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Editorial

Chronobiological research for cognitive science: A multifaceted view

Chronobiology is on the rise: The Nobel Prize in Medicine in 2017 has been awarded to three chronobiologists (Jeffrey C. Hall, Michael Rosbash, and Michael W. Young) for their work on the molecular mechanisms controlling circadian rhythms. The circadian clock represents an internal time-keeping system that generates nearly 24-hr rhythms in physiology and behavior. It provides an adaptive advantage for living organisms to the 24-hr periodicity of the Earth's rotation by anticipating environmental changes (e.g., Hastings & Goedert, 2013; Hastings, Reddy, & Maywood, 2003; Kondratova & Kondratov, 2012). Synchronization is also crucial for cognitive processes: The brain provides the temporal platform necessary for perception or attentional modulation, and being desynchronized, whatever the period of the investigated rhythm, can jeopardize brain function and associated health outcomes (Bao et al., 2015). Research on temporal organization indeed perfectly lends itself to vertical interdisciplinarity (from molecules to behavior) such that, besides the term *chronobiology*, we could equally speak today about *chrono-psycho-socio-biology*.

Extensive research over the past decades has highlighted a full range of human physiology and behavior that is under circadian control. Cell-based autonomous clocks regulate gene expression, be it at the level of transcription, post-transcription, intracellular signaling, or even at the level of mitochondrial activity (Brown, 2014). In addition, more recent studies suggest that circadian clocks play a significant role in developmental, regenerative, and degenerative cellular processes (Brown, 2014).

At the physiological level, oscillators co-ordinate or synchronize various operations within and across neuronal networks. The hypothalamic suprachiasmatic nucleus is usually referred to as the circadian "pacemaker" in mammals because it controls not only the daily fluctuations in body temperature, hormone secretion, heart rate, and blood pressure, but also the sleep and wake periods and associated cognitive and brain functions. When assessed under strictly controlled environmental conditions, cognitive performance has been shown to present circadian rhythmicity, the amplitude (and putatively also the phase) of which depends on the investigated cognitive domain (Schmidt, Collette, Cajochen, & Peigneux, 2007). A recent report further detected circadian rhythmicity in a large set of human brain responses underlying vigilant attention (Muto et al., 2016). Importantly, the phase of circadian rhythmicity was locally modulated such that the timing of peak activation depended on the investigated brain region. This is of particular relevance in our 24/7 society, where about one-fifth of the population regularly encounters some kind of shift work or where trans-meridian flights, space travel, and artificial light pollution, all sensitizing misalignment between the internal clock and the environment, are widely spread.

By providing temporal organization to the sleep–wake cycle, chronobiology is profoundly and pervasively linked to sleep research. Under entrainment, clock-induced adaptive arousal mechanisms are timed to achieve a continuous period of wakefulness during daytime and consolidated sleep during nighttime (Borbély, 1982; Daan, Beersma, & Borbély, 1984; Dijk & von Schantz, 2005). Maximal circadian wake promotion occurs towards the end of a classical waking day to maintain wakefulness despite increasing sleep pressure levels (Strogatz, Kronauer, & Czeisler, 1987). By contrast, maximal circadian sleep promotion occurs towards the end of the biological night, to maintain sleep despite dissipating sleep pressure levels. Perturbation of the fine-tuned interaction between circadian and sleep–wake-dependent processes leads to fragility of sleep and wakefulness states and associated deterioration in neurobehavioral performance (Dijk & von Schantz, 2005). As such, the interaction between these processes also determines time-of-day modulations in sleepiness and alertness levels, and affects performance in cognitive tasks.

Sleeping or being awake at adverse circadian times reflects misalignment (i.e., the offset between sleep–wake cycles and clock-regulated physiology; e.g., Wittmann, Dinich, Merrow, & Roenneberg, 2006), which has been associated with suboptimal health outcomes, including cognitive fitness (Vetter, Fischer, Matera, & Roenneberg, 2015;

Vetter, Juda, & Roenneberg, 2012). Typically reported situations of inadequate timing include total or partial sleep deprivation or nighttime and rotating shift work (Wright, Hull, Hughes, Ronda, & Czeisler, 2006). Dysfunction of the circadian clock induced by shift work, for example, significantly increases the risk of developing metabolic syndromes (e.g., diabetes, stroke), cardiovascular diseases, or cancer. Furthermore, as highlighted by a review by Helfrich-Förster (2017) in this special collection, the circadian system interacts with the stress system such that not only stress responsiveness varies over the course of the day, but repeated psychosocial stress is also able to disturb the circadian clock.

Circadian misalignment occurs in circumstances of odd timing between external or social and biological time. The interference between socioprofessional timing constraints (e.g., school or work) with individual sleep preference has been referred to as *social jetlag* (Wittmann et al., 2006). Social jetlag inherently depends on the specific chronotype of an individual. Chronotype is very generally defined as a person's preferences with regard to the times of day when they prefer to sleep or when they are most alert and is generally viewed as a continuum with a Gaussian distribution ranging from extreme morningness on one side to extreme eveningness at the other. Chronotype is estimated by specific questionnaires (Zavada, Gordijn, Beersma, Daan, & Roenneberg, 2005) and is frequently derived from sleep timing on free days, corrected or not for sleep debt on workdays. In an original report for this special collection, Kantermann and Burgess (2017) compare this index to circadian phase assessments from in-lab melatonin measures and propose the score as a proxy for circadian phase in field studies.

The process of aging significantly affects circadian and sleep variables. The biological clock of adolescents has a markedly late circadian phase compared to younger children and older adults (Roenneberg et al., 2007). Importantly, late sleep timing in adolescents stays in conflict with socially desired early school schedules leading to the accumulation of sleep debt: Late chronotypes, and thus most adolescents, show the largest differences in sleep timing between work/school and free days (Wittmann et al., 2006). In this special collection, Zerbini and Merrow (2017) provide a literature review of the relationships between chronotype and school performance and suggest mechanisms that mediate this association. In a complementary manner, data reported by Wang et al. (2017) in this special collection suggest an association between sleep length and depressive symptoms and behavior problems in a large study sample of adolescents between 9 and 20 years, coming from different cities of China.

Besides developmental and socioprofessional timing constraints, the situation of desynchronization is also frequently encountered in disease. Research on seasonal affective disorder initiated the first use of light, the main circadian time giver or zeitgeber, as an effective treatment for mood disorders (Wirz-Justice, 1996, 2003; Wirz-Justice et al., 2005). Since then, therapy has been extended to nonseasonal major depression and sleep–wake cycle disturbances in many psychiatric and medical illnesses. The notion that sufficient light is important for psychological well-being led to the development of novel lighting solutions in architecture and a more conscious use of natural light to improve lifestyle quality (Wirz-Justice, 2017).

Getting older goes along with the shift of habitual bedtimes and getting-up times to earlier hours, which has been associated with an advance in circadian phase at the physiological level (Duffy & Czeisler, 2002; Duffy, Dijk, Hall, & Czeisler, 1999). Furthermore, an amplitude reduction in circadian rhythm output markers, such as salivary melatonin or core body temperature (Münch et al., 2005), has been observed. Importantly, 24-hr modulations in neurobehavioral performance are contingent upon the chronotype, and particularly upon the synchronicity between the individual's peak periods of circadian arousal and the time of day at which testing occurs (Hasher, Goldstein, & May, 2005). Indeed, not taking into account such daily modulations when inspecting cognitive processes might lead to aberrant results, or at least increase data variability. Due to the developmental shift to an earlier phase with advanced age, the synchrony effect should be particularly considered in cognitive aging research when comparing different age populations and thus also different chronotypes. Accordingly, it was observed that classical age-related changes in memory functions were weakened or even abolished when older morning-type individuals were tested in the evening hours and compared to younger evening types tested in the morning hours (Hasher et al., 2005). Circadian regulation has also been largely underestimated as a contributing factor for shaping the cognitive aging trajectory. This appears surprising, since circadian mechanisms are active in local brain regions and may thereby impinge upon physiological and pathophysiological processes implicated in brain aging and neurodegenerative diseases (Hastings & Goedert, 2013; Kondratova & Kondratov, 2012). Globally, less daily modulation at the neuronal level might be indicative for degenerative disease (e.g., Blautzik et al., 2014).

Especially in old age, proper functioning of the circadian timing system may become more dependent on regularly timed exposure to zeitgeber stimuli (Van Someren & Riemersma-Van Der Lek, 2007) or on appropriate sleep–wake timing and amount. In this special collection, Novotny and Plischke (2017) question the benefits of light therapy in the older population and propose chromatic pupillometry as a tool to probe functionality of arousal-promoting non-visual effects of light in older adults.

In this special collection, we want to direct attention to the importance of chronobiological aspects in psychology research and cognitive neurosciences by applying a translational approach and further highlighting that chrono-psycho-biology is *bench-to-bedside* research. This special issue aims at bridging the gap between research on temporal organization within a circadian framework and research streams of the psychological sciences.

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