*, S20–S26. [[CrossRef](#)]
138. Walker, M.P.; Stickgold, R. Sleep-dependent learning and memory consolidation. *Neuron* **2004**, *44*, 121–133. [[CrossRef](#)]
139. Cain, S.W.; Chou, T.; Ralph, M.R. Circadian modulation of performance on an aversion-based place learning task in hamsters. *Behav. Brain Res.* **2004**, *150*, 201–205. [[CrossRef](#)]
140. Catala, M.D.; Pallardo, F.; Roman, A.; Villanueva, P.; Vina Giner, J.M. Effect of pinealectomy and circadian rhythm on avoidance behavior in the male rat. *Physiol. Behav.* **1985**, *34*, 327–333. [[CrossRef](#)]
141. Müller, L.; Fritzsche, P.; Weinert, D. Novel object recognition of Djungarian hamsters depends on circadian time and rhythmic phenotype. *Chronobiol. Int.* **2015**, *32*, 458–467. [[CrossRef](#)]
142. Devan, B.D.; Goad, E.H.; Petri, H.L.; Antoniadis, E.A.; Hong, N.S.; Ko, C.H.; Leblanc, L.; Lebovic, S.S.; Lo, Q.N.; Ralph, M.R.; et al. Circadian phase-shifted rats show normal acquisition but impaired long-term retention of place information in the water task. *Neurobiol. Learn. Mem.* **2001**, *75*, 51–62. [[CrossRef](#)] [[PubMed](#)]
143. Ruby, N.F.; Fernandez, F.; Garrett, A.; Klima, J.; Zhang, P.; Sapolsky, R.; Heller, H.C. Spatial memory and long-term object recognition are impaired by circadian arrhythmia and restored by the GABA_A antagonist pentylentetrazole. *PLoS ONE* **2013**, *8*, e72433. [[CrossRef](#)]
144. Ruby, N.F.; Hwang, C.E.; Wessells, C.; Fernandez, F.; Zhang, P.; Sapolsky, R.; Heller, H.C. Hippocampal-dependent learning requires a functional circadian system. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 15593–15598. [[CrossRef](#)] [[PubMed](#)]
145. Ruby, N.F.; Patton, D.F.; Bane, S.; Looi, D.; Heller, H.C. Reentrainment Impairs Spatial Working Memory until Both Activity Onset and Offset Reentrain. *J. Biol. Rhythm.* **2015**, *30*, 408–416. [[CrossRef](#)]
146. Ruby, N.F.; Barakat, M.T.; Heller, H.C. Phenotypic differences in reentrainment behavior and sensitivity to nighttime light pulses in siberian hamsters. *J. Biol. Rhythm.* **2004**, *19*, 530–541. [[CrossRef](#)]