SleepWise™ guide to daytime alertness

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1 Introduction

According to recommendations, adults should sleep 7 or more hours per night to promote optimal health (Hirshkowitz et al. 2015; Watson et al. 2015). Although people are aware of the importance of sleep, many people sleep less than recommended. Roughly 35% of adults in the United States sleep less than 7 h per night and 30% sleep less than 6 h per night (Centers for Disease Control and Prevention 2020; Ford et al. 2012). Many people also have an irregular sleep-wake rhythm. Common forms of irregular sleep-wake rhythm are shift-work, frequent traveling, and social jetlag. Roughly 20% of workforce in industrialized nations do shift-work (Wickwire et al. 2017). Travel across multiple time zones disrupts sleep-wake rhythm temporarily and causes jetlag. Frequent flyers such as athletes, businesspeople, politicians, and military may suffer from the consequences of chronic jetlag. The term ‘social jetlag’ is used to refer to the difference in sleep timing (i.e., the timing of a sleep mid-point) between workdays and free days (Wittman et al. 2006). According to a large European dataset, roughly 69% of working-age adults reported 1 h of social jetlag and 33% reported 2 h or more of social jetlag (Roenneberg et al. 2012). Findings from a global dataset using wearables have shown substantial but considerably lower levels of social jetlag. Data from wristbands indicated that at ages 19 to 55, people tend to fall asleep on average 25-35 min later and wake up 55-70 min later on weekends than on weekdays (Jonasdottir et al. 2021).

Too short or poor-quality sleep and irregular sleep-wake rhythm have negative effects on daytime alertness. Alertness refers to the state of active attention by high sensory awareness. When alertness is good, an individual is ready to perceive, understand, and act efficiently in a situation. Sleep has a direct, measurable, and predictable effect on daytime alertness and performance. Getting enough good quality sleep and keeping a regular sleep-wake schedule support optimal daytime alertness. This means better reaction time, judgement, decision-making, situational awareness, and focus – all of which contribute to performance at work and in sports. Moreover, optimal alertness lowers safety and injury risks. In the long-term, short sleep and irregular sleep-wake rhythm also have negative effects on health. Adverse health outcomes include impaired cardiovascular, metabolic, and immune functions and possible development of cardiovascular disease, diabetes, and cancer, for example (Mason et al. 2021).

This white paper describes the Polar SleepWise™ feature that visualizes how sleep contributes to daytime alertness and helps a user manage alertness with better sleep. The background section reviews how physiological sleep regulatory processes, sleep debt, and sleep-wake rhythm are linked to daytime alertness, and how alertness can be predicted with biomathematical modelling. The following sections explain the technology, algorithm, and functionalities of the Polar SleepWise™ feature as well as the scientific proof to support it. The SleepWise™ feature is developed by Polar Electro Oy and related patent applications are currently pending.

2 Background

2.1 Sleep regulation

The two-process model of sleep regulation described by Borbély in 1982 has served as a major conceptual framework in sleep research (Borbély 1982; Borbély et al. 2016). The model explains that sleep is regulated by two processes: homeostatic process and circadian process. These two processes are regulated separately but they interact continuously.

The homeostatic process balances a need for sleep and a need for wakefulness (Borbély 1982; Borbély et al. 2016). The homeostatic sleep pressure builds up across time spent awake and dissipates across time spent asleep. A full night of good quality sleep removes sleep pressure, whilst short sleep prevents the sleep pressure from dissipating fully during the night, resulting in sleep deprivation. The homeostatic sleep pressure has been linked to a neurotransmitter called adenosine (Landolt 2008; Porkka-Heiskanen et al. 1997). The levels of adenosine in the brain accumulate during wakefulness and decrease during sleep. The length of sleep one needs to feel rested in the morning is personal. Most adults need from 7 to 9 hours of sleep per day for their health and well-being (Hirshkowitz et al. 2015.). For some adults, 6 hours may be enough, and some adults may need 10 hours of sleep to get the full benefits of sleep.

The circadian process regulates wakefulness and sleepiness, roughly within a 24-hour period (Borbély 1982; Borbély et al. 2016). It promotes wakefulness during the day and sleepiness at night, and to some extent in the mid-afternoon. The circadian process is controlled by the master clock located in the suprachiasmatic nucleus in the brain. The master clock sends signals to the peripheral clocks located in nearly every tissue and organ, and in that way coordinates circadian rhythms of various physiological processes (Albrecht 2012). While the sleep-wake cycle is the most obvious circadian rhythm, the internal clocks also regulate hormone release, metabolism, digestion, and body temperature, for example.

In humans, the period of endogenous circadian rhythm is on average 24 h 11 min (Czeisler et al. 1999). Environmental “zeitgebers” (i.e., timekeepers, time cues) help keep the master clock synchronized with the 24-hour cycle of day (light) and night (dark). This is called entrainment. The major external cue is light coming through the eyes. In addition to light exposure, other cues such as physical activity, mealtimes, and social interaction affect the circadian rhythms. (Borbély et al. 2016.)

Based on light exposure the master clock regulates the production of melatonin: a hormone that promotes sleepiness. The time of the rise in melatonin levels in dimly lit surroundings is the gold standard method to assess the phase of the body’s circadian rhythm (Benloucif et al. 2008). Melatonin levels are low during the day, begin to increase around 2-3 hours prior to habitual bedtime, and peak during the night. As this dim-light melatonin onset measurement requires controlled conditions, it is best-suited for laboratory studies. Other circadian phase markers include core body temperature, wrist skin temperature, and sleep mid-point, of which the latter two are feasible for repeated measures of circadian phase in real-life settings (e.g., Roenneberg et al. 2007; Sarabia et al. 2008; Shochat et al. 1997). Circadian phase varies between individuals: being earlier in morning-type people (“larks”); and later in evening-type people (“owls”). Circadian rhythms change across the lifespan. Adolescents and younger adults are more likely to be evening-type people, whereas older adults are more likely to be evening-type people (Roenneberg et al. 2007).

2.2 Sleep debt and alertness

Sleep debt may be defined as the cumulative hours of sleep loss with respect to an individual sleep need. Sleep debt may accumulate from one night or several consecutive nights. A combination of cognitive tests and sleepiness scales have been used to assess the effects of sleep debt on alertness during waking hours (Hudson et al. 2020). These measures have been repeated many times during total sleep deprivation or partial sleep restriction for multiple days. Neurocognitive performance has typically been measured with a 10-minute, one-choice, reaction time task called the Psychomotor Vigilance Test (PVT) (Dinges & Powell 1985). Vigilant attention refers to the ability to maintain stable, focused attention. Subjective sleepiness has been assessed with questionnaires, such as Karolinska Sleepiness Scale (Åkerstedt & Gillberg 1990) or Stanford Sleepiness Scale (Hoddes et al. 1973).

In general, sleep restriction impairs neurocognitive performance and increases self-reported sleepiness. A recent review (Hudson et al. 2020) summarizes the findings from studies examining dose-response effects of sleep debt on PVT and subjective sleepiness

(Amal et al. 2015; McCauley et al. 2009; McHill et al. 2018; Rupp et al. 2009; Van Dongen et al. 2003). Performance impairs across consecutive days of sleep restriction and the magnitude of impairment is dependent on the amount of sleep restriction. During the first few days of sleep restriction, self-reported sleepiness is in line with the objectively measured performance impairment. However, as sleep restriction continues day after day, self-reported sleepiness stabilizes and does not increase in a dose-response manner. These results indicate that people are unable to recognize the impacts of chronic sleep debt effectively. When starting to pay off sleep debt, the recovery rate of performance depends on prior sleep and wake history.

2.3 Irregular sleep-wake rhythm and alertness

When an individual follows a regular sleep-wake rhythm and gets enough sleep on a daily basis, the homeostatic and circadian processes work well together (Borbély 1982; Borbély et al. 2016). A good alignment between these two processes promotes consistent and restorative sleep at the ideal time. In practice this means that it is easy to fall asleep and stay asleep, sleep quality is good, and daytime alertness and neurocognitive performance are optimal. In this ideal case, the environmental light-dark rhythm, and behavioural rhythms (eating-fasting, activity-rest) also promote good sleep.

Irregular sleep-wake rhythm makes the homeostatic and circadian processes work against each other. The term ‘Circadian Misalignment’ is used to describe an abnormal phase angle between actual sleep-wake rhythm and the body’s internal circadian rhythm (Vetter 2020). Typical examples of irregular sleep-wake rhythm are shift-work, social jetlag and traveling**.** Shift work is associated with impaired alertness and performance due to sleep debt and the misalignment between actual sleep-wake rhythm and the body’s internal circadian rhythm (e.g., Ganesan et al. 2019). Working during the night is considered the maximal challenge to the circadian system (Vetter 2020). Then, not only sleep but also light exposure, physical activity, and eating typically occur at unfavourable times. Another common form of irregular sleep-wake rhythm is social jetlag: illustrated by figure 1. It refers to a common situation in which sleep times shift later from work or school days to free days. (Wittmann et al. 2006). Then an individual’s circadian rhythm must adapt to earlier sleep timing after each weekend. Sleep problems and other symptoms are comparable to those when suffering from traveling jetlag.

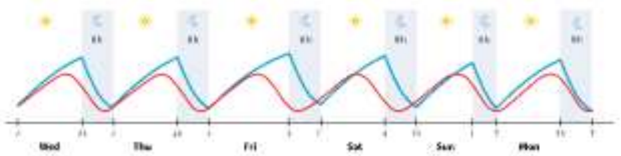

Figure 1. An example of a social jet lag. Over Wednesday and Thursday, there is a good alignment between the homeostatic process (blue) and the circadian (red) process due to consistent bed and wake-up times. Then an individual stays up late on Friday and Saturday nights and sleeps in on the following days. This shifts his/her body’s circadian rhythm forward and consequently (s)he has trouble falling asleep on Sunday night. The individual wakes up for work early Monday morning, and this short night prevents the homeostatic process from recovering fully. As a result of inconsistent bed and wake-up times, the homeostatic and circadian processes are misaligned from Saturday to Monday.

Jetlag has been shown to follow rapid travel across three or more time-zones and is typically characterised by daytime fatigue, decreased concentration and alertness, sleep disruption and gastrointestinal disturbances (Eastman & Burgess 2009; Van Rensburg 2021). These symptoms are caused by the misalignment between the body’s internal circadian rhythms and the local time. The experience of jetlag is affected by the direction of travel, flying eastward typically causes more severe jetlag symptoms than flying westward. This can be partly explained by the fact that on average, the period of endogenous circadian rhythms is slightly longer than 24 h, and thus the body can adapt quicker to staying up late than going to bed earlier than normal.

2.4 Alertness modelling

Wrist-worn devices detecting body movements by accelerometry is a generally accepted method to assess sleep and wake times. In addition to accelerometry, many wrist devices measure a range of biosignals that can be utilized to detect sleep stages and circadian rhythm. Biomathematical modelling has been used to objectively estimate the effects of sleep patterns on fatigue, alertness, and performance.

Biomathematical models in general have been shown to successfully predict neurocognitive performance and subjective sleepiness in sleep deprivation and sleep restriction experiments (Van Dongen 2004). Moreover, they have been accepted as a useful adjunction in the fatigue-related risk management in operations that include irregular sleep-wake rhythm, such as aviation, rail, maritime, and other high-risk industries (Dawson et al. 2011; Dawson et al. 2017).

There are several biomathematical models described in the scientific literature (see e.g., Borbély 1982; Dawson 2017; Hursh et al. 2004; Ingre et al. 2014; McCauley et al. 2009; Ramakrishnan et al. 2016; van Dongen 2004). While the details and terminology between the models differ, most of the models have a common basis. These models typically consider three basic components: circadian process, homeostatic process, and sleep inertia. Sleep inertia refers to the period of impaired cognitive performance and grogginess experienced after waking (Hilditch & McHill 2019). The models use the timing of prior sleep as the primary input and the time course of the predicted variables, such as fatigue, sleepiness, or alertness as the primary output. A value of the predicted variable at a certain time point depends on the interaction of several factors, including sleep history, time awake, and time of day. The difference between the circadian process and the homeostatic process is the primary determinant of the level of fatigue, alertness, and performance.

3 Polar technology and algorithm

3.1 Polar sleep measurement

Polar SleepWise™ feature has been built upon the Polar Sleep Plus Stages™ feature that automatically measures the amount, quality, and timing of sleep. The only thing the user needs to do is wear his/her watch and ensure that the continuous heart rate tracking setting is enabled. The sleep measurement is based on data from 3D-accelerometry and photoplethysmography measured from the non-dominant wrist. Photoplethysmography is an optical technique that allows the device to measure the heart's beat-to-beat intervals. Read more about Polar sleep measurement from Sleep Plus Stages™ white paper.

3.2 Principles of SleepWise™ algorithm

Figure 2 illustrates the structure of Polar SleepWise™ algorithm. The main input to the algorithm is the user's sleep data that includes "fell asleep" and "woke up" times, and the solidity and regeneration values of Polar sleep score. Other inputs are the user's real sleep need: set with 'Your preferred sleep time' -setting and geographical location given as time zone.

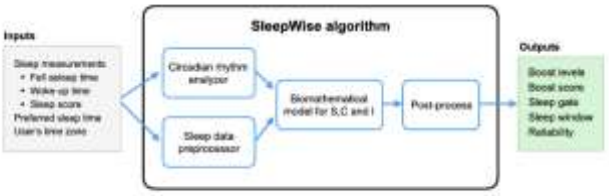

Figure 2. The structure of Polar SleepWise™ algorithm. The biomathematical model includes homeostatic process (S), circadian process (C) and sleep inertia process (I).

The circadian rhythm analyzer uses sleep data to estimate the user's circadian rhythm. A phase marker of the internal circadian rhythm is calculated recursively by combining information on recent sleep timing and the user settings. Such a calculation makes the phase marker adapt smoothly to changes in the user's sleep-wake rhythm.

The sleep data pre-processor processes the sleep data as a continuous sleep-wake signal for the simulation of the biomathematical alertness model. Most importantly, missing data points of the sleep-wake signal are handled in the pre-processing. The model requires all sleep periods to be available within the recent history. A machine learning based algorithm is used to add missing sleep periods to the sleep signal.

Generally known methods for alertness modelling have been used to develop the Polar biomathematical model for alertness (see e.g., Borbély 1982; Dawson 2017; Hursh et al. 2004; Ingre et al. 2014; McCauley et al. 2009; Ramakrishnan et al. 2016; van Dongen 2004). The model simulates the statuses of homeostatic, circadian, and sleep inertia processes as a function of time. Based on this information, it predicts temporal dynamics of alertness for the expected waking hours. The model uses sleep data from recent weeks as inputs. It takes from 1 to 2 weeks for the calculation to reach full reliability.

In post-processing, the visible components of the Polar SleepWise™ feature are produced. Boost levels are one-hour averages of the alertness signal converted to the five-level scale. Boost score is an average of the alertness signal for the expected waking hours ahead. It is expressed as a scale from 1 to 10. The timing of sleep gate considers the circadian process. The recognizability of sleep gate considers the variability of the circadian phase and the status of the homeostatic process. In addition to these visible components, the post-processing provides the reliability of the alertness prediction based on the amount of missing data.

4 Description of the SleepWise™ feature

4.1 User benefits

The SleepWise™ feature makes visible how recent sleep impacts the user's daytime alertness. Better alertness is associated with better readiness to perform by improving reaction time, accuracy, judgement, and decision-making. All these factors impact performance at work and in sports. SleepWise™ not only looks at the amount and quality of sleep, but also takes the sleep-wake rhythm into account. It looks at how well the user's sleep-wake rhythm aligns with his/her body's internal circadian rhythm.

The SleepWise™ feature provides the following benefits:

- The user can see how his/her recent sleep is expected to boost his/her alertness and readiness to perform throughout the day. This helps the user foresee when (s)he could benefit from brief alertness boosting activities.
- The user can easily compare the boost from sleep across days and weeks. (S)he can see how his/her sleep has boosted daytime alertness lately and consider making changes to his/her bed and wake-up times accordingly.
- The user can see how his/her sleep-wake rhythm is in line with the body's internal rhythm. This can help the user maintain a healthy sleep-wake rhythm and reserve enough time for sleep, and consequently manage his/her daytime alertness with better sleep.

4.2 Boost levels

SleepWise™ provides a prediction of how recent sleep is expected to contribute to the user's alertness and readiness to perform. Figure 3 shows the forecast of the user's boost levels for today with an hour-by-hour resolution. The forecast has five different boost levels: very high, high, low, very low, and minimal. The higher the bar in Figure 3, the higher the boost level. When boost level is high, the user is likely to feel attentive and ready to perform. When the boost level is lower, the user may feel less alert and less efficient. The forecast provides an overview for the coming day. As the user's boost levels are predicted from his/her recent sleep data, they do not react to any activities the user does during the day. However, the user can plan alertness boosting activities such as naps, coffee, or a walk outside based on the forecast.

Figure 3. The forecast of the user's boost levels for today. The green bars in the forecast figure show the user's boost level hour by hour. The lighter the shade of green and higher the bar, the higher the boost level. The darker the shade of green and lower the bar, the lower the boost. The purple circle shows the user's sleep gate: the time when the user's body will be ready to fall asleep. The different shades of purple colour indicate how recognizable the sleep gate is. The purple line shows the user's sleep window that is the time period when the user's body would naturally want to be asleep. The sleep window starts from the sleep gate and fades gradually towards the morning as the body is getting ready to wake up.

Even when the user is well-rested, there are natural dips and peaks in the forecast. The first dip in boost levels occurs typically in the mid-afternoon. This dip, called an afternoon slump, is caused by the sleep promoting effects of the body's circadian rhythm. In the evening, the boost levels start to decrease gradually. This decrease is due to increasing sleep pressure and decreasing circadian wakefulness. Finally, the sleep gate opens when the prediction indicates that the user's body would be ready to fall asleep.

4.3 Boost score

Boost score has been designed to make it easy to compare alertness predictions between days and identify repeating trends in the data. It summarizes each daily forecast into one number from 1 to 10. Boost score can be thought of as an average boost level for the day, calculated over the user's typical waking hours. In addition to boost score value, the user gets a short verbal feedback. It tells the user how daytime alertness has been boosted by recent sleeps. Boost score value is classified into four classes: Excellent (9.8 - 10.0), Good (9.0 - 9.7), Fair (7.0 - 8.9), and Modest (1.0 - 6.9). Excellent boost score means that the user gets all the benefits of good sleep to support his/her day. If the user has accumulated sleep debt, his/her boost score is likely to be modest. The boost score trend makes, for instance, repeating weekly patterns visible. Some people have developed a pattern of sleeping too little during weekdays and catching up during weekends. This behavior is manifested in the boost score trends as lower scores during weekdays and higher scores during weekends.

4.4 Sleep gate and sleep window

The sleep gate anticipates a time when the user's body will be ready to fall asleep (see figure 3). It is linked to a natural decrease in alertness in the late evening hours. It marks the onset of the user's sleep window. The sleep window is the time period when sleep propensity is high, and the user's body would naturally want to be asleep. Like sleep propensity that gradually decreases during nightly sleep, the sleep window fades gradually towards the morning. Sleep gate and sleep window are derived from the circadian process in the biomathematical model.

The timing of the sleep gate may change from day to day because changes in sleep duration and timing cause fluctuations in the user's internal rhythm. The user should rather plan his/her bedtimes based on his/her intended wake-up times than relying purely on his/her sleep gate. This is because the sleep gate may not always be an ideal bedtime in reality. If the user, for instance, delays his/her sleep timing day after day at the beginning of his/her vacation, the body's internal rhythm delays as well, and the sleep gate shifts forward each day. Another example where the internal rhythm may not align with the user's everyday commitments, is social jetlag. If the user is one of those people who tend to stay up late and sleep in on weekends, (s)he ends up shifting his/her internal circadian rhythm towards staying up late on Sunday night as well. Then, trouble falling asleep on Sunday night may result in starting a new working week with sleep debt. Expert advice for avoiding Sunday insomnia and sleep-deprived Mondays is to go to bed and get up at the same time every day. The second-best option is to wake-up at a usual time in the morning and compensate sleep loss with an early afternoon nap.

Figure 4. A weekly view showing the user's actual sleep period and timing of sleep gate and sleep window predicted from the user's sleep history.

One of the key elements of SleepWise™ illustrates how much the user's actual sleep-wake rhythm deviates from his/her body's internal rhythm (figure 4). Syncing these two rhythms – actual and internal – and reserving enough time for sleep can optimize daytime alertness and readiness to perform. Sticking to regular bedtimes and wake-up times is the key to sync the actual sleep-wake rhythm and the body's internal rhythm. In addition, consistent sleep-wake rhythm promotes restorative and solid sleep and allows the body to go through an optimal amount of all the sleep stages (deep, REM, and light). Ideally, the user would be able to keep his/her sleep-wake rhythm regular and get enough sleep per night so that the user's sleep gate would be clearly recognizable, and (s)he would fall asleep easily in the evening, get enough good-quality sleep, wake-up refreshed in the morning, and have optimal alertness levels during the day.

5 Scientific proof

The SleepWise™ algorithm is built on a solid foundation. Firstly, it is based on the elements presented by several biomathematical models that have been validated and applied to alertness and fatigue prediction in many study protocols and real-life settings. Secondly, simulations by Polar researchers show evidence that Polar SleepWise™ algorithm can predict the PVT data presented numerically or visually in other scientific studies. In these simulations, several sleep restriction studies with the PVT results (Belenky et al. 2003; Van Dongen et al. 2003; Whitney et al. 2015) or results from other similar reference test (Rabat et al. 2016) were selected from the scientific literature. The protocols of experimental studies included one day total sleep deprivation or sleep duration of 4 hours or more. All studies included results for the daily average of PVT lapses (i.e., response times > 500 ms) measured at multiple time points during the day. The reported time-in-bed values were used as inputs for the SleepWise™ algorithm to calculate boost score and boost level. Boost levels were taken from the same time points when the PVT lapses were measured, and these boost level values were averaged over a day. The correlations between Polar parameters and PVT lapses are shown in Figure 5. As sleep quality was not measured in the studies, the effect of sleep quality was not considered in the simulations. The SleepWise™ algorithm has not been validated yet against the PVT in a strictly controlled experimental protocol by a third party. However, the up to-date scientific background and Polar in-house simulations give confidence that the Polar model performs well.

Polar SleepWise™ algorithm utilizes Polar Sleep Plus Stages™ sleep measurement. Sleep Plus Stages™ is based on an analysis of the heart's beat-to-beat intervals and 3D accelerations measured from a wrist. Polar wrist-based method can measure the heart's beat-to-beat intervals and their variability at rest, and during sleep, with adequate accuracy (Nuuttila et al. 2022). Polar sleep measurement has been validated against polysomnography in children, adolescents (Pesonen & Kuula 2018), and adults (Miller et al. 2022) with healthy sleep. Polar sleep-wake detection is valid for the field-based assessment of the timing and duration of sleep (Miller et al. 2022; Pesonen & Kuula 2018).

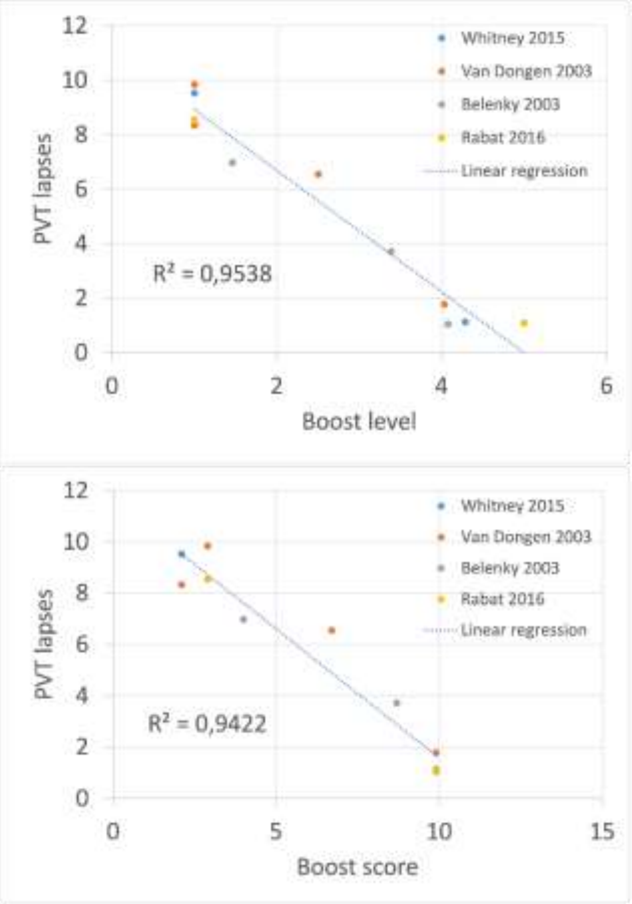

Figure 5. Correlation between boost level and lapses in the psychomotor vigilance task (PVT; on the top) and between boost score and PVT lapses (on the bottom).

6 Limitations

The SleepWise™ feature does not take naps into account. However, the SleepWise™ algorithm itself is ready to analyze how the naps contribute to the user's daytime alertness. Like most of the biomathematical models of alertness, SleepWise™ is based on sleep history. It shows how recent sleep is expected to boost the user's alertness level and performance throughout the day. As it is a sleep-based forecast, it does not react to anything the user does during the day, e.g., drinking a cup of coffee.

7 References

Albrecht U. Timing to perfection: the biology of central and peripheral circadian clocks. Neuron. 2012 Apr 26;74(2):246-60.

Arnal PJ et al. Benefits of Sleep Extension on Sustained Attention and Sleep Pressure Before and During Total Sleep Deprivation and Recovery. Sleep. 2015 Dec 1;38(12):1935-43.

Belenky G et al. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. J Sleep Res. 2003 Mar;12(1):1-12.

Benloucif S et al. Measuring melatonin in humans. J Clin Sleep Med. 2008 Feb 15;4(1):66-9.

Borbely AA et al. The two-process model of sleep regulation: a reappraisal. J Sleep Res. 2016 Apr;25(2):131-43.

Borbely AA. A two-process model of sleep regulation. Hum Neurobiol. 1982;1(3):195-204.

Centers for Disease Control and Prevention. Short Sleep Duration Among US Adults. 2020. https://www.cdc.gov/sleep/data-and-statistics/adults.html Accessed 29 November 2022.

Czeisler CA et al. Stability, precision, and near-24-hour period of the human circadian pacemaker. Science. 1999 Jun 25;284(5423):2177-81.

Dawson D et al. How should a bio-mathematical model be used within a fatigue risk management system to determine whether or not a working time arrangement is safe? Accid Anal Prev. 2017 Feb;99(Pt B):469-473.

Dawson D et al. Modelling fatigue and the use of fatigue models in work settings. Accid Anal Prev. 2011 Mar;43(2):549-64.

Dinges DF & Powell JW. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. Behav Res Meth Ins C. 1985;17:652–5.

Eastman CI & Burgess HJ. How To Travel the World Without Jet lag. Sleep Med Clin. 2009 Jun 1;4(2):241-255.

Ford ES et al. Trends in Self-Reported Sleep Duration among US Adults from 1985 to 2012. Sleep. 2015 May 1;38(5):829-32.

Ganesan S et al. The Impact of Shift Work on Sleep, Alertness and Performance in Healthcare Workers. Sci Rep. 2019 Mar 15;9(1):4635.

Hilditch CJ & McHill AW. Sleep inertia: current insights. Nat Sci Sleep. 2019 Aug 22;11:155-165.

Hirshkowitz M et al. National Sleep Foundation's sleep time duration recommendations: methodology and results summary. Sleep Health. 2015 Mar;1(1):40-43.

Hoddes E et al. Quantification of sleepiness: a new approach. Psychophysiology. 1973 Jul;10(4):431-6.

Hudson AN et al. Sleep deprivation, vigilant attention, and brain function: a review. Neuropsychopharmacology. 2020 Jan;45(1):21-30.

Hursh SR et al. Fatigue models for applied research in warfighting. Aviat Space Environ Med. 2004 Mar;75(3 Suppl):A44-53; discussion A54-60.

Ingre M et al.Validating and extending the three process model of alertness in airline operations. PLoS One. 2014 Oct 20;9(10):e108679.

Jonasdottir SS et al. Gender differences in nighttime sleep patterns and variability across the adult lifespan: a global-scale wearables study. Sleep. 2021 Feb 12;44(2):zsaa169.

Landolt HP. Sleep homeostasis: a role for adenosine in humans? Biochem Pharmacol. 2008 Jun 1;75(11):2070-9.

Mason IC et al. Circadian dysregulation and cardiometabolic and immune health. In Kryger MH et al. Kryger's principles and practice of sleep medicine. pp. 423-432. 7th edition E-book Elsevier Philadelphia 2021.

McCauley P et al. A new mathematical model for the homeostatic effects of sleep loss on neurobehavioral performance. J Theor Biol. 2009 Jan 21;256(2):227-39.

McHill AW et al. Chronic sleep curtailment, even without extended (>16-h) wakefulness, degrades human vigilance performance. Proc Natl Acad Sci U S A. 2018 Jun 5;115(23):6070-6075.

Miller DJ et al. A Validation of Six Wearable Devices for Estimating Sleep, Heart Rate and Heart Rate Variability in Healthy Adults. Sensors (Basel). 2022 Aug 22;22(16):6317.

Nuuttila OP et al. Validity of the Wrist-Worn Polar Vantage V2 to Measure Heart Rate and Heart Rate Variability at Rest. Sensors (Basel). 2021 Dec 26;22(1):137.

Pesonen AK & Kuula L. The Validity of a New Consumer-Targeted Wrist Device in Sleep Measurement: An Overnight Comparison Against Polysomnography in Children and Adolescents. J Clin Sleep Med. 2018 Apr 15;14(4):585-591.

Porkka-Heiskanen T et al. Adenosine: a mediator of the sleep-inducing effects of prolonged wakefulness. Science. 1997 May 23;276(5316):1265-8.

Rabat A et al. Differential Kinetics in Alteration and Recovery of Cognitive Processes from a Chronic Sleep Restriction in Young Healthy Men. Front Behav Neurosci. 2016 May 23;10:95.

Ramakrishnan S et al. A Unified Model of Performance: Validation of its Predictions across Different Sleep/Wake Schedules. Sleep. 2016 Jan 1;39(1):249-62.

Roenneberg T et al. Epidemiology of the human circadian clock. Sleep Med Rev. 2007 Dec;11(6):429-38.

Roenneberg T et al. Social Jetlag and Obesity. Curr Biol. 2012, 22, 939–943.

Rupp TL et al. Banking sleep: realization of benefits during subsequent sleep restriction and recovery. Sleep. 2009 Mar;32(3):311-21.

Sarabia JA et al. Circadian rhythm of wrist temperature in normal-living subjects A candidate of new index of the circadian system. Physiol Behav. 2008 Nov 28;95(4):570-80.

Shochat T et al. Nocturnal melatonin onset is phase locked to the primary sleep gate. Am J Physiol. 1997 Jul;273(1 Pt 2):R364-70.

Van Dongen HPA et al. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. Sleep. 2003 Mar 15;26(2):117-26.

Van Dongen HPA. Comparison of mathematical model predictions to experimental data of fatigue and performance. Aviat Space Environ Med. 2004 Mar;75(3 Suppl):A15-36.

Van Rensburg DCJ et al. Managing Travel Fatigue and Jet Lag in Athletes: A Review and Consensus Statement. Sports Med. 2021 Oct;51(10):2029-2050.

Vetter C. Circadian disruption: What do we actually mean? Eur J Neurosci. 2020 Jan;51(1):531-550.

Watson NF et al. Recommended Amount of Sleep for a Healthy Adult: A Joint Consensus Statement of the American Academy of Sleep Medicine and Sleep Research Society. Sleep. 2015 Jun 1;38(6):843-4.

Whitney P et al. Feedback Blunting: Total Sleep Deprivation Impairs Decision Making that Requires Updating Based on Feedback. Sleep. 2015 May 1;38(5):745-54.

Wickwire EM et al. Shift Work and Shift Work Sleep Disorder: Clinical and Organizational Perspectives. Chest. 2017 May;151(5):1156-1172.

Wittmann M et al. Social jetlag: misalignment of biological and social time. Chronobiol Int. 2006;23(1-2):497-509.

Åkerstedt T & Gillberg M. Subjective and objective sleepiness in the active individual. Int J Neurosci. 1990 May;52(1-2):29-37.