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ORIGINAL ARTICLE

## Does one hour of bright or short-wavelength filtered tablet screenlight have a meaningful effect on adolescents' pre-bedtime alertness, sleep, and daytime functioning?

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Electronic media use is prevalent among adolescent populations, as is the frequency of sleeplessness. One mechanism proposed for technology affecting adolescents' sleep is the alerting effects from bright screens. Two explanations are provided. First, screens emit significant amounts of short-wavelength light (i.e. blue), which produces acute alertness and alters sleep timing. Second, later chronotypes are hypothesised to be hypersensitive to evening light. This study analysed the pre-sleep alertness (GO/NOGO task speed, accuracy; subjective sleepiness), sleep (sleep diary, polysomnography), and morning functioning of 16 healthy adolescents ( $M = 17.4 \pm 1.9$  yrs, 56% f) who used a bright tablet screen (80 lux), dim screen (1 lux) and a filtered short-wavelength screen (f.lux; 50 lux) for 1 hr before their usual bedtime in a within-subjects protocol. Chronotype was analysed as a continuous between-subjects factor; however, no significant interactions occurred. Significant effects occurred between bright and dim screens for GO/NOGO speed and accuracy. However, the magnitude of these differences was small (e.g. GO/NOGO speed = 23 ms, accuracy = 13%), suggesting minimal clinical significance. No significant effects were found for sleep onset latency, slow-rolling eye movements, or the number of SWS and REM minutes in the first two sleep cycles. Future independent studies are needed to test short (1 hr) vs longer (>2 hrs) screen usage to provide evidence for safe-to-harmful levels of screenlight exposure before adolescents' usual bedtime.

**Keywords:** Adolescents, alertness, chronotype, light, REM sleep, sleep, technology

### INTRODUCTION

Poor sleep quality in adolescents and resultant daytime sleepiness have been associated with impaired academic performance and can cause an array of problems such as emotional instability, learning difficulties, school tardiness, and absenteeism (Carskadon et al., 2004; Cajochen et al., 2011; Dewald et al., 2010; Eggermont & van den Bulck, 2006). Furthermore, a systematic review and meta-analysis show that in many countries adolescents rarely obtain the hours of sleep needed for normal functioning (Crowley et al., 2007; Gradisar et al., 2011). With only 50% of adolescents reporting that they get a good night's sleep every (or almost every) weeknight, and up to 25% of adolescents sleeping for *less than* 6 hrs on school nights (Roberts et al., 2009), the effect of poor sleep on

adolescents' functioning and performance, and the regularity with which it occurs, is a cause for concern.

### Technology use

It has been suggested that a potential contributing factor to adolescents' poor sleep is their increasing use of screen technology (e.g. computers, televisions, and tablets) in the hours prior to sleep (Gradisar et al., 2013; Kaiser Family Foundation, 2010). A 2011 survey conducted by the National Sleep Foundation (NSF) found that *in the hour* before sleep, adolescents regularly use mobile phones (72%), computers or laptops (60%), and/or video game consoles (23%). This is a phenomenon made possible by the increased accessibility of screen technology to adolescents. In 1970, only 6% of 8-to-18-year olds had a television in their bedroom, a percentage

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that grew to 71% by 2010 (Gradisar & Short, 2013; Kaiser Family Foundation, 2010; Rideout et al., 2010; Roberts et al., 1999). One of the proposed mechanisms for technology's negative impact on sleep is exposure to bright screen light (Cain & Gradisar, 2010; Gradisar & Short, 2013). Yet, despite an abundance of media articles and webpages publicising theoretically detrimental effects of late night exposure to technology screen light (Peddie, 2012; Sisson, 2010; Sutter, 2010), there is currently little empirical evidence to support these claims, particularly in adolescents who arguably use technology the most of any other age group (Gradisar et al., 2013).

### **Alerting effects of screenlight**

Zeitgebers (external time-givers) assist humans' sleep timing to synchronize to the 24-hr day (Aschoff & Pohl, 1978; Chang et al., 2012a,b; Vandewalle et al., 2009; Wright & Lack, 2001). One of the most effective zeitgebers is light. The majority of evidence shows bright evening light exposure suppresses endogenous melatonin secretion to increase alertness and delay sleep timing (Cajochen et al., 2005, 2011; Chang et al., 2012a,b; Vandewalle et al., 2009; Wright & Lack, 2001; Wright et al., 2001); however, light also has direct links with daytime alertness, when melatonin levels are low (for review, see Cajochen, 2007). As such, the propensity for evening screenlight exposure to suppress melatonin and increase alertness could explain how late night technology screen use may affect sleep. Alertness is moderated by light intensity, with more intense light (e.g. 1000 lux) causing a greater alerting reaction (Cajochen, 2007; Cajochen et al., 2000; Duffy & Wright, 2005). However, doses as low as 100 lux also suppress melatonin and increase alertness (Boivin et al., 1996; Cajochen et al., 2000; Gooley et al., 2011; Zeitzer et al., 2000), making it possible for technological screens to instigate an alerting reaction (Krahn & Gordon, 2013). To date, studies with adults have shown 5 hrs of bright screenlight from laptops (<100 lux, Cajochen et al., 2011), or 2 to 4 hrs using electronic tablets (30–50 lux, Chang et al., 2012a,b; 40 lux, Wood et al., 2013) can significantly reduce, and delay, melatonin levels (Cajochen et al., 2011; Chang et al., 2012a,b; Wood et al., 2013), increase pre-bedtime subjective and objective alertness (Cajochen et al., 2011), and delay the onset of sleep (Chang et al., 2012a,b). In contrast, 1 hr of tablet use (40 lux) did not significantly reduce melatonin levels (Wood et al., 2013), although it is not known whether pre-bedtime alertness or sleep were affected.

There is little evidence of the alerting effect of screenlight on adolescents, despite their regular use of screen technology prior to sleep (Kaiser Family Foundation, 2010; National Sleep Foundation, 2011), and evidence suggesting changes in light sensitivity occur during adolescence (Carskadon et al., 2004; Weinert et al., 1994). Surprisingly, the ubiquitous

suggestion for adolescents to dim screenlight before bed to prevent ill effects on sleep is untested. Given bright light from tablets (~80 lux) exceeds the amount shown to affect sleep (30–50 lux), we anticipated that using an iPad on full brightness for 1 hr before bed would increase pre-bedtime alertness and delay the onset of sleep compared to a dimmed iPad.

### **Filtering short wavelength light**

Short wavelength light (e.g. blue 497 nm; green 525 nm) suppresses melatonin and increases alertness, while long wavelength light (e.g. red 660 nm; amber 595 nm) has no discernable effect (Brainard et al., 2001; Thapan et al., 2001; Wright & Lack, 2001). Prior studies have noted significant levels of short wavelength light emitted from technology screens (Cajochen et al., 2011; Figueiro et al., 2011), which may explain resultant alertness. To counter this effect, it is possible to filter short wavelength screenlight. One method is to view screens through orange-tinted glasses, which have been shown to not suppress melatonin compared to a bright screen after 2 hrs (Wood et al., 2013). Similarly, a non-LED laptop screen emitting approximately one-third less short wavelength light caused less alertness than an LED laptop after 5 hrs of usage (Cajochen et al., 2011). However, is it possible to reduce blue screen-light emissions in all screen types? *flux* (<http://stereopsis.com/flux/>, 2012) is a free app designed for several iDevices, and which alters wavelength screenlight, by reducing mainly short wavelength light (e.g. blue; colour temperature 6500 K), to mainly long wavelength light (e.g. orange; colour temperature 2600 K; see Figure 1). This study used *flux* to test whether filtered short wavelength screenlight minimizes effects on pre-bedtime alertness and sleep that may result from unfiltered bright screens.

### **Moderating effect of chronotype**

Some individuals prefer to sleep and wake early (early chronotypes), while others prefer to do so later (late chronotypes; Dagon, 2002; Roenneberg et al., 2003). Preliminary evidence suggests that the delayed sleep of late chronotypes is due to a greater sensitivity to evening light exposure (Aoki et al., 2001; Higuchi et al., 2005a). In both studies, evening melatonin suppression from bright light (1000 lux) was found to be greater in late chronotypes. Although these studies used high intensity bright light (1000 lux), much greater than an iPad screen (~80 lux), even low light levels increase alertness (Boivin et al., 1996; Cajochen et al., 2000; Duffy & Wright, 2005; Gooley et al., 2011; Zeitzer et al., 2000). In order to determine whether chronotype impacts adolescents' susceptibility to the effects of evening screen light exposure, this study compared alertness following light exposure across early and late chronotypes.

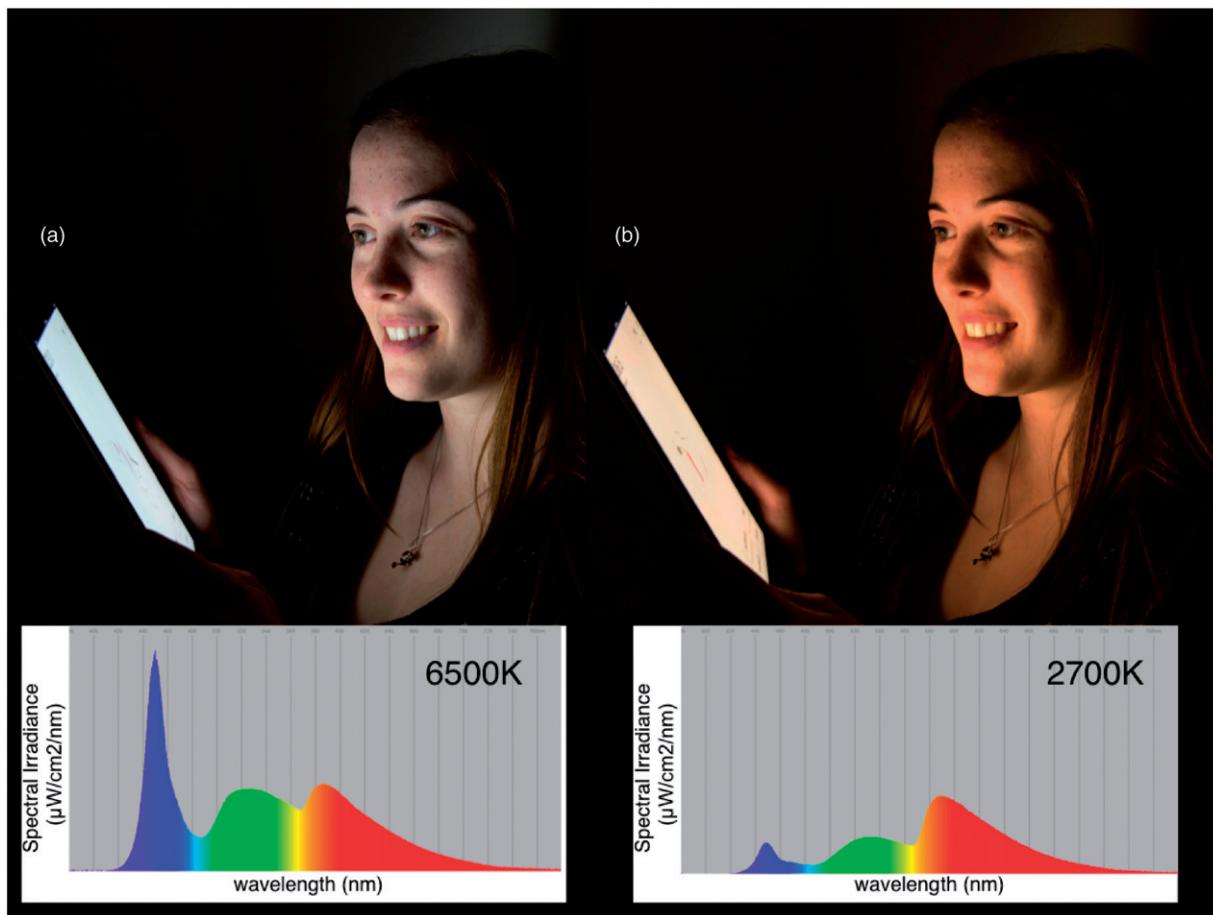


FIGURE 1. Spectral power distributions (SPD) for (a) full brightness iPad2 screenlight (color temperature = 6500 K; peak irradiance at 450 nm), and (b) *f.lux* filtered short-wavelength iPad screenlight (color temperature = 2700 K; peak irradiance at 588 nm) (b). Measured by USB2000 + RAD Spectroradiometer (Ocean Optics, FL).

### Effects on sleep architecture

Preliminary data suggest that technology screenlight may affect sleep architecture, including slow-rolling eye movements (SREMs; Cajochen et al., 2011), slow-wave sleep (SWS; Cajochen et al., 1992; Münch et al., 2006), and REM sleep (Higuchi et al., 2005a; King et al., 2013; Münch et al., 2006). Bright screens have shown less overall SREMs in the pre-sleep period (Cajochen et al., 2011). Broad spectrum or short-wavelength light before sleep has a small suppressant effect on slow-wave activity early in the sleep period (Cajochen et al., 1992; Münch et al., 2006). Although differences in the amount of REM minutes following use of a bright display or dim display were found to be nonsignificant, large effects nevertheless occurred (i.e. Cohen's  $d=0.74\text{--}0.85$ ), with fewer minutes spent in REM occurring after a bright display (Higuchi et al., 2005a). A moderate reduction in REM minutes also occurred after playing a videogame for 150 min vs 50 min ( $d=0.48$ ; King et al., 2013). Although illumination was controlled between the two conditions, there exists a possibility that the extra 100 min of light had an effect on REM minutes. Due to these preliminary findings, this study explored whether tablet screenlight had a suppressive effect on SREMs,

and minutes of SWS and REM sleep in the first two NREM-REM cycles.

### METHOD

#### Participants

Sixteen participants, aged 14–19 years (average age  $M=17.4 \pm 1.9$  yrs, 56% females) were recruited through advertisements in local schools and on social media. Exclusion criteria included factors known to affect sleep, including reports of trouble sleeping (>2 nights a week) (Léger et al., 2008); napping (>2 days a week) (Milner & Cote, 2009); transmeridian flight 3 months prior to study (Nicholson, 2006); regular snoring (>2 nights a week) (Scharf et al., 2005); use of sleeping pills (Qureshi & Lee-Chiong Jr, 2004); excessive caffeine (>200 mg a day) or alcohol consumption (Pollak & Bright, 2003; Singleton & Wolfson, 2009); smoking (Jaehne et al., 2009); psychiatric, neurological, or medical illnesses (Anderson, 2011; Lamberg, 2000; Lee & Douglas, 2010); use of psychoactive drugs known to affect sleep (DeMet & Chicz-DeMet, 1987); high levels of stress (Akerstedt et al., 2012), anxiety (Alfano et al., 2010), or depression (Sculthorpe & Douglass, 2010); and colour blindness

(Thapan et al., 2001). Informed consent was obtained from adolescents and their guardians. The study was approved by the Social and Behavioural Research Ethics Committee of Flinders University, and conforms to international ethical standards (Portaluppi et al., 2010).

## Design

A within-subjects design was employed with three counterbalanced conditions: bright unfiltered screen-light (80 lux), *f.lux* short-wavelength filtered light (50 lux), dim light (1 lux). Chronotype was measured as a continuous, between-subjects factor.

## MATERIALS

An Apple iPad 2 (LED-backlit screen = 9.7 inch (diagonal),  $1024 \times 768$  pixel resolution at 132 pixels per inch) was used as the light-emitting technological device. A Hioki Lux Meter (Hioki E.E. Corporation, Nagano, Japan) measured the amount of iPad screen light to reach the eyes when held 40 cm from the face in a dark room (bright light = 80 lux, dim light = 1 lux, *f.lux* filtered light = 50 lux). On each testing night iPad exposure totalled 48 min, split into two 24-min segments. During the first 16 min of each segment, the adolescents' played 1 of the 6 games (e.g. Snow Fight), and then watched a video compilation (e.g. Simon's Cat from YouTube) for the following 8 min. Videos and games were randomized across conditions. Selected games and videos all featured a white background, to reduce lux variation and produce maximal alertness. In conjunction with three 4-min GO/NOGO tasks (detailed later), adolescents experienced 1 hr of screen light exposure.

### *f.lux*

*f.lux* is a free software program developed for computers and other iDevices, which unobtrusively alters light spectrum emitted from screens according to clocktime (<http://stereopsis.com/flux/>, 2012). The screen remains unchanged throughout the day (6500K, peak  $\lambda = 453$  nm; Figure 1a); however, from late evening until early morning *f.lux* adjusts the screen to that of natural light, using warmer colours, such as red and orange (3400 K, peak  $\lambda = 597$  nm; Figure 1b, used in the present study), instead of blue/green light used throughout the day.

### Polysomnography

Electroencephalogram (EEG), electrooculography (EOG), and electromyography (EMG) measurements were taken using a portable Compumedics Somte (Compumedics, Melbourne, Australia). EEG readings were taken by placing two electrode pairs, in accordance with the international 10–20 system, at sites C4 and A1, and O1 and A2. EOG electrodes were placed ~1 cm lateral from the outer canthus of each eye and one on the forehead level with the eyebrows. Submental EMG

electrodes were placed ~1 cm lateral and ~1 cm down from the corners of the mouth, and one reference electrode was placed on the collarbone. Using Profusion Polysomnography (PSG) 3.0 software (Compumedics, Melbourne, Australia), a trained sleep technician (blind to conditions) calculated sleep onset latency as the time between "lights out" and the first of three 30-sec epochs of stage 1 or 2 sleep (Rechtschaffen & Kales, 1968), whether slow-rolling eye movements (SREM) were present or not (Cajochen et al., 2011) in each 30-sec epoch during the sleep onset process, and slow-wave sleep (SWS) and REM sleep as per Rechtschaffen and Kales (1968) scoring criteria.

### GO/NOGO task

The GO/NOGO task was used as an objective index of adolescents' cognitive alertness (Cajochen et al., 2011; Sagaspe et al., 2012). The 4-min computerised task displayed a series of single black letters (either "M" or "W") on a white background, using a Toshiba laptop (Tecra A9; screen dimension = 15.4 inch,  $1680 \times 1050$  pixels). Each letter was displayed for 0.216 sec and the blank inter-trial interval time varied randomly between 1300 and 1700 ms. Adolescents responded only to the letter "M" by pressing the spacebar. The response time window was between 150 ms (to stop anticipated responses) and 1500 ms. After 500 ms, a 440-Hz tone sounded for 475 ms to encourage adolescents to respond. The letter "W" appeared randomly at a frequency of 4 in every 20 letters displayed. Average reaction time (ms), and correct "no go" responses (%) were recorded. The laptop screen was adjusted to match light condition (in lux), including *f.lux*, which was activated during the GO/NOGO task in the *f.lux* condition.

### Munich ChronoType Questionnaire

The Munich ChronoType Questionnaire (MCTQ) is used to determine a person's chronotype by their midsleep point (Roenneberg et al., 2003). The midpoint of sleep on free days (i.e. no obligations), corrected for sleep debt accumulated during the week, was used to indicate whether adolescents had an early or late chronotype (Roenneberg et al., 2004b). As no normative MCTQ data exist for Australian teenagers (Randler, 2008; Roenneberg et al., 2004a), adolescents were measured on a continuum from early to late chronotypes. The mid-sleep point from the MCTQ has been shown to correlate with measures of eveningness-morningness (i.e.  $r = 0.60\text{--}0.72$ ; Zavada et al., 2005).

## PROCEDURE

Prior to acceptance into the study, adolescents were screened for exclusion criteria. A general health questionnaire was used to identify sleep habits, health problems, and sleeping difficulties. The DASS<sub>21</sub> (Lovibond & Lovibond, 1995) was used to screen

emotional disturbance (acceptance if <14 for depression, <10 for anxiety, <19 for stress subscales). Adolescents also underwent the PseudoIsochromatic Plate Ishihara Compatible Colour Vision Test (Waggoner, 2005) to screen colour blindness.

Between June and August 2012, adolescents visited the Flinders University Sleep Laboratory for 3 nights, and a 1 hr familiarisation session intended to reduce to the first-night effect and prepare for the GO/NOGO task (Tamaki et al., 2005). Laboratory nights occurred over a 3-week period, preferably on the same school-night. Seven days prior to each laboratory night, adolescents wore a MicroMini-Motionlogger Actiwatch (Ambulatory Monitoring Inc., Ardsley, NY) and completed a 7-day sleep diary to ensure a regular sleep/wake schedule.

Adolescents arrived at the Sleep Laboratory at ~17:00 h. Adolescents waited in a communal area and engaged in quiet activities until dinner (~4200 kjs) was provided at 18:30 h. At 19:00 h, all technology and time devices were removed. Adolescents changed into night attire, and PSG electrodes were applied. Data collection was timed according to each adolescent's typical bedtime (derived from their sleep diary and actigraphy), in order to prevent confounding objective sleep onset latency with variable levels of homeostatic sleep pressure (Borbély, 1982; Higuchi et al., 2005b). Two hours before bedtime, the experimental protocol began with each adolescent completing 1 hr of dark habituation where they engaged in quiet activities in their dimly lit room (<10 lux), set at a steady temperature of 22 °C (Cajochen et al., 2011). The Stanford Sleepiness Scale was completed at the beginning of dark habituation, and then before, mid-way, and at the end of screenlight exposure. Screenlight condition (bright, *f.lux*, dim) was counterbalanced across participants. In both the bright and *f.lux* conditions, screen brightness was set to the highest setting and then to the lowest setting for the dim condition. iPad exposure in all three conditions was performed in darkness. Adolescents sat in a semi-upright position while holding the iPad 40 cm away from the face. Compliance was monitored by periodic checks by MH, CS and KB. A final Stanford Sleepiness Scale was given before the adolescents were allowed to sleep.

The adolescents' wake-up times were calculated from their sleep diary and actigraphy. Five minutes after waking, each adolescent completed a sleep diary for the previous night, reporting their subjective sleep onset latency, and indicating how refreshed and alert they currently felt on a 10 cm Visual Analogue Scale (VAS). Adolescents completed the VAS by marking the 10 cm line. VASs were scored by measuring (in mm) from the left most point of each scale to the adolescent's mark, with higher scores reflecting greater morning alertness and feeling more refreshed. After their third and final laboratory night, adolescents reported any notable difference in iPad screens between light conditions.

They were given an AUS\$40 voucher for their involvement, and debriefed about the true nature of the study (i.e. not the advertised "effect of technology use on brainwaves").

### Statistical analyses

Subjective and objective SOL data were found to be skewed (i.e. skewness/SE skewness <-2.575 or >2.575; Tabachnick & Fidell, 2007), which were corrected via transformations. When Mauchly's test of sphericity was violated ( $p < 0.05$ ), the Huynh-Feldt correction was applied (Tabachnick & Fidell, 2007). Due to technical failures, PSG data were missing for 3 of the 16 adolescents. In addition, GO/NOGO data were missing for two participants in the *f.lux* condition due to technical difficulties. Data for all other measures were complete. Over two thirds of adolescents (68.8%,  $N = 11$ ) noticed no difference between conditions. Of those reporting a difference, only 2 (12.5%) correctly identified the brightest screen, with those remaining incorrectly suspecting one of the other conditions (18.7%,  $N = 3$ ). As the majority of adolescents either did not notice a difference, or identified the bright condition incorrectly, it can be assumed that adolescents were not aware of the true purpose of the study, thus minimising demand effects on self-reported data. Mixed-model ANOVAs were used for complete pre-sleep GO/NOGO and subjective sleepiness data to assess differences between conditions and over time. Repeated measures ANOVAs were used to tests differences between conditions on SOL, SREMs, SWS and REM sleep, and morning VAS data. As SREMs were dependent on the length of sleep onset latency, these were analysed as a percentage. To test for the moderating effect of chronotype on data between conditions over time, a repeated-measures multiple regression was used (Ruscher, n.d.). Although the order of conditions was counterbalanced, "condition order" was entered as a covariate in each analysis, but was found to not change the pattern of results.

## RESULTS

### Chronotype

The corrected midsleep point, used to assess chronotype (Roenneberg et al., 2003), ranged from 02:32 h to 06:12 h ( $M = 04:17 \text{ h} \pm 1 \text{ h } 1 \text{ min}$ ). A repeated-measures multiple regression analysis including "chronotype" as a continuous between-subjects variable (Ruscher, 2012) was conducted on all analyses, to determine whether chronotype modified any of the effects of screenlight on outcome variables. When chronotype was entered as a moderator in each analysis, no significant main effects or interactions were found involving chronotype for any measure (all  $p > 0.05$ ).

### Cognitive alertness

There were no significant main effects of screenlight (bright, dim, *f.lux*),  $F(1.39, 18.08) = 5.13$ ,  $p = 0.26$ , partial

FIGURE 2. Mean reaction time (ms) and standard errors on the GO/NOGO task over three timepoints of iPad use, by light condition. The asterix (\*) at mid-iPad use denotes a significant difference between the bright and dim condition.

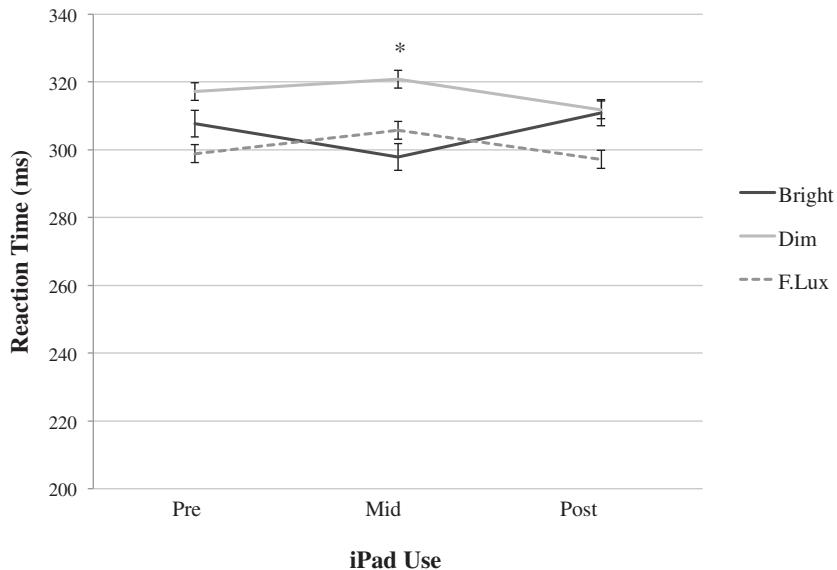
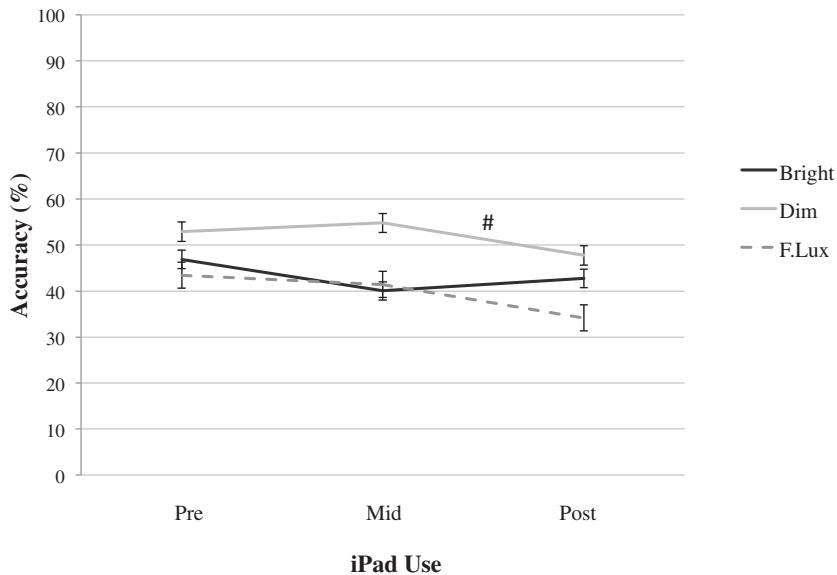


FIGURE 3. Mean percentage accuracy (%) of withheld responses on the GO/NOGO task over three timepoints of iPad use, by light condition. Errors bars are standard errors. The hash symbol (#) represents a significant difference between post-iPad use and both mid- and pre-iPad use.



$\eta^2=0.28$ , or time,  $F(2,26)=0.11$ ,  $p=0.89$ , partial  $\eta^2=0.01$  on GO/NOGO reaction times. However, a significant interaction was found,  $F(4,52)=2.65$ ,  $p=0.04$ , partial  $\eta^2=0.17$  (Figure 2). A post-hoc analysis shows that this is due to the largest difference (23 ms) between the bright and dim conditions after 30 min of iPad use,  $F(1,13)=9.58$ ,  $p=0.009$ .

For the GO/NOGO task accuracy (i.e. withheld responses), the analysis revealed a significant main effect of screenlight,  $F(2,26)=4.23$ ,  $p=0.03$ , partial  $\eta^2=0.25$ , indicating that accuracy was best in the dim condition followed by bright and then *flux* (Figure 3). Unsurprisingly, a main effect of time,  $F(2,26)=5.06$ ,  $p=0.01$ , partial  $\eta^2=0.28$ , shows adolescents in all conditions became less accurate over time, as they approached sleep. This is likely due to a significant decrease in accuracy just prior to bedtime, with this timepoint being significantly different from accuracy mid-way,  $F(1,43)=4.08$ ,  $p=0.05$ , partial  $\eta^2=0.09$ , and

prior to iPad use,  $F(1,43)=7.19$ ,  $p=0.10$ , partial  $\eta^2=0.14$ . However, the interaction between light and time was found to be non-significant,  $F(4,52)=0.84$ ,  $p=0.51$ , partial  $\eta^2=0.06$ .

### Subjective sleepiness

A mixed-model ANOVA revealed no main effect of screenlight on subjective sleepiness while using the iPad,  $F(2,30)=1.71$ ,  $p=0.20$ , partial  $\eta^2=0.10$ . A significant main effect of time indicated that adolescents felt more sleepy over time,  $F(1.37,20.52)=23.21$ ,  $p<0.001$ , partial  $\eta^2=0.61$ . The interaction between light and time was not significant,  $F(4,60)=2.34$ ,  $p=0.07$ , partial  $\eta^2=0.14$ .

### Sleep onset latency and SREMs

A repeated-measures ANOVA on the objective PSG data revealed no significant effect of screenlight condition on sleep onset latency,  $F(2,22)=0.00$ ,  $p=0.99$ , partial

TABLE 1. Descriptive data (Means and SDs) for sleep latency, slow-rolling eye movements (SREMs), minutes of SWS and REM sleep.

	Light condition		
	Bright	f.flux	Dim
Sleep latency (diary)	18.8 (14.1)	24.4 (27.4)	20.3 (17.3)
Sleep latency (PSG)	14.7 (17.1)	23.1 (23.9)	11.4 (18.8)
SREMs (%)	48.1 (22.6)	43.7 (24.3)	63.2 (31.3)
SWS (min)			
1st NREM-REM	62.5 (27.0)	61.7 (24.9)	41.9 (24.8)
2nd NREM-REM	34.1 (15.3)	40.2 (17.9)	31.2 (15.9)
REM (min)			
1st NREM-REM	11.0 (9.5)	11.1 (12.4)	17.7 (12.9)
2nd NREM-REM	22.0 (13.3)	18.6 (9.5)	28.6 (11.3)

N = 13; SREMs = slow-rolling eye movements; SWS = slow-wave sleep; NREM = non-REM sleep.

$\eta^2=0.00$  (see Table 1 for descriptive statistics). Similarly, subjective reporting of sleep onset latency was not significantly different between screenlight conditions,  $F(2,30)=0.63$ ,  $p=0.54$ , partial  $\eta^2=0.04$ . To explore the effect of screenlight on SREMs, a repeated-measures ANOVA revealed no significant differences between conditions,  $F(2,22)=0.98$ ,  $p=0.39$ , partial  $\eta^2=0.08$ .

### Sleep architecture (SWS and REM)

Table 1 presents the descriptive data for the number of minutes of SWS and REM sleep in the first two NREM-REM cycles. No significant differences were found between conditions for SWS minutes in either NREM-REM cycle; 1st,  $F(2,22)=0.21$ ,  $p=0.81$ , partial  $\eta^2=0.02$ , 2nd,  $F(2,22)=1.37$ ,  $p=0.28$ , partial  $\eta^2=0.11$ . Similarly, no significant difference was found between screenlight conditions for the number of REM minutes in the first,  $F(2,24)=1.60$ ,  $p=0.22$ , partial  $\eta^2=0.12$ , or second,  $F(2,20)=2.27$ ,  $p=0.13$ , partial  $\eta^2=0.19$ , NREM-REM cycle.

### Morning functioning

The morning following each sleep at the laboratory, adolescents rated how alert and refreshed they felt. This was performed in case screen light had an effect on sleep, and to determine whether such an effect was meaningful. A repeated-measures ANOVA revealed no significant differences between the bright ( $M=2.19$ ,  $SD=0.75$ ) and dim ( $M=2.13$ ,  $SD=0.72$ ) or f.flux ( $M=2.19$ ,  $SD=.54$ ) conditions  $F(2,30)=0.09$ ,  $p=0.92$ , partial  $\eta^2=0.01$ . The average scores in both conditions are between 2, “a little worse than usual” and 3 “about usual.”

## DISCUSSION

The gap between the scientific evidence and information on the Internet about screenlight on sleep is currently too vast (Gradisar & Short, 2013). Previous studies have demonstrated significant effects on

melatonin suppression and alertness after 2 to 5 hrs of bright screen use (Cajochen et al., 2011; Wood et al., 2013). Although the findings in this study suggest that 1 hr of tablet screenlight produces some significant effects on pre-sleep cognitive alertness, the clinical significance of these effects are questionable. For instance, none of the subjective assessments of self-rated pre-sleep sleepiness, subjective and objective sleep onset latency, slow-rolling eye movements (SREMs), minutes of SWS and REM, or morning functioning were noticeably different between the bright, dim, and filtered short-wavelength (f.flux) screenlight. This latter measurement of morning functioning is important, as even if the computerised GO/Nogo task was able to detect differences in performance and sleep, adolescents’ did not feel these effects the next morning. We will now review each of these significant findings.

### Immediate alerting effects from screens

In the 1 hr before bed, adolescents’ speed and accuracy on the GO/Nogo task were assessed at the beginning, middle, and end of tablet use in the three conditions. A significant interaction for speed, due to the bright screen producing a 23 ms higher speed than the dim screen after 30 min of iPad use, supports previous work (Cajochen et al., 2011; Chellappa et al., 2011). However, 23 ms is in the realm of spinal monosynaptic reflexes, which are single synaptic connections, too fast to be noticeably observed (Chen et al., 2003). Thus, the clinical significance of this statistical effect is questionable. In contrast, accuracy was significantly better using dim screens over bright screens, which conflicts with previous findings (e.g. Cajochen et al., 2011). Although a 13% difference in accuracy is small, on some occasions, this could mean the difference between passing and failing for adolescents. However, it is difficult to imagine a real-world task older adolescents would perform on a screen at night that involved response inhibition. Nevertheless, it suggests that adolescents using the bright screen were sacrificing speed for accuracy. As there is a small benefit of accuracy over speed for 1 hr of dim screen versus bright screen use, these preliminary findings suggest dimming the screen for marginally better cognitive performance.

### Screen effects on sleep

Technology use has been associated with a lengthened sleep latency (Gaina et al., 2005, 2006; Johnson et al., 2004; King et al., 2013; van den Bulck, 2000) and one plausible explanation is the alerting effects from bright screens (Cain & Gradisar, 2010; Gradisar & Short, 2013). In contrast to previous studies, we found no differences for subjective and objective sleep latency (Cajochen et al., 1992), SREMs (Cajochen et al., 2011), or SWS sleep in the first two NREM-REM cycles (Cajochen et al., 1992; Münch et al., 2006) in response to using a bright screen before bed. Two plausible explanations for the lack of findings in the present study are (1) that we provided a

shorter duration of light exposure (1 hr) compared to previous studies (e.g. 2 hrs, Münch et al., 2006; 3 hrs and 5 hrs, respectively, Cajochen et al., 1992, 2011), and (2) that the lux from the bright iPad screen (80 lux) was lower than that used in previous studies (e.g. 2500 lux, Cajochen et al., 1992). Although the lux could be increased by shortening the distance of the iPad to <40 cm from participants, this may not seem ecologically valid although many adolescents do use tablets at shorter distances (e.g. Shan et al., 2013). However, future studies could examine duration of tablet screenlight exposure beyond 1 hr, which is likely to more closely approximate adolescents' use in the home environment (e.g. 1.5–2 hrs; Shan et al., 2013).

REM minutes in the first two NREM-REM cycles were not significantly different between conditions. This finding does not support the moderate effects found in previous videogaming studies, either comparing bright versus dim screens (Higuchi et al., 2005a), or possibly providing longer light exposure (King et al., 2013). The proposed mechanism for this REM reduction is that mental excitement increases heart rate and subsequent catecholamine excretion (Higuchi et al., 2005a). As for the SWS findings above, it may be that effects on the number of REM minutes in the early part of the sleep period are affected by longer exposure to pre-sleep light than was performed in this study. We encourage future investigations of screenlight on sleep to verify alterations in sleep architecture in response to longer doses of light (i.e. >1 hr) and explore potential mechanisms (e.g. heart rate, catecholamine levels).

#### **Chronotype sensitivities to screenlight**

We predicted from the limited knowledge base those adolescents endorsing a later chronotype would show greater alerting effects to bright screenlight than those reporting earlier chronotypes (Aoki et al., 2001; Higuchi et al., 2005a). No significant interactions were found for chronotype in any of the analyses. There are two possible explanations. First, the hypothesis that the delayed sleep timing of later chronotypes may be due to hypersensitivity to evening light (Crowley et al., 2007) has received very little scientific support. It is plausible that this hypothesis is not true. Second, this study used a light device emitting less bright light than previous studies (80 lux vs 1000 lux). It is also plausible that the alerting effect from hypersensitive later chronotypes is very small. The field requires future studies investigating this hypothesis to report their findings, regardless of whether the hypothesis is supported or not, in case a publication bias exists (i.e. a number of unpublished studies have not found later chronotypes to be hypersensitive to evening light).

#### **Limitations and recommendations**

Many experimental laboratory studies have employed a within-subjects design with small sample sizes

(e.g. range of  $N=7$ –16; Higuchi et al., 2005a; King et al., 2013). Although advantages of these protocols include greater control over extraneous factors (e.g. bedroom conditions, parental influences, consumption of alerting substances), a disadvantage includes reduced generalisability to the population. Within the sample size limitations of this study, we found no evidence that chronotype moderates screenlight effects on sleep variables (including alertness). Laboratory studies using large samples and/or prospective designs (e.g. ABAB) in the home environment will add value to the existing literature. On a related point, this study assessed adolescents' tablet use on single nights. We do not know whether repeated exposure to a bright tablet screen has a cumulative alerting effect, or even if habituation occurs, as has been noted in videogaming studies (Ivarsson et al., 2009, 2013). To the authors' knowledge, this is the first study to assess alertness and sleep from using an app to filter short-wavelength light. More independent studies are needed to assess the effects resulting from *f.lux*, especially with varying doses of light (e.g. 1 hr vs 2 hrs before bedtime). Due to funding limitations, we were unable to concurrently measure melatonin during light exposure, thus we recommend future research to conduct such assessments to help explain possibly mechanisms between screenlight, alertness, and sleep.

#### **CONCLUSION**

Although some significant effects were found from using a bright screen versus a dim screen on objective measurements of pre-sleep alertness, the clinical significance of these differences is small. This suggests that the amount of lux, and the type of wavelength, emitted over 1 hr of tablet use before bedtime cannot explain significant sleep disruptions in adolescents. We do not preclude that longer exposures (e.g.  $\geq 2$  hrs), using a bright screen beyond bedtime, repeated nightly exposure, or the content on tablets (e.g. social networking), have an effect on adolescents' sleep. What we do know is that more experimental studies are needed to provide an evidence base that will inform adolescents and families about safe and harmful limits of technology use near sleep.

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## DECLARATION OF INTEREST

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