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Review Article

The Revival of Active Behavioural Devices for Measuring Sleep Latency

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Abstract

The current gold standard for objectively measuring sleep latency, polysomnography (PSG), requires specialised equipment and trained individuals to administer. As such, PSG is an expensive and cumbersome procedure, particularly for use in the home environment. Actigraphy devices are a common practical alternative that can be used in the home environment, but they often underestimate sleep latency. For these reasons, it is difficult to accurately measure sleep latency outside of the sleep laboratory setting.

This problem has led to the revival of active behavioural devices for measuring sleep latency. Thim is a small active behavioural device that uses behavioural responses to stimuli to measure the onset of sleep. The design of Thim is based on previous research with similar devices, which were found to accurately measure sleep latency. If found to accurately measure sleep onset, Thim could be used for many potential applications, including facilitating 10-minute power naps and administering a novel, effective treatment for insomnia called Intensive Sleep Retraining (ISR) in the home environment. This review will highlight current methods for objectively measuring sleep latency, the limits of commonly-used devices and how active behavioural devices such as Thim could allow for the accurate measurement of sleep latency in the home environment.

Current Methods of Measuring Sleep Latency

While PSG is an effective and accurate measure of what is understood to be sleep, there are many limitations of this method that make it impractical for use outside of the laboratory setting. PSG is resource-heavy and expensive because specialised equipment and trained individuals are needed to administer the procedure and score the data. Even though ambulatory PSG devices can be used in the home environment, the equipment and consumables are still expensive and not readily available for use in many situations. Furthermore, in applications requiring instant knowledge of sleep onset, PSG recordings depending on subsequent analysis are of no use. Other automated simpler EEG based sleep systems that could provide instant assessment of sleep state are inaccurate in detecting Stage 1 sleep [1]. People having their sleep monitored via PSG are often inconvenienced by having to attend a sleep laboratory for setup for ambulatory monitoring, and people often experience discomfort while attempting to sleep with PSG, at least on the first night. These limitations are exacerbated when attempting to monitor sleep over multiple nights. Therefore, PSG is an impractical, often unavailable and unnecessarily cumbersome method for measuring sleep onset in many situations.

Actigraphy is a common alternative used to monitor sleep in the home environment. These devices are inexpensive, convenient and widely-available, meaning that they are a practical method of measuring sleep. However, research-grade actigraphy devices are often inaccurate for estimating sleep onset [2,3]. As for consumer actigraphy devices, many have no empirical evidence publicly available to support their validity [4], and those that do, consistently underestimate sleep latency [5,6]. The underlying premise of actigraphy is that the cessation of limb movement is equivalent to the onset of sleep. However, people often cease activity long before they actually fall asleep, thus actigraphy devices often underestimate sleep latency [7]. The accuracy of actigraphy also varies considerably between individuals, and often underestimates sleep latency to a greater extent for sleep-disordered populations [8, 9]. Though they are practical measures of sleep, it is clear that actigraphy devices are unsuitable for situations which require the precise estimation of sleep latency.

Active Behavioural Devices

Out of practical necessity, researchers are beginning to re-investigate active behavioural devices for measuring sleep latency. Originally used to validate the scoring of PSG-sleep [10,11], these devices require responses to stimuli to measure sleep latency. Typically, auditory tones are emitted at regular intervals with users required to depress a micro-switch held in their hand in response to the auditory stimulus. If the device registers a response, it assumes that the user is awake, and when the user fails to respond to the stimuli (typically, to at least two consecutive stimuli), the device assumes that the user has fallen asleep by the first of the two missed stimuli. Thus, active behavioural devices operationalized sleep onset as the beginning of the sustained cessation of responses to stimuli.

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Compared to PSG, active behavioural devices provide accurate estimations of sleep latency. Research has consistently found a high degree of correspondence between these behavioural devices and PSG-sleep onset, with small discrepancies in the order of 2-3 minutes [12-14]. People tend to stop responding to stimuli during late-N1 sleep or the beginning of N2 sleep, though it is interesting to note that people can still give a behavioural response to a stimulus during PSG-defined initial light sleep [14-16]. However, the stimulus intensity required to arouse a person after PSG-sleep onset rises considerably and continues rising as they progress into deeper stages of sleep [17], particularly for neutral stimuli that are unimportant to the individual [18]. Consequently, physiological and behavioural sleep onset correlate to a reasonable degree of accuracy.

Despite the advantages of active behavioural devices, these devices may have their limitations. For example, they may disrupt or delay the process of falling asleep [19]. Although the small amount of relevant empirical evidence doesn't support the disruption [12], it is plausible particularly for more intense stimuli or effortful responses. The presentation of the stimulus and the degree of motor effort required to respond to the stimuli may be arousing for the users, inhibiting their ability to fall asleep. This limitation resulted in passive behavioural methods of measuring sleep, such as actigraphy, becoming more attractive to researchers and consumers. However, recent technological advancements have allowed for the development of an active behavioural device that appears to overcome this limitation.

Thim

Thim (Figure 1) is an active behavioural device that uses a minimal behavioural response to vibratory stimuli to measure sleep latency [20]. Worn on the index finger, the device emits low-intensity vibratory stimuli to which the user responds by gently twitching their finger. With a discreet stimulus and a minimal behavioural response requiring little motor effort to exert, it is likely that Thim will not significantly disrupt the sleep onset process. Because the finger twitch response is so minimal, users may be more willing to continue responding during wakefulness than with other active behavioural devices. Thim is also small, lightweight and relatively comfortable to wear and requires no effort to hold it in place, an undesirable feature of earlier devices. The device is inexpensive, readily available online and easy to use over a long period of time in the home environment, though the battery does require charging every 2-3 days. However, the accuracy of Thim is currently unknown. Research is currently being conducted to investigate the correspondence between PSG and Thim which, based on previous research with similar devices [14], is expected to show that Thim is accurate for measuring sleep latency (Figure 1).

Discrepancy between physiological and behavioural sleep

When assessing the accuracy of active behavioural devices such as Thim, it is important to consider the characteristics of sleep onset. Rather than a precise point in time, sleep onset is a dynamic process marked by physiological, behavioural and subjective changes occurring at different points in time. The PSG methodology encapsulates many of the physiological changes that occur during this transitional period. But, PSG standardised scoring criteria identifies sleep onset as a relatively specific point in time: a reduction of alpha waves to less than 50% of the epoch and the dominance of low voltage, mixed frequency waves [21]. This point in time does not perfectly align with behavioural changes that occur during the sleep onset period [16,22]. Active behavioural devices are actually measuring a different point in time during the sleep onset period compared to PSG, though they do correlate to a reasonable degree [23]. Therefore, Thim-defined sleep onset will not perfectly align with the definition of Stage 1 PSG sleep onset, but it is expected to correspond with PSG to a reasonable degree of accuracy. Nonetheless, the measurement of behavioural sleep latency using Thim may be suitable for some situations, particularly for situations where PSG is too impractical and actigraphy is too inaccurate to use.

Applications Involving the Measurement of Sleep Latency

Power naps

For instance, Thim could be used to facilitate the optimal 10-minute power nap in the home environment. Brief naps have consistently been shown to improve daytime alertness and functioning. Importantly, the duration of the nap can significantly affect subsequent daytime functioning. Very brief naps (less than 5-minutes duration) do not lead to significant improvements in alertness, while longer naps (30 minute duration) result in sleep inertia upon waking that reduces immediate daytime functioning before the benefits of the nap emerge [24,25]. Naps of a 10-minute duration of sleep are optimal because they avoid the detrimental effects of sleep inertia but still lead to significant improvements in daytime functioning, which emerge immediately after waking [25-27]. Achieving the optimal power nap requires the accurate measurement of sleep onset so that the individual can be woken after the appropriate elapsed 10 minutes of sleep.

Outside of the sleep laboratory setting, it is difficult to obtain a precise amount of sleep. People may set an alarm to wake them after a pre-determined duration of time, requiring the person to

Figure 1: A side view of the Thim device.

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estimate how long it will take them to fall asleep. This is a difficult task, meaning that they are unlikely to set an alarm that will wake them after obtaining precisely 10 minutes of sleep. For example, if the person sets an alarm to wake them after 30 minutes, expecting to take approximately 15 minutes to fall asleep, but they fall asleep after only 5 minutes, they will get 25 minutes of sleep and awake feeling groggy with sleep inertia. On the other hand, if the person is still awake after 20 minutes, they may become anxious that they will not fall asleep at all which is likely to become self-fulfilling, making the whole attempt to nap a waste of 30 minutes of time. Actigraphy devices cannot accurately and instantly estimate sleep onset and are therefore impractical for the purpose of facilitating a power nap. If the Thim device could accurately measure sleep onset, it could be used to awaken the user after precisely 10 minutes of sleep and facilitate the optimal power nap in the home environment.

Intensive Sleep Retraining

Similarly, Intensive Sleep Retraining (ISR) also requires the immediate and accurate detection of sleep onset so people can be woken at the appropriate time. ISR is a novel behavioural treatment for insomnia [28,29]. The procedure requires the patient to lie in bed at the start of their typical sleep period and attempt to fall asleep. After a brief period of light sleep (in the order of 2-3 minutes), the patient is woken up and must get out of bed. They are allowed a short break before returning to bed and attempting to fall asleep again on the next trial. These trials are repeated as the night progresses. Deprived of recuperative sleep, the patient's homeostatic sleep drive increases across the night, helping them to fall asleep more rapidly with each subsequent sleep onset trial. Sleep onsets are also facilitated in the early morning hours (3-6am) by the maximal circadian rhythm sleep drive typical at that time [30]. In recent research studies, these sleep onset trials continued for 25 hours with participants experiencing up to 50 rapid sleep onsets [29]. After the sleep onset trials, patients experienced a full recovery sleep on the following night and had a much better sleep on subsequent nights compared to their sleep before treatment. The randomised control trial of ISR showed that improvements in sleep and daytime functioning were sustained up to the final follow-up assessment, six months post-treatment [29]. Thus ISR promises to be a highly effective and rapid treatment of chronic insomnia [31].

For ISR to be administered effectively, the precise point of sleep onset must be measured so that patients can be woken after only 2-3 minutes of light sleep. Disturbing the patient too early may not allow them to experience sleep onset, whereas waking the patient too late may cause a significant reduction in sleep pressure, reducing the likelihood of falling asleep quickly on subsequent trials. For this reason, the original ISR studies were conducted in the sleep laboratory so trained sleep technicians could monitor the participant's brain activity to wake them at the appropriate moment. Consequently, the original ISR procedure was an expensive and virtually unavailable treatment for insomnia. Thim has been designed specifically to administer ISR, and could be used to translate this effective treatment for chronic insomnia to the home environment [32].

Sleep tracking

Behavioural responses to stimuli could also be used in conjunction with actigraphy to accurately monitor sleep and wakefulness across a whole night's sleep [23]. Thim could accurately determine sleep latency by having users respond to the vibratory stimuli until they cease responding, followed by the monitoring of movement across the night using the actigraphy function of Thim. If the accelerometer detects a significant amount of movement indicative of wakefulness, Thim could resume emitting stimuli until the user ceases responding, thus accurately measuring wakeful periods across the night. This could result in a highly accurate device for measuring sleep and wakefulness across the night compared to other passive actigraphy devices. Thim is currently being assessed for its validity in measuring PSG defined sleep.

Conclusion

It is clear that an accurate but practical device is needed to measure sleep latency for situations where PSG and actigraphy are unsuitable or unobtainable. Active behavioural devices such as Thim may sufficiently balance the trade-off between precision and practicality by accurately measuring sleep latency using a minimal stimulus-response paradigm. This device could allow for the effective administration of applications such as power napping and ISR insomnia treatment in the home environment. Research is needed to optimise and validate active behavioural devices, and to evaluate their effectiveness for facilitating their potential applications. Advances in wearable sleep technology will only broaden the capabilities of these devices, with the challenge for research being to try and keep pace with developments.

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