Sleep and Fatigue Science 101

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It seems inevitable that irregular work shifts and working the backside of the clock are associated with fatigue. However, knowledge of the main biological mechanisms underlying fatigue, and the nature of its effects on the brain, may help to manage fatigue and its adverse consequences on performance and safety.

Sleep regulation—specifically the natural timing and duration of sleep—is governed by two key biological processes. One of these processes is called the homeostatic process, and its function is to balance the amount of wakefulness and sleep. Simply put, the longer one is awake, the greater the pressure for sleep becomes, and the longer one sleeps, the more that pressure is reduced. Thus, staying up late makes one sleepy, and getting up early leaves a person with leftover sleep pressure (still tired).

The other process is called the circadian process, which is a 24-hour internal rhythm produced by the biological clock. It promotes sleep during the night and wakefulness during the day. This is the reason why getting enough sleep is more difficult during the day than during the night, and why staying awake through the night continues to be a challenge even if one manages to get enough sleep beforehand.

The homeostatic process and the circadian process together determine the level of fatigue and how it changes over time. This means that fatigue is a function of both time awake and time of day, and that knowledge of a person's sleep/wake history and the time of day on his/her biological clock makes fatigue predictable. This is illustrated in figures 1 and 2.

Figure 1 (p.9) shows fatigue predictions and vigilance performance data from a laboratory study involving 62 hours of total sleep deprivation. Although most workers would not stay awake for this length of time, the study reveals that a simple calculation of adding up the pressures for sleep from the homeostatic process and from the circadian process yields a good prediction of the effects of fatigue on performance over time.

Figure 2 (p. 10) shows the interplay of the two processes in a night shift worker. In this particular example, the person wakes up at 20:00, at which time the homeostatic process begins to increase the pressure for sleep with each passing hour of wakefulness. Also, at the beginning of the night, the circadian process increases its pressure for sleep. The net result is that whereas fatigue is relatively low at the beginning of the night shift, there is a steady increase of fatigue through to the end of the night and into the early morning. Indeed, fatigue may peak around the time of the commute back home, putting the individual at increased risk of a car accident.

However, later in the morning, the circadian process begins to promote wakefulness, and fatigue is reduced despite the increasing time awake. This may make it difficult to get sleep until later in the afternoon; in the example of figure 2, the person finally goes to bed at 16:00.

During the sleep period, the pressure for sleep from the homeostatic process is dissipated, but the pressure for wakefulness from the circadian process is still high and soon becomes the dominant force (the so-called "wake maintenance zone" in the early to late evening). This situation results in awakening prematurely, which is the reason why most shift workers manage to get only about 5 hours of sleep per day.

In the example of figure 2, the person wakes up spontaneously at 20:00, and the pattern then repeats itself. Recent studies have shown that over time, repeated loss of sleep like that associated with night and shift work enhances the sensitivity to sleep loss, resulting in a further build-up of fatigue across days and weeks. Interestingly, perhaps because this is such a slow process, the build-up of fatigue over sustained periods of sleep loss is not accurately reflected in self-reported levels of fatigue.

Importantly, even short-term increases in fatigue may not be readily noticed. This is due to how fatigue affects brain functioning, which is illustrated in figure 3 (p. 10) with an example of an individual who stayed up all night and into the next day. Performing a simple, 10-minute psychomotor vigilance reaction time task, the person showed both errors of omission (lapses of attention) and errors of commission (false starts) owing to fatigue. However, these errors occurred in the midst of otherwise normal, fast responses (less than 500 ms).

This is a hallmark of the effects of fatigue on performance: the brain functions well most of the time, but at random moments there are sudden failures—in other words, performance becomes unstable. Therein lies a particular danger: a significantly fatigued person can continue to work without problems most of the time, but at an unexpected moment may experience performance instability and thus cannot be fully relied upon. Moreover, because performance may return to normal just moments later, the fact that a fatigue problem occurred briefly could well go unnoticed. This is one of many reasons why in safety-sensitive operations it is important to have one's work signed off on by others.

Although specific instances of fatigue-related error are difficult to anticipate because they can occur so randomly, fortunately, the overall increase in a person's risk due to fatigue can be predicted as long as the homeostatic and circadian processes can be tracked. There are a number of mathematical models of fatigue and performance that can be used for this purpose, several of which require only information about a person's sleep/wake history and the time of day. Such mathematical models are at the heart of model-based fatigue risk management systems (FRMS), which allow for risk evaluations of work schedules and may guide the deployment of fatigue countermeasures. Several different countermeasures could be considered, including shift changes that result in less predicted fatigue, rest breaks to avoid working at times of greatest fatigue, strategic napping to reduce sleep pressure, and a variety of other options such as caffeine.

Model-based FRMS tools can be used as part of the shift scheduling process to minimize fatigue risk and promote safety while maintaining efficiency and productivity. This idea is currently under consideration in the rule-making process for new hours of service regulations governing flight crew in commercial aviation. It would be fruitful and relatively straightforward to extend the approach to aviation maintenance operations. Until such time, approved maintenance organizations may want to obtain a license for a mathematical and performance, or join forces to have one developed that can be freely distributed to all aviation maintenance workers, so that they may begin to explore new ways to mitigate fatigue-related safety risks based on the science of sleep and fatigue.

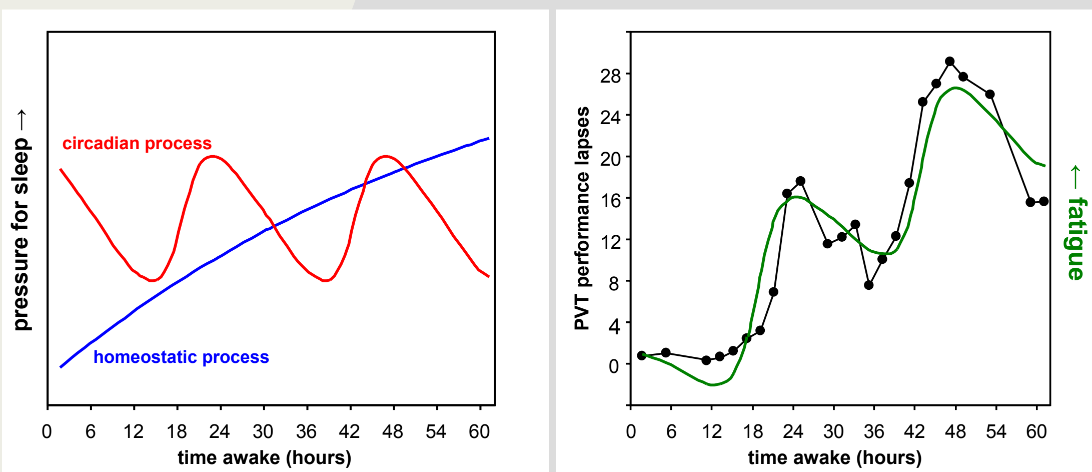

Figure 1: Changes in fatigue levels over time due to the homeostatic and circadian processes, as illustrated across 62 hours of continuous wakefulness. In the left panel, the blue curve shows the gradual increase of pressure for sleep from the homeostatic process over time awake, and the red curve shows the waxing and waning of pressure for sleep from the circadian process over the 24 hours of each day. In the right panel, the green curve shows how these two processes combine to predict fatigue (green curve = sum of blue and red curves). These predictions are a close match to actual observations of performance impairment, as measured on a 10-minute psychomotor vigilance test (PVT) administered multiple times during a laboratory study of 62 hours of continuous wakefulness—the black dots represent performance lapses (defined as reaction times > 500 ms) averaged over 12 individuals. Adapted from Van Dongen & Belenky, Industrial Health 2009, 47, 518–526.

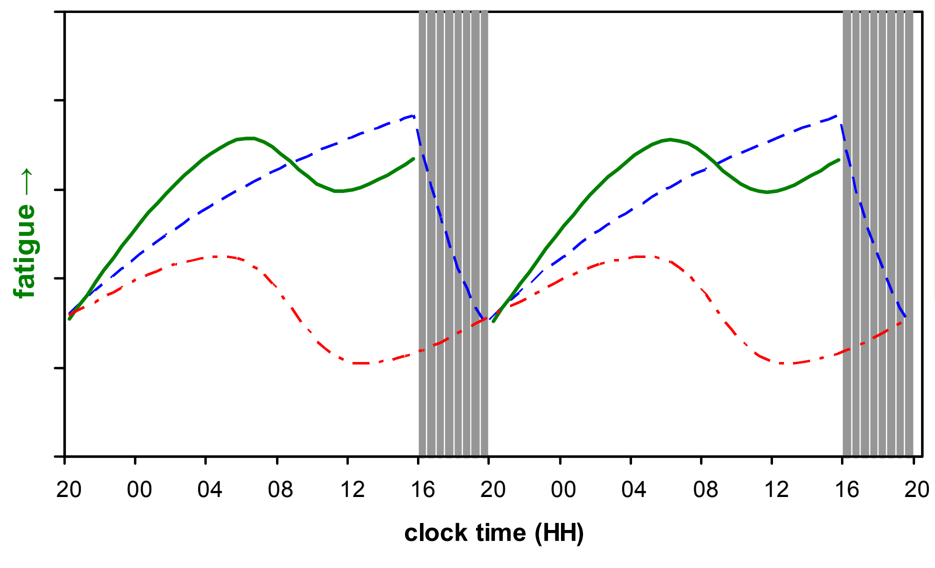

Figure 2: Changes in fatigue levels over time, as illustrated over two days with night shift work. The blue curve shows the gradual increase of pressure for sleep from the homeostatic process during wakefulness (white periods), and the dissipation of that pressure during sleep (gray hatched periods). The red curve shows the waxing and waning of pressure for sleep from the circadian process over the 24 hours of each day. The green curve shows these two processes combined, predicting the level of fatigue during wakefulness. Based on Van Dongen, Chronobiology International 2006, 23, 1139–1147.

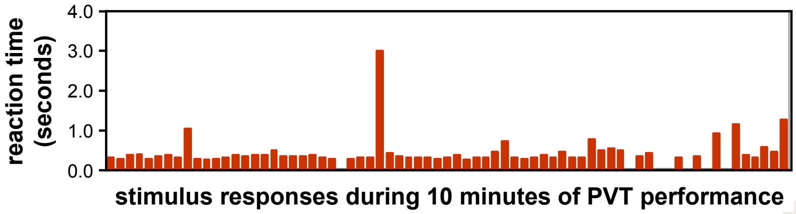

Figure 3: Reaction times to individual stimuli over the 10-minute duration of a psychomotor vigilance test (PVT) for an individual who has been awake for 36 hours. Notice the random occurrence of lapses of attention (long reaction times) and false starts (gaps). Adapted from Doran, Van Dongen & Dinges, Archives of Italian Biology 2001, 139, 253–267.