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A bidirectional model of sleep and technology use: A theoretical review of How much, for whom, and which mechanisms

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ABSTRACT

The link between technology and sleep is more complex than originally thought. In this updated theoretical review, we propose a new model informed by the growing body of evidence in the area over the past 10 years. The main theoretical change is the addition of bi-directional links between the use of technology and sleep problems. We begin by reviewing the evidence to date for the originally proposed mechanisms of bright light, arousal, nighttime sleep disruptions, and sleep displacement. Then, in support of the new direction of effect (sleep problems preceding technology use), we propose two new mechanisms: technology before sleep might be used as a time filler and/or as an emotional regulation strategy to facilitate the sleep-onset process. Finally, we present potential moderators of the association between technology and sleep, in recognition of protective and vulnerability factors that may mitigate or exacerbate the effects of technology on sleep and vice versa. The goal of this theoretical review is to update the field, guide future public health messages, and to prompt new research into *how much* technology and sleep affect each other, *for whom* it may be problematic, and *which mechanisms* may explain their association.

1. Introduction

Technological advances have been developing in concert with decreasing sleep duration. But are these two phenomena connected? It is intuitive to believe they are. Indeed, we invite the reader to think of their own experiences using technology close to ‘bedtime’. Many readers will retrieve early memories of such occasions, and the accumulation of these life experiences help to shape their own beliefs and schemas about how technology influences sleep [1]. As a consequence, many people - including scientists, health professionals, and social media influencers (to name a few) – believe the direction of effect between technology use and sleep is uni-directional. That is, using technology in the evening has a causal influence on sleep.

Early theoretical models of the association between technology use and sleep formed in the early 2010s [2,3]. Indeed, these models implied an uni-directional link from technology use and sleep, despite being based primarily on data that do not confirm a direction of the relationship (i.e., cross-sectional surveys). Experimental studies that can inform of the direction of effect were rare at the time. More than a decade has passed since then, and despite this opportunity, the sleep science field still lacks a wealth of controlled experimental studies that can advance our knowledge of this hot topic [4]. On a positive note, there have been a growing number of longitudinal studies observing natural changes in people’s technological and sleep habits. Together, we are now presented with data that challenge our original notion that evening technology use always causes an effect on sleep – and not vice versa. Several recent reviews on the topic acknowledge the possibility that the link between technology use and sleep is bi-directional [4–6], however, a thorough review of the mechanisms in both directions and an update of the theoretical model has not been presented yet.

The primary aim of this review is to provide an over-arching

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Glossary of terms

DLMO	dim light melatonin onset
EEG	electro-encephalography
FoMO	fear of missing out
IRL	in real life
LED	light emitting diodes
Nomophobia	anxiety about not having access to a mobile phone
SOL	sleep onset latency

synthesis of the scientific evidence for the links between technology use and sleep. This synthesis will lead to an updated theoretical and mechanistic model, that we hope will not only provide directions for future research studies, but also shape public health messages about this hot topic (see Fig. 1). We begin with the bright light hypothesis, which is arguably been the most popular mechanism explaining the link between technology use and sleep.

1.1. Mechanisms: update on evidence

1.1.1. The bright light hypothesis

Bright light has both a direct and indirect effect on alertness [7]. Bright light pulses (e.g., time-limited exposure of 5000 broad-spectrum 'white' light) can cause both subjective and objective evening alertness in humans within an hour [8]. Evening bright light suppresses the release of melatonin, which is assumed to tightly correlate with alertness (e.g., latency to sleep onset), whereas the indirect effect of light may occur via phase-shifting of circadian timing [7]. Single or repeated administrations of bright light exposure in the evening can delay circadian timing (e.g., a delay in the timing of dim light melatonin onset [DLMO] or core body temperature minimum) which has been shown from pre-school children [9] to adults [10,11]. Broad spectrum light can exert these alerting effects, as can the short-wavelength light (perceived as blue-to-green light) contained within perceived white light. As screen technology has advanced from older technologies like cathode-ray tubes to light-emitting diode (LED) technology, there has been an increase in the concentration of predominantly blue light emissions from screens (see Fig. 2, right panel). Due to concerns about the alerting effects from what we will call here 'blue screenlight', there have been scientific evaluations of reducing blue screenlight via apps (e.g., Fig. 2, both panels) and bluelight blocking glasses. Thus, there have been various perspectives taken to test the bright light hypothesis.

Soon after the emergence of the 2010 theories, Cajochen and colleagues [12] compared effects from 5-hrs of a bright laptop screen to a dim screen in the evening, using predominantly a white background. They found that a bright screen attenuated the release of melatonin and caused both objective and subjective pre-sleep alertness, however they did not measure sleep. In 2012, Wood et al. [13] compared 1-hr vs 2-hrs of a bright vs a dim tablet screen in the evening. They confirm Cajochen et al.'s melatonin suppression findings, but after 2-hrs of bright screen use – not 1 h of use. Likewise, Wood et al. [13] did not measure sleep.

Our group compared tablet use between three conditions in the hour before sleep: i) a bright white screen, ii) a dim white screen, and iii) a bright white screen with an app to reduce blue light emissions (*f.lux*[1] [14]). Although melatonin was not measured, we confirmed Cajochen et al.'s [12] elevated objective and subjective alertness in response to a bright screen and in the lead-up to sleep. However, this is where the alerting effects ended. Compared to the dim screen condition, the extension of sleep latency in the bright screen condition was a mean difference of 3.3 min. The following year saw two excellent studies that helped to focus the field's thinking as to whether the bright light hypothesis is 'true'.

First, van der Lely and colleagues [15] tested a bright tablet screen, with and without bluelight-blocking glasses, in the 3 h before sleep. They discovered that the suppression of melatonin occurred slightly earlier than the Wood et al. study [13] - 1.5 h after sustained bright screen use. Van der Lely [15] also confirmed previous studies' findings of elevated objective and subjective pre-sleep alertness. They also confirmed Heath et al.'s [14] finding that the effects on sleep latency from a bright screen was minimal (i.e., mean difference of −1.9 min in favour of a bright screen *without* bluelight-blocking glasses after 3 h of exposure). A common limitation with the abovementioned experimental studies is that they tested a condition (e.g., bright screen use) on a single night, rather than use on consecutive nights, which is likely what people do in the home environment. Chang and colleagues [16] addressed this limitation by testing 5 consecutive nights of reading an e-book vs 5 nights of reading a printed book under dim light. Although their report showed a statistically significant extension of sleep latency after using an e-book compared to a printed book, the mean difference was nevertheless 9.9 min. Despite this small difference, they discovered that the screen use condition caused a 90-min delay of circadian timing of DLMO.

Since these seminal studies there have been several more tests of the bright light hypothesis (see Table 1). A perplexing observation is the consistency of the small extensions on sleep latency resulting from bright screen use. Indeed, in some studies, the mean sleep latency was shorter in the bright screen condition than the control [15,17,18]. The fact that this consistent outcome occurs from independent studies, using various samples (e.g., teenagers, people experiencing insomnia, athletes, healthy sleepers), different objective sleep measures, different research designs (i.e., between-vs within-subjects), with some performed under controlled laboratory conditions and others in the home environment, leads us to believe that we will continue to witness this consistency in future studies. What is equally interesting is the consistency of melatonin suppression seen across studies. These data suggest an uncoupling of the tight connection assumed to exist between pre-sleep melatonin levels and sleep onset latency.

It is worth noting that most – but not all – of the studies testing the bright light hypothesis administer bright screenlight before participants' usual sleep-onset time, which affords a test of light's alerting effects free from potential confounds (i.e., increasing sleep homeostatic pressure if light exposure occurs after one's usual sleep onset). It is worth noting that these studies required a period of darkness prior to evening light exposure to ensure participant's eyes were 'reset' to a baseline each testing night. When pre-darkness conditions are not present (e.g., like IRL[2]), natural daylight exposure mitigates the effects of evening artificial light [20]. This phenomenon further challenges the bright light hypothesis as the reason to explain effects of technology use on sleep. Whilst bright light is the most popular mechanism describing the alerting response to technology use, it is not the only one.

1.1.2. The arousal hypothesis

Sleep hygiene recommendations generally recommend lower stimulation in the hours before bed, and at times the instructions have included exciting content from technology [25]. The notion is that the media content we consume before bed may cause arousal (e.g., elevated pre-sleep heart rate or EEG activity), making it difficult to fall asleep (i.e., longer sleep latency). This has led scientists who test the arousal hypothesis to inevitably compare different technological devices (e.g., videogame machines vs TV) or different content (e.g., non-violent vs. violent content) – or both – and examine the effects on sleep.

One of the earliest tests compared videogaming to mental arithmetic.

[1] *f.lux* is an app that reduces the emissions of short-wavelength light (see Fig. 2).

[2] IRL = in real life.

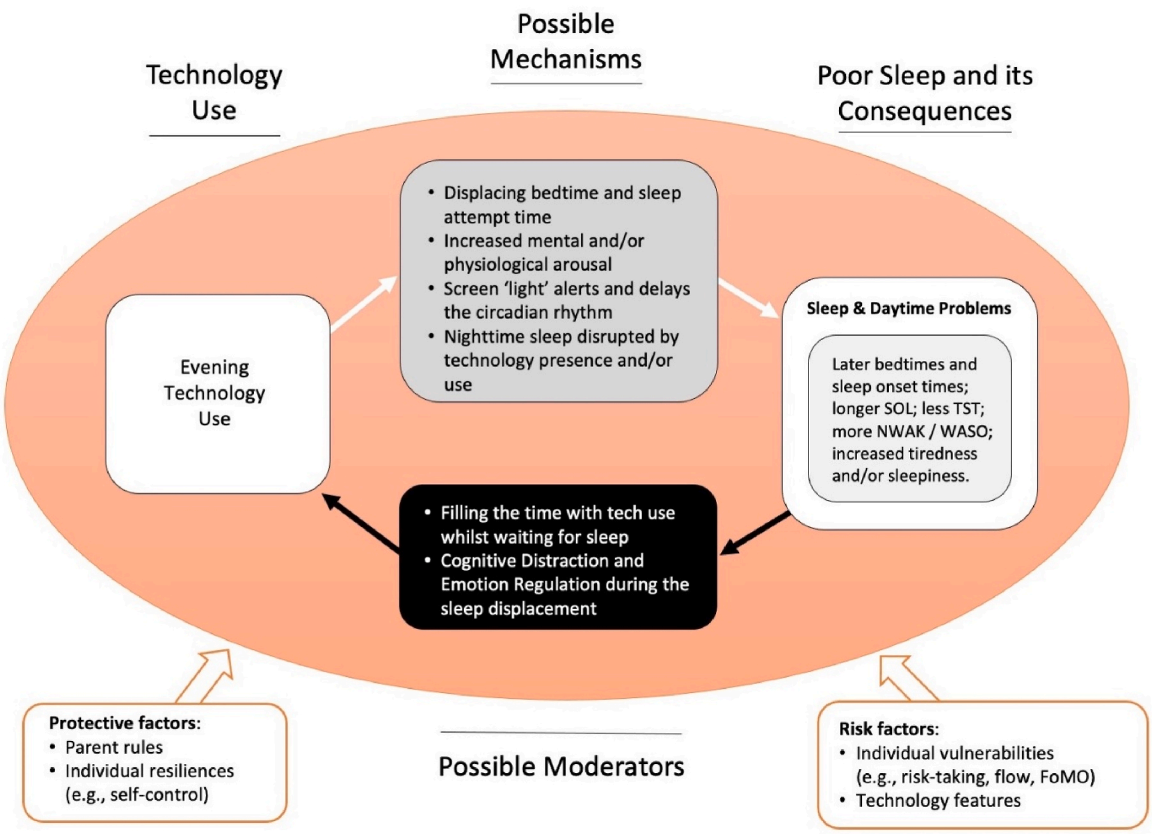

Fig. 1. Updated bi-directional model of the links between technology use and sleep.
Note. The model proposed in this review includes three important changes: 1) the addition of the direction of effect from sleep problems to technology use and the recognition of bi-directionality, 2) two potential mechanisms underlying this direction of effect: emotion regulation and time filler, 3) and updated and organized moderators, including risk- and protective-factors for the link between technology use and sleep problems.

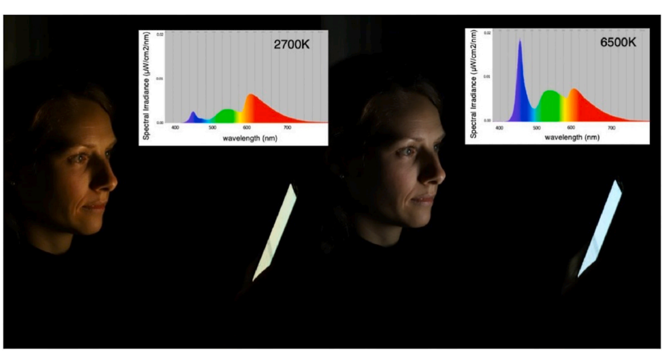

Fig. 2. Spectral analysis of smartphone screens set to full brightness, without a short wavelength filter (right panel) and with blue light filter activated (left panel). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Of note, participants undertook these activities hours past their usual bedtime that would have increased their sleep homeostatic pressure. This confound likely explains the 2-min mean difference in sleep latency between conditions [26]. Since then, researchers have controlled for the confounding effects of sleep pressure by exposing study participants to varying media content prior to their usual sleep-onset time. The alerting effects found in these studies, including the arousal mechanisms (e.g., heart rate) and sleep outcome (i.e., sleep latency) are presented in Table 2.

Unlike the consistency found in the 'mechanism' testing the bright light hypothesis (i.e., melatonin suppression), there is a lack of consistent findings in the arousal mechanisms. Yet, these studies consistently show small extensions on sleep latency, akin to what has been observed for the bright screenlight studies. This occurs regardless of the type of device, or the engagement of the content, or in some cases both (i.e., violent videogaming). At the other end of the spectrum, it is

Table 1
Sleep onset latency differences (SOL_{diff}) between a bright screen condition and control comparison across independent studies.

Author	Year	Measure	Setting	Intervention	SOL_{bright}	SOL_{diff}
Heath [14]	2014	PSG	Lab	App	14.7	3.3
Van Der Lely [15]	2015	PSG	Lab	BB	4.9	−1.9
Chang [16]	2015	PSG	Lab	Print	25.7	9.9
Grønli [17]	2016	Act	Home	Print	15.8	−2.0
17Ayaki [19]	2016	Act	Lab	BB	13.2	7.5
Rångtell [20]	2016	PSG	Lab	Print	14.1	0.4
Green [21]	2017	PSG	Lab	App#	11.9	5.7
Ostrin [18]	2017	Act	Home	BB	12.4	−3.9
Shechter [22]	2018	Act	Home	BB	16.2	4.9
Knufinke [23]	2018	Act	Home	BB	11.0	5.0
Duraccio [24]	2021	Act	Home	App	11.9	0.5

Note: PSG = polysomnography; Act = wrist actigraphy; BB = blue blocking glasses; Print = printed book; SOL_{bright} = sleep latency (minutes) in the bright screen condition; # - wavelength of light from a PC was stated to be "adjusted using a light metering device".

Table 2
Sleep onset latency differences (SOL_{diff}) in minutes of laboratory examinations of arousing technological content.

Author	Year	Measure	Setting	Media	Arousal	$SOL_{arousal}$	SOL_{diff}
Higuchi [26]	2005	PSG	Lab	VG	HR=Y	6.2	3.2
Ivarsson [27]	2009	Diary	Home	VG	HRV=Y	20.4	5.6
Weaver [28]	2010	PSG	Lab	VG	HR=N	7.5	4.5
Ivarsson [29]	2013	Act	Home	VG	HR=Y	37.6	8.5
King [30]	2013	PSG	Lab	VG	HR=N	16.1	3.5
Combertaldi [31]	2021	PSG	Lab	App	HRV=Y	19.2	4.4
Baselgia [32]	2023	PSG	Lab	TV	HR=N	10.0	−5.3

Note: PSG = polysomnography; Act = wrist actigraphyDiary = sleep diary; VG = violent video game; App = social messaging app; HR = heart rate; HRV = heart rate variability; Y = significant effect found; N = no significant effect found; $SOL_{arousal}$ = SOL (in minutes) for the arousal condition; SOL_{diff} = the difference in sleep onset latency (in minutes) between the arousal and control/comparison conditions.

interesting to learn from these studies that watching TV has produced little-to-no effects on sleep, despite sleep hygiene recommendations. Indeed, Weaver and colleagues [29] noted that 30 % of their sample fell asleep watching TV in the hour before bed.

These small effects persist despite the advancement of streaming services and strategies employed by media companies to keep their consumers engaged [33,34]. For example, in a more recent novel laboratory study, participants watched 3-to-4 episodes of a neutral TV series or a suspenseful TV series, with or without a 'cliff-hanger'[3] [32]. In the time between lights out and sleep onset, pre-sleep arousal was significantly higher in the cliff-hanger group, but not the suspense-only group. Self-reported stress was also higher after watching a suspenseful series, yet surprisingly, the suspenseful cliff-hanger group had the shortest sleep latency (mean difference of 5-min). No differences in night wakings or sleep duration were observed. In a randomized-controlled intervention study with pre-schoolers (Mage 4.2), altering TV and video content substituting violent content with prosocial-educational content resulted in significantly lower odds of reporting sleep problems at follow-up (including frequency of sleep latency >20 min, repeated night wakings, nightmares, difficulty waking in the morning, and daytime tiredness), with the largest effect on difficulties waking up in the morning [35]. Unfortunately, this study did not measure sleep latency or duration, and it is therefore difficult to quantify the magnitude of the change in relation to other studies (see Table 2).

Most experimental studies have tested offline media content due to the difficulties in examining media with highly variable content (e.g., social media). More recently, Combertaldi et al. [31] tested the effects of 30-min of social media use (restricted to Snapchat and Whatsapp) compared to 30-min of progressive muscle relaxation and a control condition (i.e., simply going to bed). Social media use did not alter heart rate nor heart rate variability compared to the control condition, although relaxation decreased heart rate compared to the other two conditions. Regardless, participants slept only 6 min less in the media condition compared to the control group. Worth noting was that bedtime was 30-min earlier in the control condition vs active conditions.

Taken together, this highlights the need for not only device, but also content, to be scrutinised when exploring mechanisms between pre-sleep technology use and sleep [36,37]. Using technology before bed *may* increase pre-sleep cognitive or physiological arousal, but the consequent alerting impact on sleep is likely to be less than originally assumed. Effects on sleep duration and sleep latency seem less than 10 min - if at all.

At this point, it is worth mentioning one outlier study that was excluded from Table 2. Unlike all other studies that exposed participants to technology use in the hour/s leading up to bedtime, Dworak and colleagues' [38] participants performed 1 h of either video gaming or watching TV, which *ceased* 2–3 h before bed. Yet, compared to a baseline sleep latency of 10.8 min, video gaming resulted in a 21.7-min extension of sleep latency. This distal screen exposure causing a large SOL extension is an oddity in the literature, and as arousal was not measured in this study, the explanation for these results is inexplicable.

Taken together, the empirical evidence testing the bright screenlight and arousal hypotheses suggest that these mechanisms play a small-to-negligible influence on sleep, especially if technology is consumed prior to one's usual sleep onset time. In these situations, sleep appears surprisingly resilient to prior technology use, even in the face of elevated cognitive and/or physiological arousal assessed by objective or subjective means. Yet, as devices often 'sleep' with their owners, is it the case that sleep may be fragmented by them?

1.1.3. Nighttime sleep disruption

Approximately 20 years ago, Jan van den Bulck [39] wrote a letter to the editor of the *Journal of Sleep Research*, calling to our attention the possible impact of a novel cause to sleep disruption – nighttime media alerts [39]. In his 2003 study, 43 % of adolescents reported being woken up at night by incoming text messages at least once a month, with 11 % being woken at least once per week. Since then, evidence supports the notion that technology directly interrupts sleep after its onset, and that these interruptions may constitute a meaningful mechanism underlying the link between increased technology use and poorer sleep. Moreover, the extent of these nighttime interruptions seems to have risen considerably, given the ever-growing 24-h usage of smartphones [40]. More recently, analysis of objectively recorded text message data revealed that over 70 % of youth sent at least one text message between 10 p.m. and 6 a.m. over the course of a week [41]. These findings dovetail with evidence from young adult studies, demonstrating the ubiquity of individuals keeping their phones close overnight, leaving their ringers on, and regularly checking their notifications throughout the sleep period [40,42–44].

Several studies have directly examined the links between nighttime technology interruptions and sleep in adolescents. In a recent investigation of over 10,000 adolescents, those who left their phone ringer on overnight were significantly more likely to experience trouble falling asleep, staying asleep, and overall sleep disturbance compared to adolescents who turned their phones off at night [45]. It is likely that this night-time behaviour may be habit-forming, as longitudinal work has found those who experienced phone-related nocturnal awakenings had over 3 times higher odds of developing difficulties falling asleep and more than 5 times higher odds of experiencing restless sleep 1 year later [46]. These findings remained stable, highlighting the specific role that phone-related nocturnal awakenings may play in disrupting sleep. Thus, while several studies have demonstrated associations between adolescent nighttime media use and poorer sleep outcomes [47,48], differentiating between technology use before and after sleep onset could provide more detailed insights into the intricate relationship between technology use and sleep.

Technology-related disruptions occurring after sleep onset may negatively impact sleep in various ways. Incoming alerts, ringers, and notifications may occur at any stage of the sleep cycle, potentially

[3] a 'cliffhanger' is defined as an exciting moment that is not concluded despite occurring at the end of an episode. It therefore encourages continued viewing.

disrupting its natural architectural progression. Once awakened, adolescents may be inclined to engage with media screens, making it challenging to resume sleep, and the temptation to prioritize media use over sleep (e.g., while awaiting further communications). Whilst there has been a focus by virtually all stakeholders on the effects of pre-sleep technology, it may be more likely that post-sleep technology use reduces sleep duration. For instance, a study of undergraduate students found that frequent smartphone-interrupted sleep was associated with 48 min shorter sleep duration on average than those whose sleep remained undisturbed by media devices [40]. It is worth considering that young people who extensively engage with digital media devices or experience fear of missing out (FoMO) or nomophobia could be more inclined to keep these devices within reach and active during the night, thereby increasing the likelihood of nighttime interruptions (see *Moderating Factors* below for further discussion [49,50]).

Lastly, recognizing the potential adverse consequences of nighttime technology-related sleep interruptions, a recent large-scale study endeavored to mitigate such issues through a national mass media campaign [51]. Over 25,000 participants contributed data to this "SmartSleep Experiment". The findings indicated that 15 % of participants who initially reported smartphone use during sleep hours reported, with 83 % of these individuals indicating a reduction in smartphone use following the campaign. Furthermore, approximately one-third of participants who altered their nighttime smartphone behaviour reported implementing preventative measures, such as placing their phones out of reach (29 %) or activating silent, flight, or do not disturb modes overnight (36 %). Unfortunately, sleep was not measured, and further studies are needed to investigate these strategies' impact on sleep duration and quality.

The night-time disruption hypothesis appears a promising lead as a mechanism with a potentially large influence on sleep. Yet, the sleep science field's downfall is that night-time disruptions from technology is a niche and understudied area.

1.1.4. The sleep displacement hypothesis

The idea of 'sleep displacement' via technology use was fully conceptualised almost two decades ago [52], off the back of an earlier study of young school children that theorised "Television viewing may simply serve to displace sleep time, thus shortening sleep duration to unacceptable limits." (page 1) [53]. The sleep displacement hypothesis suggests that time spent using technology leads to later bedtimes and overall shorter sleep duration (i.e., the time using technology replaces time that might otherwise have been spent sleeping; [3,52]. With the introduction of portable electronic media (e.g., mobile phones), technology can now be effortlessly transported not only into the bedroom, but also into bed, facilitating its use before attempting sleep. In recent years sleep displacement has been theorised to be a two-step process whereby bedtime (i.e., getting into bed) is separated and distinguished from "shut-eye" time (i.e., the time one attempts to sleep once in bed [54]; Fig. 3).

Data from correlational research in adults and adolescents has provided support for this theory and highlighted the desire to report 'shut-eye time' or 'device stop-time' in subjective measures of sleep - as it can no longer be assumed when sleep is attempted and/or device use ceases (e.g., after bedtime or lights out time [35,53–55]). In fact, one study of 4010 adolescents found time in bed met current recommendations for adolescents' sleep (i.e., 8+ hours), however long shut-eye latencies appeared to reduce sleep opportunity, and thus indicating short sleep durations on school nights (i.e., less than 8 h sleep [56]).

As mentioned above, early experimental studies tested pre-sleep technology use prior to the individual's usual bedtime [14,29,31]. Some studies then began allowing participants to use technology not just before bedtime, 'but for as long as they want' [57,58]. In this way, participants are asked to self-select their own bedtime. For example, when adolescents played a novel videogame without an externally-imposed bedtime, their self-selected bedtime has been up to a 1 h and 15 min later on a school night [58]. As we will elaborate later in this paper (see *Moderators*), not all adolescents are the same, with some adolescents in these studies ceasing their videogaming after midnight on a school night, even after being informed that the researchers would wake them up at 7:00 a.m. [57,58]. These convergent findings demonstrate a meaningful impact of pre-sleep technology use on sleep according to the sleep displacement theory. Unlike the tests of the bright light and arousal hypotheses that show a delay of sleep onset of, at best, 9.9 and 8.5 min, respectively, it is clear that a delaying of more than 1 h of 'shut-eye time' (and hence sleep onset) is more profound when examining the sleep displacement mechanism.

1.1.5. Summary of original mechanisms

Despite the popular belief that the arousing stimulation resulting from using technology before bed leads to sleep problems, the research conducted up until now shows some consistency (i.e., sleep latencies from multiple independent studies) that do not support such a belief. We posit this as the first challenge for individuals to rethink their position on the influences from bright screens and the content on them. In contrast, we cannot ignore that the most understudied mechanisms, those of nighttime sleep disruption and sleep displacement, support the first two sentences in this paper – that technology use and sleep are *meaningfully* connected. Not only are they connected, but it appears that allowing oneself to use technology beyond their own 'bedtime' and/or having their sleep interrupted by their phones may each reduce the sleep opportunity by an hour or more. We now move onto the second challenge

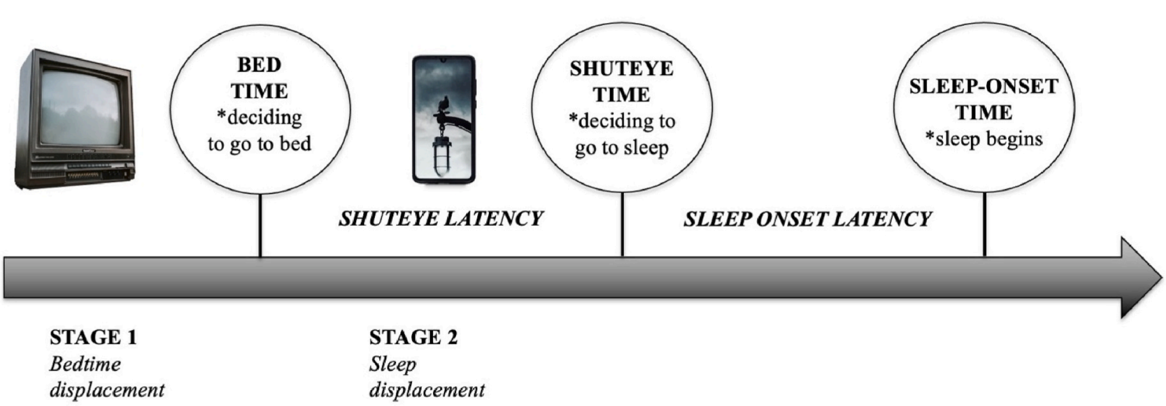

Fig. 3. Sleep displacement as a two-stage process.
Note. Stage 1, bedtime may be displaced by pre-bedtime technology use. Stage 2, in-bed use of technology begins the period 'shuteye latency', thus sleep is displaced. Shuteye time occurs when the decision to attempt sleep occurs and technology use ceases. This begins the new version of sleep onset latency. Based on Exelmans & van den Bulck model [49].

to the collective wisdom on this hot topic. That it is also possible that sleep problems can influence our use of evening technology.

1.2. Reverse mechanisms

1.2.1. Can sleep problems precede technology use increases?

The idea that technology could be used as a way to facilitate sleep was studied as early as 2006, with a novel survey finding most adolescents used devices fall asleep (e.g., 60 % = music; 55 % = books; television = 37 %; 22 % = computer games [52]. Except books, adolescents using technology as a sleep aid reported later bedtimes, shorter sleep duration, and more tiredness. These results were replicated in an adult sample 10 years later, with the addition of internet use (23.3 % of the sample [59]). Again, using technology as a sleep aid was associated with poorer sleep quality and fatigue. These studies suggest that technology may be used as a sleep-onset aid, albeit not a very efficacious one. Thus, is the sleep problem *leading* to the use of technology or vice versa?

Longitudinal studies have explored bi-directional links between the use of technology and sleep. The first study of its kind found support for sleep problems predicting increased television and online social networking, but not vice versa [60]. Subsequent studies found support for both directions [61–63]. Interestingly, the direction of effect varied depending on media activity (e.g., internet use was linked to consequent bedtime problems and sleepiness [63]) and sleep feature (e.g., morningness/eveningness was linked to consequent technology use [62]). The next part of this review will focus on the mechanisms that may explain how sleep problems can be a precursor of technology use.

1.2.2. Technology use as a time filler

As adolescents mature, the delaying of the circadian rhythm and reduction in sleep homeostatic pressure collude to push sleep onset to a later time of night, that often extends into young adulthood [64].

One of the immediate results of this maturation is the organic “freeing up” of time in the evening. It is thus plausible that technology use may serve as a form of entertainment or “time filler”, offering adolescents a means to occupy themselves during this wake-maintenance zone before sleep onset. Individuals tend to engage with digital media devices when they are in between activities or experience boredom [65]. Correspondingly, qualitative studies of adolescents’ experiences with technology have found that teenagers tend to turn to their phones to “fill the void” in situations when they had “nothing else to do” such as “before sleeping” [66,67]. In line with this qualitative evidence, recent evidence from diaries shows individual variations in day-to-day technology use were associated with trivial positive changes in sleep onset and duration [68–70]. Thus, suggesting that the time spent on devices before sleep is time that would have still been spent awake, rather than biting into their sleep opportunity. Therefore, the sleep-tech link may be mediated by adolescents’ use of devices to simply pass the time until they are physiologically prepared to fall asleep.

1.2.3. Technology use as an emotion regulation tool

Of course, for many adolescents, the period preceding sleep onset is not merely a neutral phase to be filled. Rather, it may be a highly distressful time, marked by intrusive thoughts and negative emotions. To regulate such negative emotions and cope with this heightened state of arousal, individuals may turn to various strategies, including a very accessible and appealing tool – their phone.

Adolescents experiencing sleep onset difficulties may employ their devices as sleep aids in various ways. First, they can turn to screens as a distraction, serving to divert attention away from negative thoughts. In a recent study involving 684 adolescents, 62 % reported using technology as a means of distraction from negative thoughts [71]. Notably, those who reported using technology as a distraction were significantly more likely to report experiencing longer sleep latency, and thus later sleep onset times. Qualitative investigations into the motivations behind technology use among adolescents revealed that devices offer a “comfort bubble” [67], that could facilitate sleep in stressful moments [72]. These findings dovetail in that technology use may provide a “security blanket” in anxiety-inducing situations, helping to alleviate worries and stress [73,74]. Alongside distraction, adolescents facing sleep-onset difficulties may also employ technology to directly down-regulate negative emotions. Examples include seeking social support by engaging in nighttime texting with peers to share concerns [41] and searching for online information to address sources of distress [73]. Additionally, adolescents may use apps specifically designed for emotion regulation, such as those offering guided meditation, mindfulness exercises, or therapy resources [75,76]. Therefore, for these young people, removing screens from their bedroom might ultimately have a negative impact on their sleep because of an increase in negative thoughts and no tools to handle them. It should be noted that while technology use may be beneficial for some adolescents struggling to fall asleep, this strategy may also contribute to the perpetuation of sleep difficulties over the long term, given the mechanistic pathways discussed above (namely, heightened arousal, light exposure, time displacement, and nighttime interruption by technology devices). Recognizing and addressing this potential cycle is essential to safeguard adolescent health and well-being.

The research presented above supports the opposite direction of effect. Namely, sleep disturbances may be a precursor to the use of technology at bedtime, either as a way to fill the void while waiting to fall asleep, or as a regulatory strategy to deal with unwanted thoughts and emotions during the sleep-onset process. Yet, this direction needs to be tested more rigorously with experimental studies. The next part of the review is going to explore what makes certain individuals at higher risk for using technology in a way that is harmful for sleep, or for turning to technology when sleep does not come easy.

1.3. Moderators - risk factors

1.3.1. Individual vulnerabilities x technological algorithms

The evolution of theoretical models from 2010 to 2017 saw the introduction of what were labelled ‘moderators’. That is, a meaningful link between evening technology use and sleep might only occur when certain conditions are at play. As a few researchers have discovered, there are some conditions that are required within the human (i.e., personality characteristics) and others within the device (i.e., an automatic algorithm targeting specific personality characteristics). This new research into the interaction between an individual’s personality characteristics and the type of technology was initially inspired by the work led by Malena Ivarsson in the late 2000s [28,30]. This Swedish research group noticed that adolescents differed in their physiological responses to violent videogaming (i.e., heart rate variability), which was moderated by their previous gaming experiences. Specifically, adolescents with more gaming experience showed differences in their heart rate variability, depending on whether they played a violent-versus a non-violent videogame [30]. Despite these individual differences at play, there were not meaningful influences on the participants’ sleep. These lack of effects on sleep due to the moderating influence of gamer experience were also confirmed independently [57]. Nonetheless, some research groups continued to explore and identify other personality characteristics that may moderate the link between evening technology use and sleep. These influential contributing factors can be grouped into two main categories: 1) an individual’s vulnerability to the media itself, and 2) protective factors which may help people to be more resilient to some of the potential harmful effects related to technology use.

1.3.2. Risk-taking

Young people (children, adolescents, young adults) have an affinity for using technology. Across these developmental periods, they may experience a cognitive imbalance depicted by an *under*-active behaviour regulation system (dorsolateral prefrontal cortex), and an *over*-active reward-seeking system (insula and ventral striatum) [77]. Research has shown that when performing certain technological activities, young people may be particularly vulnerable to making risky decisions (e.g., continuing to play their videogame) – and chasing rewards (e.g., checking reactions on social media apps) - and this imbalance is made worse when they experience sleep loss [77].

Risk-taking was an individual vulnerability tested within the context of pre-sleep technology use. Adolescents' trait-like aspects of risk taking – their perceptions of the consequences of taking risks, as well as their perceptions of the rewards from taking risks – were measured before engaging in a novel videogame in a laboratory setting [57]. Adolescents were informed that they may play their offline game for as long as they want, with the knowledge that they would be woken at 7:00 a.m. to get ready for school [57]. This research design demonstrated that adolescents varied in their bedtimes, with some delaying their bedtime more than others. Their bedtime delay was moderated by their perception of the consequences of taking risks. Of note, the magnitiude of the effect in this study was such that every 1-unit increase on the risk-taking measure (e.g., the difference in a negative consequence being '*moderately likely*' to '*extremely likely*') equated to a 38-min later bedtime [57]. When comparing this time difference of 38 min to the common sleep latency extensions found in studies testing the bright light and arousal hypotheses, it opened the possibility that the sleep displacement theory was the best explanation connecting evening technology use and sleep.

1.3.3. Flow state

During the Reynolds and colleagues study [57], a personality characteristic, known as the flow state, was also examined to see if it moderated the continued use of adolescents' videogaming. A flow state consists of a number of different yet inter-related elements, including: i) flowing from one moment to the next, (ii) little-to-no distinction between one's self and their environment (e.g., becoming immersed in their activity; losing track of time), and iii) a blending of past, present and future [78]. Flow was measured by asking adolescents in real-time to guess how much time had passed whilst gaming [57], yet in the end, flow was not a significant moderator, likely due to the measurement interrupting adolescents' flow state.

In a follow-up study, self-reported flow was measured as both a trait and as a state characteristic [58], and by using this alternative method of measurement, both were found to moderate the association between evening videogaming and adolescents' self-selected bedtime. Interestingly, when the videogame difficulty level was set to 'hard', adolescents selected a later bedtime if they reported higher trait flow [58]. The significance of this experimental study was that the magnitude of the bedtime delay was around 90 min between adolescents with a high-versus low-trait flow – again supporting the sleep displacement theory as the leading mechanism. What was also discovered in the development of this experiment was that videogame companies were already aware of the psychology of flow states, and had integrated algorithms within their games, known as dynamic game balancing [58]. This meant that technology companies were moving at a faster pace than researchers.

1.3.4. Fear of missing out (FoMO) and bedtime procrastination

With the rapid access to social media use in the past decade, young people may have become particularly vulnerable to socio-emotional pressures around the clock. Some insights come from a large-scale study of over 3000 adolescents who reported high scores on a FoMO scale (including items such as staying connected to peers, and following social etiquette), also reported delayed sleep onset, short sleep duration and poor sleep quality [79]. Young people also cite concerns about the negative consequences if they are disconnected from peers, including peer exclusion from missing out and social disapproval [80]. These abovementioned findings are supported by independent research, showing adolescents delay going to sleep because they did not want to miss both individual and group conversations on social media, saying it was "embarrassing" to stop the conversation and go to sleep [81]. Bedtimes have also been delayed because adolescents wanted to watch TV programs their friends would discuss the next day [81]. The social norms and pressure involved in the use of technology at night cannot be ignored to fully understand and potentially change sleep-technology behaviours in young people.

Since these discoveries, a new personality characteristic called 'bedtime procrastination' (BP) has also been tested. BP can be defined as a delaying going to bed at the intended time, without any external circumstances causing the delay [82–84], and has been investigated with predominantly smart phones [84,85]. In sum, BP shows a moderate correlation with sleep insufficiency [82], which is likely driven by later sleep-onset time [86–88]. It is worth highlighting that the vast majority of research designs in this emerging area are correlational in nature [82]. Recent work has demonstrated that a novel intervention to target BP saw a mean reduction of 46 min of BP, including minimizing the amount of BP that occurs between bedtime and light out (i.e., shuteye latency [89]). We note here, that BP is not only a potential risk factor for delaying people's bedtimes (and thus sleep), but it also overlaps significantly, and in the opposite direction, to a potentially important personality factor to protect people's sleep – self-control [82].

1.4. Moderators – protective factors

1.4.1. Self-control

Self-control is defined as the ability to regulate our affective, cognitive, and behavioural response tendencies (or impulses), that is seen as an effortful and conscious process [90]. Exelmans and Van den Bulck [91] have been the first to investigate the relationship between self-control, one form of electronic media use (i.e., watching television) and bedtime procrastination together. They found lower levels of trait self-control (i.e., those who reported a struggle to resist short-term gratification over long-term goals) were associated with more bedtime procrastination, and more temptation to engage in television viewing in the evening [91]. While this novel study provided insight into how these mechanisms may be linked, television was the only electronic media included, and sleep was unfortunately not an outcome measure [91].

In today's "attention economy", many devices and apps (e.g., YouTube) are designed to interfere with their users' sense of agency [34]. Features such as "autoplay" and the constant stream of content intend to make it difficult to use these apps in a structured way, and therefore may result in people remaining engaged with their screens for unintended periods of time. For example, participants in a YouTube study reported finding it difficult to resist engaging in "just one more video" [34], and unplanned and regretful use, where videos from the algorithm were perceived as too engaging to disengage from, leading them to getting stuck in a "rabbit hole" of videos [34]. It follows that self-control may be protective against "tempting" technology features.

Theoretically, self-control may be an important catalyst in the relationship between electronic media and sleep (for a review see Ref. [92]). Similar to a battery, self-control can be recharged after a good night's sleep and last until bedtime. Thus, forming a protective loop of self-control, conscious use of technology, and preserved sleep quality and quantity. In addition, individuals with higher trait self-control may be protected from using technology beyond their bedtime. The latter (i.e., individual differences in trait self-control), rather than daily variations in state self-control, has more support in the scientific literature [93,94]. Nevertheless, more studies investigating sleep, self-control and technology use simultaneously are needed.

1.4.2. Technology rules

The transition towards self-reliance and autonomy often occurs during early adolescence. Yet when it comes to sleep health, parents and caregivers still have an important supportive role [95]. Adolescents have even expressed their desire for parent support (e.g., parental warmth, engagement, and setting routines), noting these parental factors were helpful for their own sleep [96]. It is therefore not surprising that there is a solid evidence base that suggests parent-set bedtimes are a protective factor for adolescent sleep [95,97,98].

There is also emerging evidence suggesting parent-set technology rules – where access to devices or the internet is restricted - could be protective for adolescent sleep. Such rules have been associated with less time spent on devices [99], earlier bedtimes [87], longer time in bed [95,100], and increased total sleep time [101,102]. There is also evidence to suggest that having a rule that restricts access to the internet in the evening (i.e., a Wi-Fi rule) has the potential to limit the amount of activities available to use on mobile devices and time spent on them [99]. In contrast, one study found that when parent-set media rules were absent, electronic media was more likely to be used for longer durations, and in the hour before sleep [100]. When rules are combined (e.g., set bedtimes and phone restriction in boarding houses) adolescents have slept 40 min longer on school nights compared to their peers [103]. Although rules can be set by parents (or teaching staff) compliance to these rules is another angle to consider. A recent study that investigated adolescents' self-reported compliance to their parent-set rules, found that compliance to technology rules (i.e., device and/or internet restriction) was linked to earlier lights out times and more sleep on school nights compared to their peers who reported they did not comply, or did not have any rules at all [96]. Non-compliance might explain some contradicting evidence of no sleep improvements when parental rules are in place [62,104]. Taken together, the current evidence base seems to suggest that parent-set rules around devices and bedtimes could serve as a protective factor to the possible negative effects technology can have on sleep. However, since most of the research to date is correlational, it cannot be ruled out that the reverse may also be true (e.g., adolescents who sleep well might be more likely to accept their parents' rules about technology use at bedtime). Experimental studies are needed to determine whether parent-set bedtime and technology rules are indeed protective for adolescent sleep. Nevertheless, parental rules are included as a protective factor in our updated theoretical model (see Fig. 1).

1.5. Future research directions

One of the goals of this review is to spur new, exciting research into the much-discussed link between sleep and technology use. As demonstrated by the overview of the evidence base, the mechanisms commonly thought to explain why technology use would *cause* sleep problems (i.e., arousal and bright light) are not well supported. These two hypotheses have been tested in well-designed experimental studies from different research groups around the world. The next step is to redirect the same effort towards other promising mechanisms, such as the sleep displacement hypothesis and nighttime disruptions. While experimental laboratory studies are the gold standard for establishing causal associations (i.e., isolation of a phenomenon from external influences), they pose a challenge concerning ecological validity. Isolating the effects of social media is such an example, where it might be difficult to reproduce the experience of multitasking and variety of stimuli a person is normally exposed to during the evening, while also rigorously controlling for the source of the influence. Ecological Momentary Assessment (EMA) studies might provide an elegant solution and complement to laboratory studies. EMA allows researchers to zoom into the daily bi-directional sequence of technology use, sleep, worries, arousal, self-regulation, and more, without altering the person's behaviours. For example, it is possible to measure smartphone use directly through an app and estimate sleep and arousal with wearables [69]. Moreover, these studies can explore both links within individuals (i.e., daily variation in technology use being linked to sleep disturbances) and between individuals (i.e., traits linked to a stronger link between technology use and sleep) [69]. Further, intervention studies can also test causal links. One intriguing question is whether altering sleep (i.e., advancing sleep-onset time) may subsequently reduce technology use - thus supporting the idea that technology use might be used to facilitate the sleep-onset process. Once the sleep-onset process is limited in its timeframe, devices are needed less. Moreover, we encourage intervention studies supporting parental rules about technology, which is a promising protective factor.

To date, longitudinal studies have provided some intriguing insights (reverse direction of effect), and such designs may in the future help to capture the influence of risk and protective factors on these bi-directional links [60–63]. Further, they can do so in large population-based studies that help generalizability, which is a limitation of experimental and EMA studies. In particular, person-oriented analyses can help to profile individuals at risk for a negative association between technology and sleep. Importantly, reporting effect sizes will be crucial to be able to compare the effects of these different bi-directional mechanisms and will guide the way forward.

While cross-sectional studies initially helped to map the basic links and extent of technology use and sleep over the past decade or so, correlational studies are not necessarily adding to our knowledge going forward. There is still a place for correlational studies, specifically for exploring new mechanisms and testing novel ideas (e.g. Ref. [71]), which can be further tested in experimental studies. Another good starting point for exploring novel ideas is qualitative studies, such as focus group interviews, to garner rich knowledge and a deeper understanding of technology users' experiences of what happens to their sleep when using screens. One such example is the adolescents' testimony of two contradictory but co-existing aspects of technology as a detrimental distraction from sleep as well as a helpful sleep aid, which suggests potential individual differences (i.e., 'one size does not fit all') and possibly a vicious cycle (e.g. Ref. [81]).

Finally, as observed in recent reviews (e.g. Refs. [105,106]), most of the attention in studying the link between sleep and technology use has been on adolescents and young adults, whereas studies in younger children and adults are lacking. This limits the generalizability of the theoretical model presented here and represents a major area for future research.

1.6. Public health implications

Where intervention work may target the individual or groups, public health aims to target the population. This up-to-date theoretical review presents multiple implications for public health messages, all of which rest on the backbone of closely translating the scientific evidence to the population. Such messages can be categorized into two components: i) what are the likely causes for evening technology use affecting our sleep, and ii) in what ways can people minimize these harmful effects.

In terms of the public messages about how technology use affects our sleep, it has become clear that the most prevalent explanations have been centred on the bright light and arousal hypotheses. Although the number of these population-based messages being spread across the internet is incalculable, we demonstrate here a recent and powerful example of the evolution of sleep science translation. Professor Matthew Walker's book titled "*Why We Sleep*" has been an international phenomenon [107], garnering best seller awards (including selection in Bill Gates Top 5 books for Christmas 2019), and an array of subsequent podcasts that have been listened to and/or viewed by tens of millions of people. Walker has demonstrated to us that it is possible for scientists to be the direct translator of science to the public. On the topic of technology's effects on sleep, Walker's book and podcasts highlight a single study that tested the bright light hypothesis [16], which showed the greatest extension of sleep latency (9.9 min). The conclusion has often been that bright light may be the leading cause explaining technology's effect on sleep. We stress here though, that this popular message predates the publication of "*Why We Sleep*", and has likely been amplified on social media by thousands of 'coaches' who prospered since the world

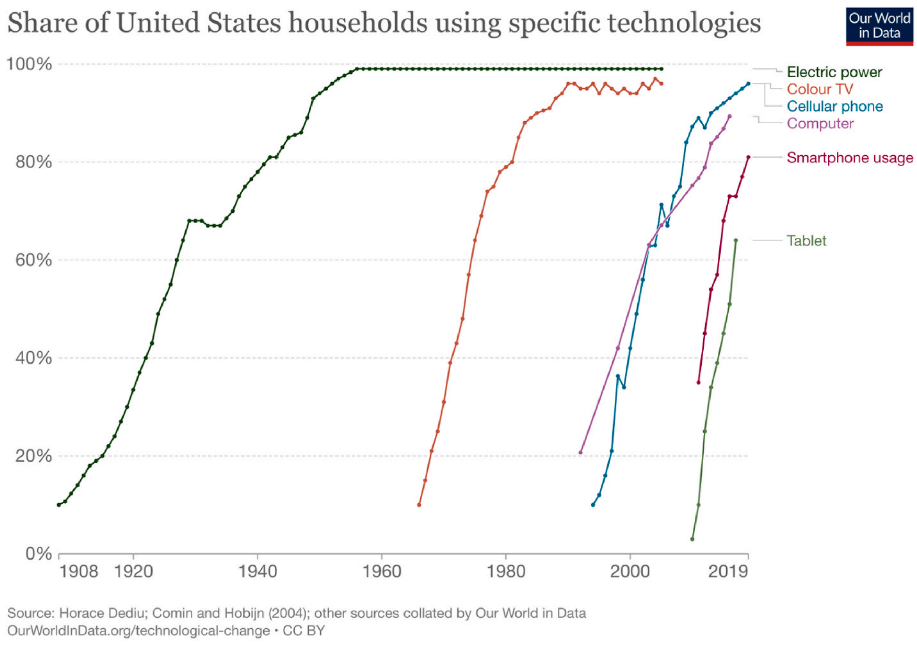

Fig. 4. Percentage increases in electric power and technological devices in homes in the USA over an 111-year period.

became more digital as a result of the COVID-19 pandemic [108,109]. To Walker's credit, he has changed his public health message, by dampening the significance of the bright light hypothesis on more recent and highly popular podcasts.[4] This change in belief of a powerful messenger is laudable, yet it also raises an important question for public health research – if the message from a powerful messenger is changed, can it change the beliefs of a population? This idea also pertains to our second question of communicating the evidence-based solutions to the population.

Originally, the most common solution to minimizing the harmful effects of technology was to not introduce devices into the bedroom - and if they already were - to remove them [110]. This solution was based on early cross-sectional evidence of differences in sleep between those who possessed at least one device in their bedroom (i.e., up to 36-min less sleep per night [110,111]). One may argue that with the advent of more portable devices (i.e., smart phones), there likely became resistance to this idea. For example, Fig. 4 shows the rapid increases in both cellular phones and smartphone usage in households since their introduction, which are now exceeding 90 % and 80 %, respectively. Yet, the same graph shows a strikingly similar increase in household adoption of the colour TVs from the 1960s. It is therefore of interest that even in the mid-2000s, both children and parents were resistant to the idea of removing TVs from the bedroom [112], which is likely to extend to smart phones today. It follows that public health messages eventually turned to limiting evening technology use, especially in the hour before bed [113] - a message that persists today [114]. However, it has become clear that there is equally resistance in following such advice [115], especially given low participation rates in evening technology restriction studies [116]. Based on the present theoretical review, what advice should public health outlets provide as a solution that will be accepted and followed by the masses?

Our view remains consistent with our predecessors, in that evening technology use is "here to stay" [117]. Rather than restrict it, we may need to impart scientific-based messages that utilize a 'harm minimization' approach. For example, overall, the data to date show that TV watching is one of the least harmful technological activities. There is a near-zero weighted correlation between TV watching and 'sleep' [97]; there is evidence that people fall asleep in the hour before bed when watching TV [29]; and that whilst 'cliffhangers' induce a physiological response, they nevertheless result in quicker sleep latencies [33]. These examples contradict the decades of messaging from classical stimulus control instructions to only use the bedroom for sleep and sex [118]. It follows that even if it takes decades to reverse this thinking – and behaviour – that starting now may see future generations of digital-savvy humans sleeping better than we currently are.

2. Conclusions

The over-arching aim of this theoretical review was to update our original 2010 model that implied a causal uni-directional link from technology use to sleep problems. In the many years since, it is no longer plausible to deny that two links exist between these two concepts, thus forming bi-directionality. In terms of mechanistic actions, we hope we have began to shift readers' beliefs. That, the magnitude of the effects explained by bright screens and arousing content are weaker than first hypothesised. This shift in thinking is extremely important for future exploration of this hot topic, and the seemingly impossible task of reversing some of the public's thinking. That is, we hope this new model will help to update public health messages more in line with the evidence-base available, and spur new research focusing on: *How much? For whom? And which mechanisms?*

Practice points.

- For some individuals and families, removing technology from bedrooms overnight could be a helpful way to prevent any possible impacts of technology use on sleep. However, restricting devices may not suit everyone, or for some families this could be difficult to implement.
- Technology is here to stay, and a harm minimization approach is warranted – technology can be in the bedroom but to avoid a negative impact on sleep it should not disturb during the night (e.g., flight mode), it should not be used later than the intended bedtime (e.g., settings and alarms can aid time management), it should be used for less engaging activities (e.g., TV watching).

[4] These podcasts include ones by Stephen Bartlett (*Diary of a CEO*) and Peter Attia (*Peter Attia, MD*).

- Technology is programmed to keep us engaged, entertained, and in a flow state. Awareness of technology features is the first step to take control and initiate behavioural changes. This knowledge may also guide harm minimization approaches (e.g., choosing less harmful apps and activities at bedtime).
- Some individuals may be more vulnerable than others to the negative effects of technology on sleep and intervention efforts should focus on such characteristics and subgroups (e.g., self-control). For example, individuals with low self-control might instead benefit from adapting their sleep environment so that it limits temptations (e.g., not keeping stimulating technology at arm's reach in the bedroom).
- Information concerning *why* technology affects sleep needs updating: Bright light and arousal do not seem to matter as much as how we manage our screentime in the evening.
- While restricting technology from the bedroom could be an effective solution, people may use technology to facilitate sleep. Therefore, removing all technology from the bedroom may not always be helpful and may lead to more negative thoughts, arousal and eventually fuel insomnia symptoms. We encourage practitioners working with young people to ask about the use of technology as a sleep-onset aid and work around harm minimization.

Research agenda.

- Qualitative studies are welcome to explore technology users' experiences and understanding of the complex association between sleep and technology use.
- Additional cross-sectional studies on the link between technology and sleep are not needed unless they explore novel mechanisms or epidemiological 'snapshots'.
- Longitudinal studies can inform on risk- and protective factors at a population level. Person-oriented studies in particular can identify who is vulnerable for the negative effects of technology use on sleep. However, given the pace at which technology is developing and the daily dynamics between technology, sleep and contextual events (e.g., stress), short intervals between measurement points might be more appropriate.
- Ecological Momentary Assessment studies provide valuable information about the daily influences of technology, sleep, and contextual and psychosocial influences. They also provide two helpful levels of understanding: between-subject (individual differences) and within-subject (daily variations).
- Experimental studies are the gold standard for establishing *how* sleep and technology are causally linked and quantifying *how much* they affect each other. Both laboratory studies and home studies/intervention studies should be prioritized to test the understudied but promising mechanisms of bedtime displacement and nighttime disruptions, as well as the newly proposed mechanisms in the opposite direction of effect: the time filler and emotion regulation hypotheses.
- Objective measurement of sleep and technology use is needed. New technologies may present opportunities and challenges (e.g., privacy, ethical concerns) for in-home studies.
- Moderators should also be a focus in future research, given the complex interaction between individual and technology characteristics.
- More studies in younger children and adult samples are needed.
- Once effects from individual technologies are known, research should move onto exploring the compounding effects of simultaneous technology use (multi-tasking).

Declaration of competing interest

Dr. Gradisar reports that he is the CEO of WINK Sleep Pty Ltd which provides professional training for the treatment of sleep disorders, and is employed by Sleep Cycle AB, a listed company whose app tracks sleep.

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