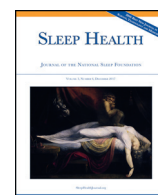




Contents lists available at ScienceDirect

Sleep Health

Journal of the National Sleep Foundation

journal homepage: sleephealthjournal.orgRethinking the sleep–health link[☆]

Lisa Matricciani, B.Pod Hons, MNurs^{a,b,*}, Yu Sun Bin, PhD^{c,d}, Tea Lallukka, PhD^e, Erkki Kronholm, PhD^e,
Melissa Wake, MD^{b,f,g}, Catherine Paquet, PhD^h, Dorothea Dumuid, B.Physio, Hons^a, Tim Olds, PhD^{a,b}

^a Sansom Institute, Alliance for Research in Exercise, Nutrition and Activity (ARENA), University of South Australia, Adelaide, Australia

^b Murdoch Children's Research Institute, Melbourne, Australia

^c Sleep Group, Charles Perkins Centre, University of Sydney, Sydney, NSW, Australia

^d Central Clinical School, Sydney Medical School, NSW, Australia

^e Finnish Institute of Occupational Health, Helsinki, Finland

^f The University of Melbourne, Parkville, VIC, Australia

^g The University of Auckland, Grafton, Auckland, New Zealand

^h Sansom Institute, Centre for Population Health Research, University of South Australia, Adelaide, SA, Australia

ARTICLE INFO

Article history:

Received 11 October 2017

Received in revised form 12 April 2018

Accepted 8 May 2018

Available online xxxxx

Keywords:

Sleep

Trends

Children

Adults

Health

ABSTRACT

Sleep is important for the physical, social and mental well-being of both children and adults. In this paper, we discuss the need to consider sleep as a multidimensional construct and as a component of total 24-hour activity. First, we make a case for considering sleep as a multidimensional construct, whereby all characteristics of sleep (including duration, quality, timing, and variability) and their links with health are examined. Second, we argue that sleep should also be conceptualized as part of the daily spectrum of time-use, along with other types of activity. We propose novel statistical models, in particular compositional data analysis (CoDA), as appropriate analytical methods for a new sleep paradigm.

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Introduction

Sleep characteristics such as duration, quality, timing and variability have been associated with a wide range of health outcomes, including cognitive,¹ psychosocial² and cardiometabolic health,³ as well as specific conditions such as Type 2 diabetes,⁴ cardiovascular disease,⁵ stroke⁶ and obesity.⁷

Accordingly, sleep is increasingly being recognized as a central concern for population health. Heffron,⁸ for example, argues that “sleep is one of the three pillars (diet, exercise and sleep) of a healthy lifestyle”, while Perry and colleagues⁹ emphasize the need to

consider sleep as “being as critical to health as diet and physical activity”. In line with these messages, the American Academy of Sleep Medicine, the Centers for Disease Control and Prevention, and the Sleep Research Society partnered on the *Healthy Sleep Project*, in an effort to improve public health by promoting healthy sleep.⁸ The initiative included the *Sleep Well, Be Well* campaign, which highlighted the importance of adequate and consistent sleep, avoiding alcohol and caffeine before bed and seeking medical advice for sleep problems. Similarly, the (American) National Sleep Foundation has recently proposed the “Sleep Health Index”, which attempts to capture the construct of sleep health based on multiple sleep characteristics.¹⁰ These two approaches represent a shift in the conceptualisation of sleep in relation to population health.

Historical attempts to improve sleep largely focused on sleep duration.¹¹ In contrast, conceptualizing sleep as a multidimensional construct¹² and treating sleep holistically recognizes that sleep duration, as well as other sleep characteristics such as quality, timing and variability, may all be important for health.^{8,12} Sleep has also traditionally been considered as divorced from the 24-hour day. However, any change in sleep duration will necessarily entail changes in the other time-use components of that day. Conceptualizing sleep as a

[☆] Funding/acknowledgements: Dorothea Dumuid was supported by Australian Government Research Training Program Scholarships. Tea Lallukka was supported by the Academy of Finland (grant numbers #287488, #294096). Yu Sun Bin was supported by a 2017 Career Development Award from the Sleep Research Society Foundation. Melissa Wake was supported by Australian National Health & Medical Research Council Senior Research Fellowship 1046518 and by Cure Kids New Zealand. Research at the Murdoch Children's Research Institute.

* Corresponding author at: School of Health Sciences, University of South Australia, City East, Adelaide, SA 5000.

E-mail address: Matla005@mymail.unisa.edu.au (L. Matricciani).

component of 24-hour time use recognizes that sleep duration does not occur in isolation from other time-use domains (i.e. sedentary time and physical activity), which are also known to affect health.¹³ While these two approaches may seem contradictory, they each provide a complementary and unique insight into the role of sleep.

In spite of these new perspectives, our current understanding of sleep stems from studies that examine the association between an individual sleep characteristic (often sleep duration) and a given health outcome. To date, relatively few studies have considered sleep as a multidimensional construct or as a component of daily time use. There is also no agreed framework for considering sleep in these new ways.

The purpose of this paper is, therefore, to present a rationale and a methodology for conceptualizing sleep both as a multidimensional construct and as a component of daily time use. Specifically, we discuss why sleep should be considered from these perspectives and describe statistical techniques for the analysis of sleep data within this new paradigm.

Sleep as a multidimensional construct

Over the years, there has been increasing awareness that sleep duration may not be the only characteristic contributing to optimal health and well-being. It has been recognized that other characteristics of sleep, such as sleep quality, timing and variability, may all play an important role.¹² Indeed, a Scopus database search conducted on the 25th of July 2017 reveals that the number of hits returned for publications with title or abstract key words containing a specific sleep characteristic has risen exponentially over the last twenty years, with particular growth in characteristics other than duration (Fig. 1a). Although an increase has also been observed for studies of multiple sleep characteristics, these are more recent and fewer in number (Fig. 1b). These searches were exploratory and illustrative, where sleep characteristics were entered into Scopus' key word/abstract search engine and the number of hits per year function was used to generate the graph.

Studies that examine the association between sleep and health have traditionally focused on specific sleep characteristics as individual qualities.^{2,3,5,14} Recent studies have begun to examine the association of multiple sleep characteristics on a given health outcome. In a systematic review of sleep and cognition, Astill and colleagues found that sleep duration, but not sleep efficiency (a measure of sleep quality), was associated with measures of cognition and behavioral problems.¹ In contrast, Cappuccio and colleagues identified both sleep duration and quality as predictors of future risk of developing type 2 diabetes in a systematic review and meta-analysis.⁴

While considering multiple sleep characteristics as independent predictors of health acknowledges their coexistence, this approach does not account for the potential interactions between characteristics, or the inherently multidimensional nature of sleep. Indeed, the very notion of an 'independent risk factor' is complex and dependent on the statistical model.¹⁵ Therefore, the conceptualization of the sleep-health link should shift from considering individual sleep characteristics as independent entities to understanding how multiple sleep characteristics and their interactions explain variance in health outcomes.

In the next sections, we discuss how sleep may be considered in terms of a multidimensional construct (section 2.1), which analytical techniques will help us achieve this (section 2.2), studies that have examined the multidimensionality of sleep (section 2.3), and methodological considerations for examining multiple sleep characteristics (section 2.4).

Conceptualizing sleep as a multidimensional construct

Conceptualizing sleep as a multidimensional construct is akin to the conceptualisation of other movement-based activities. Just as physical activity can be described in terms of frequency, intensity, time, and type,¹⁶ so too can sleep be described in terms of duration, quality, timing and variability. It is possible that each characteristic of sleep has an important and unique effect on health, in the same way that different characteristics of physical activity contribute to health outcomes. For example, a 'weekend warrior' is a person who is very physically active on the weekend but mostly sedentary on weekdays, but this pattern of activity has been shown to be protective against all-cause mortality,¹⁷ while increasing the risk of injury.¹⁸ Similarly, more interruptions in sedentary time have been shown to reduce metabolic risk, independent of total sedentary time and levels of physical activity, suggesting that the manner in which physical activity is accumulated is important for health.¹⁹

Sleep characteristics may be conceptualized as 'time-based' or 'perception-based' measures.²⁰ While we acknowledge that there may be a role for subjective, 'perception-based', sleep characteristics (e.g. perceived sleep quality), in this paper we consider only objectively quantified time-based sleep characteristics, and which are increasingly monitored at population²¹ and individual²⁰ levels. We suggest four key sleep characteristics: sleep duration, timing, quality and day-to-day variability.

Objectively-quantified time-based sleep characteristics may be conceptualized, defined and operationalized in a variety of ways. Given that sleep quality may be conceptualized as both a 'time-based' or 'perception-based' measures, we will refer to sleep continuity as a proxy measures for sleep quality. This approach has been adopted by Buysse¹² as well as The National Sleep Foundation, who recently released evidence-based recommendations and guidance on indicators of good sleep quality across the lifespan.²² This review identified objective measures of sleep continuity (sleep latency, number of awakenings, wake after sleep onset, and sleep efficiency) as appropriate indicators of sleep quality.²² While we acknowledge that sleep characteristics may be defined in a variety of ways, how to best to define and operationalize each characteristic is beyond the scope of this paper.

Examining sleep as a multidimensional construct

We discuss three ways in which the association between sleep characteristics and health could be examined. The first method is to look at additive associations of multiple sleep characteristics. This involves examining two or more sleep characteristics within the same statistical model, considering how each accounts for others and ideally considering interaction effects between sleep characteristics. The second method is to create a composite sleep score, whereby sleep characteristics are computed to create an index of how 'good' sleep is overall. The third method provides further insight into the multidimensional nature of sleep by examining sleep profiles within individuals. A sleep profile refers to the specific combinations of different levels of different sleep characteristics experienced by individuals. For example, the sleep profile of one person may involve long, inefficient sleep times with early bed- and late rise-times that are highly variable across a week, while the sleep profile of another person may involve short, efficient sleep with late bed- and early rise-times that are fairly consistent throughout the week. Sleep profiles experienced by individuals are then associated with a given health outcome.

Studying additive associations and composite indices involve variable-based approaches, while studying individual profiles of sleep is necessarily a person-based approach. A person-based approach defines different subtypes of individuals that exhibit similar patterns

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