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The protective effect of daytime sleep on planning and risk-related decision-making in emerging adults

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Abstract

We assessed the effect of a daytime sleep opportunity on planning and risk-related decision-making in emerging adults using multiple neurobehavioral assessments. A total of 136 healthy emerging adults (20.0 ± 1.5 years), 65% female, performed the Risky-Gains Task and the Tower of London test twice. Between these assessments, they were randomized to either have a sleep opportunity monitored by polysomnography (Sleep group, $n = 101$) or to stay awake (Wake group, $n = 35$). During Test 2, in comparison to the Sleep group, the Wake group showed increased sleepiness, worse planning ability and more decrease in reaction times when selecting risky choices. Changes in Tower of London test steps used and Risky-Gains Task response time correlated with the number of central and frontal fast sleep spindles, respectively. These results indicate that among emerging adults who commonly have poor sleep patterns, a daytime sleep opportunity was related to better planning ability, better psychomotor vigilance and stable response speeds in risk-related decision-making. Changes in planning and risk-related decision-making correlated with the number of sleep spindles during the nap, supporting a specific role for sleep in modulating planning and potentially other higher-order cognitive functions.

Key words: impulsivity; risk-taking; planning and problem solving; daytime sleep; sleep spindles; vigilance; naps

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Introduction

The opportunities for independent decision-making and the attendant risks increase with age from childhood to young adulthood. Sleep duration and quality often decline over the same interval (Gradisar *et al.*, 2011; Steinberg, 2014), and inadequate sleep in young people has also increased over recent generations (Bin *et al.*, 2012; Matricciani *et al.*, 2012). Studies involving overnight sleep deprivation (Killgore *et al.*, 2006; McKenna *et al.*, 2007) or comparing periods of overnight sleep and daytime wakefulness (Seeley *et al.*, 2014; Karmarkar *et al.*, 2017) have shown that sleep modulates planning ability and the quality of decision-making. There is little evidence, however, about the effects of daytime sleep opportunities on these measures and about the neural mechanisms contributing to these effects. In addition, studies have typically used a single behavioural assessment to measure planning and decision-making tendency (Nielsen *et al.*, 2015), rendering it difficult to construct a pattern of performance based on multiple tasks.

Sleep, planning and decision-making

Effects of sleep on planning and decision-making ability have been studied mostly using a sleep deprivation paradigm, and the results were mixed. Total sleep deprivation studies using gambling tasks found that healthy adults made more risky selections when compared to their own baseline performance (Bechara *et al.*, 2000; Killgore *et al.*, 2006). Sleep-deprived individuals were also more inclined to take risks in pursuing higher monetary rewards, whereas those with adequate sleep were more concerned with defending against potential heavy losses (McKenna *et al.*, 2007; Venkatraman *et al.*, 2011). However, studies that combined tests of choices between immediate and delayed monetary gains along with behavioural inhibition tasks found that sleep deprivation did not impact participants' reward-related decision-making but rather their self-control and behavioural inhibition (Libedinsky *et al.*, 2013; Demos *et al.*, 2016).

In contrast to sleep deprivation studies, a recent large-scale, cross-sectional study ($N = 1190$) found that self-reported short sleep duration correlated with increased delayed discounting, in which participants tended to select short-term immediate rewards over delayed rewards of greater incentive value (Curtis *et al.*, 2018). Another recent longitudinal study also found that habitual short sleep duration interacted with sleep need in predicting increased risky decision-making (Lau *et al.*, 2019). Thus, research using different paradigms might lead to different results and conclusions.

Given that night-time sleep restriction and disturbances are common in young adulthood (Wong *et al.*, 2013), it would be valuable to know whether daytime sleep can reduce risky decision-making in this population. To our knowledge, such effects have not yet been documented, even though daytime sleep has been shown to benefit neurocognitive functions including vigilance, learning and recall, perceptual memory, cognitive flexibility and working memory (Mednick *et al.*, 2003; Smith, 2003; Wamsley *et al.*, 2010; Baran *et al.*, 2012; Lau *et al.*, 2015 2018; Payne *et al.*, 2015; Saletin *et al.*, 2017).

Sleep physiology correlates of decision-making behaviours

Sleep spindles recorded primarily during non-rapid-eye-movement (NREM) stage 2 (N2) have been suggested to contribute to several cognitive functions, including memory, planning and decision-making, as well as other functions involving interconnectivity between the prefrontal cortex and subcortical areas (Mander *et al.*, 2011; Vermeulen *et al.*, 2019). For instance, sleep spindle numbers were found to be higher during sleep after performing a learning task compared to a non-learning task, and to correlate with recall performance before and after sleep (Gais *et al.*, 2002). In particular, fast spindles (~13–15 Hz) in the lateral prefrontal cortex correlated with episodic learning, and it was proposed that spindle activities might represent a process of facilitating communication from hippocampus to prefrontal cortex (Fogel and Smith, 2011; Mander *et al.*, 2011; Rasch and Born, 2013). A recent study also showed that stimulation of thalamic spindles improved consolidation of hippocampal-dependent memory in mice (Latchoumane *et al.*, 2017). In another study, community young to middle-aged adults completed the Tower of Hanoi, a planning and decision-making task, before and after a night of sleep; task improvement after sleep was found to be correlated with sleep spindle density (Nielsen *et al.*, 2015). Similar findings of an association between sleep spindles and Tower of Hanoi performance were also recently reported among school-aged children (Vermeulen *et al.*, 2019).

These findings indicate that N2 sleep spindles have a role in cognitive functions sustained by connectivity between prefrontal cortex and subcortical regions. These same mechanisms may also be associated with sleep-dependent changes in planning and decision-making processes, which are subserved by prefrontal-subcortical systems, including ventral medial prefrontal cortex, anterior cingulate, insula and ventral striatum (Knutson *et al.*, 2000; Lee *et al.*, 2008). It is particularly relevant to address the role of sleep physiology in executive functions during late adolescence and young adulthood, which are critical periods for maturation of the prefrontal cortex (Blakemore and Choudhury, 2006).

Decision-making behaviours and daytime sleep in college students

With their typically delayed sleep phase, early school start times, academic demands and use of electronics and social media, adolescents and young adults around the world had restricted sleep (Carskadon *et al.*, 1993; Twenge *et al.*, 2017). Daytime sleep may be a viable strategy for increasing total daily sleep amounts. The average sleep duration on school days for college students in Hong Kong was reported to be ~6.6 h (Wong *et al.*, 2013), and 65% of college students reported daytime sleep at least once a week (Wong *et al.*, 2012). We therefore used multiple measures to assess how habitual sleep and a daytime sleep opportunity affect planning and decision-making behaviours in this population.

We hypothesized that healthy emerging adults would show better planning ability and less inclination to take risks after a daytime sleep opportunity as compared to after wakefulness during the same period. We considered faster response times and more risky decisions on the Risky-Gains Task (RGT) to reflect increased risk-taking, and faster response times associated with more steps used on the Tower of London (TOL) to reflect worse planning ability.

A secondary research aim was to develop preliminary data related to whether performance changes in planning and risk-related decision-making are related to sleep physiology during daytime sleep. A particular focus was on fast sleep spindles, based on the reported link between sleep spindles with other learning and cognitive processes involved in planning and

decision-making (Nielsen *et al.*, 2015). A related exploratory aim was to assess whether participants' baseline sleep and circadian characteristics, i.e. sleep quality, daytime sleepiness and circadian preference, were related to changes in planning and decision-making after daytime sleep.

Methods

Ethics approval was obtained from the Institutional Human Research Ethics Committee of The University of Hong Kong, and all participants provided written consent. The protocol was in compliance with the Declaration of Helsinki and international ethical standards for human research on biological rhythms (Portaluppi *et al.*, 2010).

Design and procedures

Participants were recruited through university mass e-mails. Interested participants were invited for a screening session, in which they were asked to complete questionnaires related to demographic characteristics, sleep quality and circadian preference. Recruited participants were instructed to record their sleep patterns by completing a sleep diary and wearing an actigraph throughout the 7 day study protocol. On Day 6, each participant arrived at the laboratory at 13:00, rated their affect and sleepiness level, and then completed an initial assessment of vigilance, planning and decision-making (Test 1). Each participant was then randomized to the Wake condition or the Sleep condition (1:3 ratio). Participants in the Wake condition remained awake in the company of a research assistant in the laboratory. They were allowed to read, talk, work on assignments or use the computer without watching emotionally arousing materials. Participants in the Sleep condition were given a 90 min polysomnography (PSG)-monitored sleep opportunity during 14:30–16:00 in the laboratory. At ~17:30, all participants repeated the same vigilance, planning and decision-making tasks (Test 2). On Day 7, participants returned the sleep diary and actigraph, and were debriefed and given 200 Hong Kong dollars (~£20) as compensation for their time and effort.

Participants

To test between-group differences (Sleep/Wake) with 80% power at alpha = 0.05, at least 25 subjects are required in each condition to achieve an effect size of $d = 0.81$, based on previous studies with a similar design (Nishida *et al.*, 2009; van der Helm *et al.*, 2011). Given our secondary research aim in exploring the relationship between sleep physiology and changes in risk-taking and planning ability after daytime sleep, we randomized participants to the Wake and Sleep groups in a 1:3 ratio. The final sample included 136 out of 201 participants recruited (67.7%); 65 participants were excluded because of invalid data on the RGT or the TOL task or because they provided fewer than 7 nights of actigraphy data (see Section 'Statistical Analyses'). A health interview addressing sleep conditions and substance use was conducted by personnel trained and supervised by a clinical psychologist (EYYL) for screening regarding the inclusion/exclusion criteria: (1) no diagnosis of a sleep disorder; (2) no active use of medications affecting sleep and cognitive performance for 2 weeks prior to the experimental session; (3) no caffeine and/or alcohol use within 24 hours prior to the experimental session and (4) no history of head trauma that led to prolonged loss of consciousness or cognitive dysfunction. Participants' baseline sleep patterns, caffeine and alcohol consumption were also monitored by actigraphy and a sleep diary that incorporated records of mood states and caffeine/alcohol use. We also telephoned each participant the day before the experimental day (Day 6) to remind them not to consume any caffeine or alcohol before coming in for the experiment.

Measurements

All study materials were in Chinese, and the experiments were conducted in Cantonese.

Demographics. Background information including sex, age, years of education, family income and body mass index were obtained (Table 1).

Table 1. Demographic and sleep variables

	All	Sleep	Wake	F or χ^2	P
N	136	101	35		
Age	20.0(1.5)	20.0 (1.5)	20.0 (1.6)	0.077	0.782
Sex—%male	34.8	36.0	31.4	0.239	0.625
Body mass index	20.0 (2.9)	20.1 (3.0)	19.8 (2.4)	0.404	0.526
Sleep onset time—7-day (h)	02:26 (1.5)	02:24 (1.5)	02:29 (1.5)	0.085	0.771
Wakeup time—7-day (h)	10:01 (1.5)	09:55 (1.4)	10:14 (1.7)	1.121	0.292
Total sleep time—7-day (h)	7.5 (0.8)	7.5 (0.8)	7.6 (0.8)	0.044	0.833
Sleep efficiency—7-day (%)	97.1 (3.5)	97.2 (1.8)	96.7 (6.2)	0.553	0.459
SOL—7-day (min)	5.0 (5.6)	5.0 (5.6)	4.9 (5.9)	0.009	0.925
WASO—7-day (min)	13.1 (14.5)	12.6 (8.0)	14.7 (25.3)	0.580	0.448
Epworth Sleepiness Scale	11.4 (3.9)	11.4 (3.6)	11.6 (4.7)	0.104	0.748
PSQI	6.4 (2.5)	6.4 (2.5)	6.4 (2.6)	0.002	0.966
CSM	28.9 (5.7)	29.3 (5.8)	27.8 (5.4)	1.696	0.195

Note: Values are means (± s.d.). Chi-square test was used to compare the sex distribution between groups, and other group differences were tested by one-way ANOVA. SOL: sleep onset latency; WASO: wake after sleep onset; PSQI: Pittsburgh Sleep Quality Index; CSM: Composite Scale of Morningness; 7 day: the 7-day average of the corresponding sleep variable measured by actigraphy.

Sleep characteristics. The following measures were used to evaluate participants' sleep behaviours subjectively and objectively.

Sleep diary and actigraphy. Participants were instructed to record their sleep-wake pattern for a week using a sleep diary (Carney *et al.*, 2012). They also wore an actigraph (Micro Motionloggers; Ambulatory Monitoring, Inc., Ardsley, NY) on their non-dominant hand throughout the study protocol as an objective measure correlated with sleep. Participants were asked to press the event marker before going to bed. Actigraphic data were acquired in 1 min bins using the zero-crossing mode and Action 4 software (Ambulatory Monitoring Inc.) and scored as sleep or wake based on a validated algorithm (Sadeh *et al.*, 1994), and with reference to sleep diary data. Variables of interest included total sleep time (TST), sleep onset latency (SOL) and sleep efficiency (SE). TST was calculated by deducting SOL and wake after sleep onset (WASO) from time in bed. SE was calculated as TST divided by TIB.

Pittsburgh Sleep Quality Index (PSQI; Buysse *et al.*, 1989; Tsai *et al.*, 2005). An 18-item self-reported questionnaire validated in Chinese populations was used to assess participants' sleep quality over the past month with 7 components; namely, subjective sleep quality, sleep latency, sleep duration, habitual SE, sleep disturbances, use of sleeping medications and daytime dysfunction. Global scores range from 0 to 21, with higher scores indicating poorer sleep quality. Poor sleepers were identified as those with a PSQI global score > 5.

Epworth Sleepiness Scale (ESS; Johns, 1991; Chen *et al.*, 2002). There are eight items in the ESS asking about the likelihood of dozing off under different situations, with a higher score indicating a higher level of daytime sleepiness.

Composite Scale of Morningness (CSM; Smith *et al.*, 1989). There are 13 items in the CSM assessing chronotype with a higher score indicating a tendency toward morningness.

PSG recordings. Electroencephalography (EEG), electrooculography and electromyography signals were recorded using a Compumedics E-series amplifier system (Compumedics Ltd, Abbotsford, Victoria, Australia). A sleep technologist blind to the study objectives scored sleep stages with reference to the guidelines of the American Academy of Sleep Medicine (Iber *et al.*, 2007). Polysomnographic measures included TST, SOL, WASO, SE, percentage of NREM stages N1, N2 and SWS (combining stages 3 and 4), REM sleep and REM sleep latency (Table 2).

Table 2. Polysomnographic measures during daytime sleep

	Mean	s.d.	Range
Total sleep time	78.3	16.3	31–90
Sleep efficiency (%)	79.0	0.18	31–100
Sleep onset latency	8.5	5.8	0–31
Wake after sleep onset	10.0	13.1	0–54
REM latency	65.0	15.5	6–87
REM duration	8.47	8.7	0–41
Stage 1 duration	13.2	8.3	1–43
Stage 2 duration	38.3	13.6	0–69
Slow wave sleep	17.7	13.5	0–48

REM: rapid eye movement sleep; all durations are reported in minutes.

The EEG recording montage in this study included frontal (F3), central (C3) and occipital (O1) electrodes referenced to A2 and a central (C4) electrode referenced to A1 according to the international 10–20 system of electrode placement. EEG data were filtered with a 30 Hz low-pass filter and digitized at a sampling rate of 200 Hz. Spindles were identified automatically at F3, C3 and O1 during stage 2 sleep. Data were bandpass-filtered from 12 to 15 Hz (slow spindles: 11–13 Hz; fast spindles: 13–15 Hz) using the 1-order Butterworth IIR filters. A spindle was detected when the root mean square of the filtered signal with a 0.1 s time window exceeded the threshold of the duration criterion of 0.5 to 3 s.

State measurements

*Stanford Sleepiness Scale (*Hoddes *et al.*, 1973). A 7-point Likert-type scale was used to quantify participants' momentary alertness, with higher scores indicating higher degrees of sleepiness.

*Positive and negative affect schedule (*PANAS, Watson *et al.*, 1988). This questionnaire contained a scale measuring positive affective states (PA scale) and another measuring negative affective states (NA scale). Participants were told to respond to the 20 items by indicating, in the range from 1 (very slightly or not at all) to 5 (extremely), how they felt at the time they completed the questionnaire.

Neurocognitive assessment

Psychomotor Vigilance Test (PVT). Participants completed a 5-min handheld version of the PVT (Thorne *et al.*, 2005), in which they pressed a button as soon as a stimulus appeared on the screen. Variables of interest included the mean reciprocal of response times (1/RT) (Lim and Dinges, 2008).

Risky-Gains Task. Risk-related decision-making was assessed with the RGT (Paulus *et al.*, 2003), which has been used among Chinese populations in neuroimaging studies of decision-making (Lee *et al.*, 2008). Participants were presented with three numbers (20, 40, 80) in sequential order, and they were asked to collect as many points as possible. Whereas 20 was a safe option (always positive) which guaranteed a gain of 20 points, 40 and 80 were risky options as they might represent either negative or positive values and carried a significant risk of losing the corresponding number of points. There were 96 trials in total, including 3 trial types: 20, 40 and 80 non-punished trials ($n = 54$), −40 punished trials ($n = 24$), and −80 punished trials ($n = 18$), which were presented in a randomized order in 4 blocks, separated by 3 short breaks. Fast response times and high frequencies in selecting risky choices reflected a risk-taking decision-making style.

Tower of London task. The computerised Tower of London task from the Psychology Experiment Building Language test battery was used to assess participants' planning and problem-solving ability (Phillips, 1999; Mueller and Piper, 2014). Participants were instructed to rearrange the beads on their pegs following the target configuration as presented in each of the eight trials, with the goal of using as few steps as possible. Two 8-trial problem-sets of TOL were used, with all participants completing Trial A set during Test 1 and Trial B set during Test 2. Higher numbers of steps used, and slower response times averaged over all eight trials, were considered to reflect worse planning ability.

Statistical analyses

All statistical analyses were performed using SPSS version 24. Values that fell outside of the mean score by more than 3 standard deviations (s.d.) were considered as outliers. We Winsorized the outliers in all outcome measures, including PVT, self-reported sleepiness (SSS), PANAS, RGT and TOL, by resetting them to the closest values within 3 s.d. of the mean (Bogdan *et al.*, 2014). Between-group differences in demographic data, sleep characteristics and state measurements were compared using one-way analysis of variance (ANOVA) and chi-square test. To examine the effects of daytime sleep opportunity on planning and decision-making, a 2×2 mixed factorial model with a within-subject factor (time; Test 1 vs. Test 2) and a between-subject factor (condition; Sleep vs. Wake) was used, with a significance level of 0.05. Performance changes on the state and decision-making measures were computed by subtracting Test 2 performance from Test 1 performance, with higher values indicating a reduction in steps used, faster response time on the TOL task, decreased risky choices and faster response times on the RGT, and fewer lapses and faster response times on the PVT. Associations between performance change after daytime sleep and polysomnographic features, especially sleep spindles were explored by correlational analyses. All original *P*-values are adjusted for multiple comparisons following the Benjamini–Hochberg procedure (Benjamini and Hochberg, 1995) as follows: (1) All of the *P*-values in the factorial analyses as in Sections 'Effects of sleep on psychomotor vigilance, sleepiness and affective states' and 'Effects of sleep on planning and decision-making' ($n = 24$) are adjusted with a false discovery rate (FDR) of 5%; (2) All of the post-hoc paired-sample *t*-tests for the significant interaction effect in the factorial analyses as in Sections 'Effects of sleep on psychomotor vigilance, sleepiness and affective states' and 'Effects of sleep on planning and decision-making' are adjusted with an FDR of 5% and (3) All of the correlational analyses in Section 3.4 are adjusted for type-I error with an FDR of 0.15 separately from the primary analyses (FDR: 0.05), since the correlational analyses are conducted for an exploratory research aim, for identification of new targets for future studies (Benjamini and Hochberg, 1995; Lee and Lee, 2018; Slavish *et al.*, 2019). An FDR of 0.15 is selected based on previous methodological papers (e.g. Lee and Lee, 2018) which advised a high FDR, from 0.10 to 0.20, to be used when there is a low cost of experiments with high cost of losing new findings with a low FDR.

Results

Sample characteristics

The demographic information and sleep characteristics of the participants are presented in Table 1. The final sample consisted of 136 undergraduate students, aged 17–25 with 65.2% female. Participants had an average sleep duration of 7.5 h (s.d. = 0.8 h) with SE of 97.1% (s.d. = 3.5%), and SOL of 5.0 min (s.d. = 5.6). There was about 66.2% with excessive daytime sleepiness defined by ESS, 61.9% with poor sleep quality defined by PSQI,

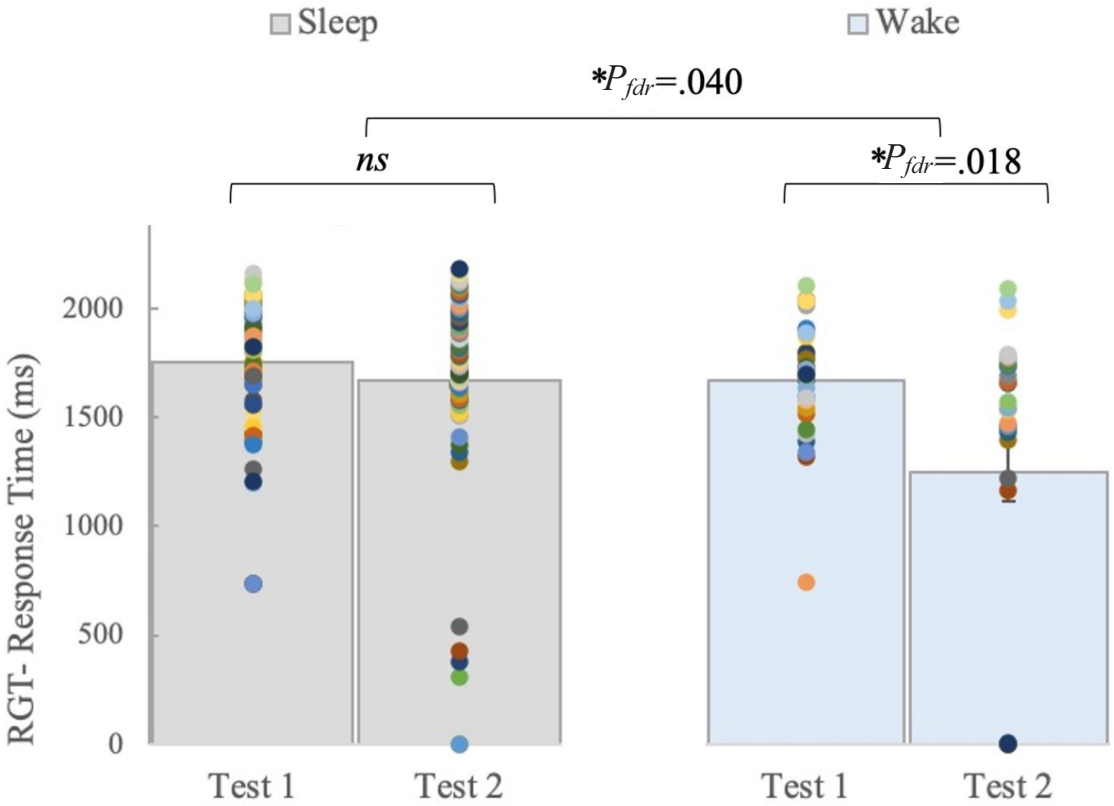

Fig. 1. Individual data point of number of steps used in the Tower of London (TOL) planning task. Outliers (>3 s.d. or <3s.d.) are Winsorized. The Wake group showed a non-significant trend towards increased steps used and the Sleep group showed a non-significant trend towards decreased steps used during Test 2. Error bars in each figure represent the standard error. *Significant *P*-values after adjustment for multiple comparisons.

as well as 16.2% evening-type and 2.3% morning-type defined by CSM. The Sleep and Wake groups were not significantly different Ps > 0.05 on demographics and sleep characteristics (Table 1).

Effects of sleep on psychomotor vigilance, sleepiness and affective states

On the PVT, there was a significant interaction effect of time × condition on mean reciprocal response time, $F(1135) = 22.34$, $P_{fdr} < 0.001$, partial eta squared, $\eta_p^2 = 0.259$, while the main effects of time and condition were not statistically significant. Paired-sample *t*-test showed that the Sleep group had faster reaction times after the sleep opportunity, $t(99) = -5.08$, $P_{fdr} < 0.001$. Among the Wake group, though there was a trend toward slower reaction time in Test 2, $t(33) = 2.19$, $P_{fdr} = 0.064$, the relationship did not survive after adjustment for multiple comparison (FDR = 5%).

For SSS, there was a significant main effect of time, $F(1132) = 6.22$, $P_{fdr} = 0.037$, $\eta_p^2 = 0.045$, and a significant interaction effect of time × condition, $F(1132) = 17.50$, $P_{fdr} < 0.001$, $\eta_p^2 = 0.117$. Paired-sample *t*-test showed that the Sleep group had decreased sleepiness after the sleep opportunity, $t(98) = 6.19$, $P_{fdr} < 0.001$, but there was no significant change in sleepiness in the Wake group, $t(34) = -1.20$, $P_{fdr} = 0.267$.

There was a significant main effect of condition on positive affect measured by PANAS scores, $F(1133) = 5.68$, $P_{fdr} = 0.037$, $\eta_p^2 = 0.041$, and an interaction effect of time × condition, $F(1133) = 24.54$, $P_{fdr} < 0.001$, $\eta_p^2 = 0.156$, while the main effect of time was not significant. Paired-sample *t*-tests showed that while the Sleep group had increased positive affect after the sleep opportunity, $t(99) = -3.62$, $P_{fdr} = 0.002$, the Wake group had significantly decreased positive affect, $t(34) = 3.63$, $P_{fdr} = 0.002$. For negative affect, there was only a significant main effect of time, $F(1133) = 83.70$, $P_{fdr} < 0.001$, $\eta_p^2 = 0.386$, indicating decreased negative affect at Test 2 for both groups.

Effects of sleep on planning and decision-making

On the TOL, the factorial model for the number of steps as a dependent variable showed a significant interaction effect of time × condition, $F(1132) = 5.78$, $P_{fdr} = 0.038$, $\eta_p^2 = 0.042$, with non-significant main effects of time or condition. Paired sample *t*-test showed that the Sleep group had a non-significant trend toward decreasing number of steps, $t(98) = 1.05$, $P_{fdr} = 0.294$.

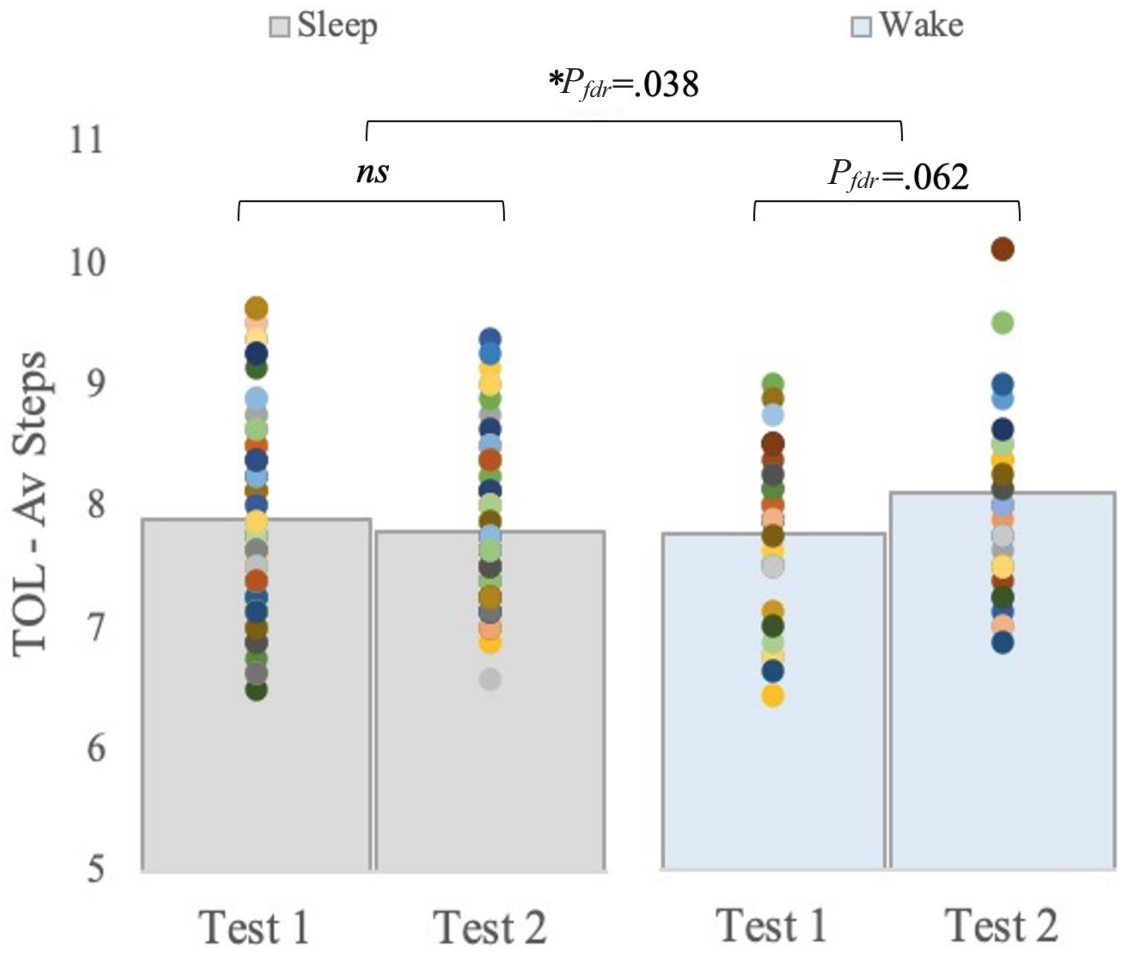

Fig. 2. Individual data points showing response times in making risky choices in the Risky-Gains Task. Outliers (>3 s.d. or <3 s.d. from the mean) are Winsorized. The Wake group showed a significantly greater decrease in response latencies when making risky choices during Test 2 than the Sleep group, which had a 90 min sleep opportunity between Test 1 and Test 2. RT is the latency to show a response after presentation of a new choice (range: Sleep group: 735–2162 ms (Test 1) and 2–2183 ms (Test 2); Wake group: 736–2091 ms (Test 1) and 2–2078 ms (Test 2). Error bars in each figure represent the standard error. *P values remain significant after false discovery rate adjustments for multiple comparisons.

While the Wake group showed a trend toward increasing number of steps, $t(34) = -2.10$, $P_{fdr} = 0.062$, the relationship did not survive after adjustment for multiple comparison (Figure 1). The factorial model on total response time showed only a significant main effect of time, $F(1132) = 130.45$, $P_{fdr} < 0.001$, $\eta_p^2 = 0.497$, indicating faster response times during Test 2 in both groups.

On the RGT, the factorial model with the number of risky choices as dependent measure showed a significant main effect of time, $F(1131) = 7.56$, $P_{fdr} = 0.020$, $\eta_p^2 = 0.055$, with both groups showing more risky choices at Test 2. With response time in making risky choices as dependent measure, there was a significant main effect of time, $F(1111) = 14.14$, $P_{fdr} = 0.001$, $\eta_p^2 = 0.113$, and condition, $F(1111) = 9.95$, $P_{fdr} = 0.007$, $\eta_p^2 = 0.082$, and an interaction effect of time × condition, $F(1111) = 5.89$, $P_{fdr} = 0.040$, $\eta_p^2 = 0.050$. Post-hoc paired-sample *t*-tests showed that while the Wake group's response time in making risky choices became faster, $t(28) = 2.51$, $P_{fdr} = 0.036$, there was no significant change in the Sleep group at Test 2, $t(83) = 1.64$, $P_{fdr} = 0.132$. (Figure 2). To ascertain any potential effects of demographics in the associations of these variables, we conducted the same ANOVAs with age and sex as covariates, which resulted in the same pattern of findings with no significant covariate effects.

Associations between sleep physiology and performance change after daytime sleep

As there were significant time × condition interaction effects on both TOL number of steps and RGT response time, we proceeded to explore the multiple correlations between performance changes on these two tasks with sleep spindles (Table 3). Reduced number of TOL steps was significantly correlated with more fast spindles detected at C3, $r(87) = -0.240$, $P_{fdr} = 0.038$ (Supplementary Figure S1). Change in RGT response times correlated with greater fast spindle number, $r(74) = 0.258$, $P_{fdr} = 0.140$ (Supplementary Figure S2) and higher density detected at F3, $r(74) = 0.316$, $P_{fdr} = 0.097$ (Supplementary Figure S3). No other statistically significant relationships were noted at other sites after adjustment for multiple comparison (FDR = 15%).

Other exploratory correlations of PSG variables with performance changes in risk-related decision-making and planning ability are presented in Supplementary Table S1. Similarly, correlations between changes in RGT response times and TOL-step numbers with baseline sleep characteristics (i.e. sleep quality, daytime sleepiness and circadian preference) are presented in Supplementary Table S2.

Table 3. Correlation between sleep spindles with changes from Test 1 to Test 2 in response times in the Risky-Gains Task (RGT) and number of steps in the Tower of London test (TOL)

	TOL Number of steps	RGT Response time
TOL—Number of steps	1	−0.077
RGT—Response time	−0.126	1
F3 Fast spindle number	−0.170	0.254*
F3 Fast spindle density	−0.132	0.316*
C3 Fast spindle number	−0.240*	0.140
C3 Fast spindle density	−0.220	0.187
F3 Slow spindle number	−0.131	0.157
F3 Slow spindle density	−0.116	0.211
C3 Slow spindle number	0.196	0.172
C3 slow spindle density	−0.169	0.185

*Statistically significant after adjusting for false discovery rate.

Discussion

This study examined the impacts of daytime sleep on planning and risk-related decision-making patterns in emerging adults and explored the potential mechanism underlying these effects. Consistent with our hypothesis, we noted differential changes in decision-making and planning performances following a daytime nap when compared to wakefulness for the same period of time. Following a daytime sleep opportunity, participants showed significantly higher psychomotor vigilance, positive affect with maintained planning performance when comparing to those who stayed awake for the same period of time. In terms of risk-related decision-making pattern, while both groups had increased number of risky choices on Test 2, only the Wake group responded faster in making risky decisions, suggesting a hastier decision-making pattern. The Wake group also displayed deteriorated psychomotor vigilance on Test 2, in contrast with the sleep group, who showed stables response time in making risky decisions in Test 2 and had better psychomotor vigilance performance.

These results indicate different patterns of change in risk-related decision-making style in the two groups. The Wake group appeared to display a higher risk-taking tendency, accompanied by increased sleepiness, characterizing an impulsive pattern of decision-making (Wickelgren, 1977; Heitz, 2014). The Sleep group maintained stable latencies to make risky decisions and a concomitant improvement in psychomotor vigilance, sleepiness and planning ability, suggesting increased efficiency in planning, without the increased impulsivity observed in the Wake group. These findings indicate that a daytime sleep opportunity could reverse the characteristic pattern across the day of deteriorating planning ability and more impulsive decision-making toward risks. Apart from homeostatic sleep drive, circadian factors have also been suggested to affect cognition and reward sensitivity (e.g. Logan *et al.*, 2018). In our study, participants had their first session on early post-lunch dip and second session on early evening, when their body temperature, muscle strength and other body functions are expected to increase to peak level, and so as their cognitive functions. However, our results instead showed better psychomotor vigilance and planning and problem-solving ability at the first session, which appeared to favour the account of homeostatic sleep drive influence over our sample's cognitive functions.

Our findings are consistent with those from other age groups, who showed better planning and decision-making performance after sleep at night compared to those kept awake (Nielsen *et al.*, 2015; Vermeulen *et al.*, 2019). The more rapid decision-making observed in the Wake group may be explained on the basis of the impacts in this age group of inadequate sleep and circadian phase misalignment on reward sensitivity and risky behaviours (see Logan *et al.*, 2018 for review). As observed in our sample and also other emerging adults, individuals in this developmental period tend to have delayed bed times, restricted sleep durations and daytime sleepiness. These characteristics undermine the regulation of emotional responses towards external stimuli, which might potentially manifest in suboptimal planning, problem-solving ability and risk-related decision-making ability.

Sleep spindles and neurocognitive processes

We observed significant associations between sleep spindle and altered performance on the planning and risk-related decision-making tasks after a daytime sleep opportunity, with improved planning performance correlating with increased number of

central (C3) fast spindles. Few studies have examined the impact of sleep on planning ability, but one also reported a correlation between higher density of sleep spindles and improvement in Tower of Hanoi performance after a night of sleep (Nielsen *et al.*, 2015).

We also found that a greater number and higher density of frontal (F3) spindles were associated with faster response times on the risk-related decision-making task. One interpretation is that sleep spindles facilitate the learning process, which in turn speed up decision-making. Cortical spindles are a product of thalamocortical interactions (Fuentealba and Steriade, 2005) that have been proposed to more broadly reflect communication between cortical and several subcortical regions. Frontal and central cortical areas, along with subcortical regions including the thalamus and the striatum, have been implicated in decision-making processes (Farrar *et al.*, 2018). Our results are therefore consistent with the hypothesis that frontal and central cortical sleep spindles reflect neural communication that subserves neurocognitive functions including decision-making (Vermeulen *et al.*, 2019). It should be noted that in the absence of baseline recordings of sleep spindles before the experiences involved in Test 1, we cannot distinguish whether higher spindle numbers reflect a hypothesized, but controversial, persistent trait (e.g. greater general intelligence) or stronger consolidation processes related to what was experienced during that test (Schabus *et al.*, 2008; Hoedlmoser *et al.*, 2014; Pesonen *et al.*, 2019).

Another potential interpretation is that improved planning and risk-related decision-making could be due to sleep-related enhancement of other cognitive processes, e.g. motor learning or reaction time (Tamaki *et al.*, 2008) or working memory (Lau *et al.*, 2015). Results from our correlational analyses showed that there were no significant correlations among performance changes in risk-related decision-making, planning ability and psychomotor vigilance. This lack of significant relationship suggests the changes observed in these measures after sleep are not influenced by a common third factor. However, future studies using more comprehensive measures of cognitive functions would be needed to determine whether other sleep-related common factors might influence these and other cognitive functions.

The results of this study demonstrate that daytime sleep and sleep spindle activity modulate the risk-taking behaviour and planning ability of young people with characteristic poor baseline sleep characteristics. There are, however, several limitations of the current study. Firstly, participants did not undergo functional neuroimaging when completing our assessments, and hence there was no neurophysiological data other than the sleep physiological features to explain the neural mechanism underlying the changes on planning and decision-making. Secondly, our risk-related decision-making task did not involve real-world rewards (e.g. money) or behaviours (e.g. gambling). Future studies should combine different forms of assessment to develop a more comprehensive understanding of sleep's impact on decision-making and planning. Thirdly, our sample included more than 60% of participants who reported poor sleep quality and excessive daytime sleepiness. We do not know whether the impact of daytime sleep on the measured variables would be different for individuals with better quality sleep at baseline. Nevertheless, these sleep characteristics were generally similar to those of participants in larger studies involving this population (e.g. Wong *et al.*, 2013) and are probably common in this age group (Crowley *et al.*, 2018). Furthermore, the baseline sleep quality and daytime sleepiness level were not found to correlate with the between-session changes in performance on risk-related decision-making or planning ability tasks. Future studies assessing the impact of baseline sleep and napping impact on higher-order cognitive functions are needed to better understand the relationship between baseline sleep characteristics, napping and daytime performance. Finally, the correlation analyses involving sleep features were exploratory in nature and we used an FDR of <0.15, which would increase the probability of false positive results. This choice was intended to reduce false negatives and allow for identification of potential targets for future studies, given the limited existing literature on sleep physiology in relation to planning and decision-making. Nevertheless, the results with respect to the relations between sleep spindles and risk-taking and planning should be regarded as provisional.

In conclusion, the present study provides initial data documenting the impact of daytime sleep on higher-order cognitive functions of planning and risk-related decision-making among emerging adults. The role of sleep, and fast sleep spindles in particular, is highlighted as a potential target for further investigation of the neural mechanisms underlying these cognitive functions. Our findings complement previous conclusions that adequate sleep can benefit decision-making and planning in young adulthood, a developmental period during which prefrontal cortical mechanisms involved in risk modulation are evolving.

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Supplementary data

Supplementary data is available at *SCAN* online.

Conflict of interest statement

None declared.

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