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The impact of breaking up prolonged sitting with physical activity during simulated dayshifts and nightshifts on sleep architecture: a randomised controlled trial

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Inadequate sleep is common and contributes to poor health outcomes. Physical activity has a positive impact on sleep outcomes, however the prevalence of physical inactivity is increasing, coupled with the rise of sedentary behaviour at work. Interventions that promote physical activity and reduce sedentary behaviour are essential, as they can improve sleep. The current study investigated the effects of breaking up prolonged sitting with physical activity during the day or night, compared to not breaking up sitting, on sleep architecture during a 9 h or 5 h sleep opportunity. Participants (n = 125, 51% male, 23.4 ± 4.8 years of age) completed an in-laboratory sleep study, with five simulated shifts during the day or night. Sleep opportunities were either 9 h or 5 h following each shift. Participants were allocated to one of six conditions: Sit9D or Break9D (sedentary or breaking up sitting day and 9 h sleep opportunity), Sit5D or Break5D (sedentary or breaking up sitting day and 5 h sleep opportunity), or Sit9N or Break9N (sedentary or breaking up sitting night and 9 h sleep opportunity). Sleep was monitored using polysomnography. In the analysis of day shifts, mixed model ANOVAs demonstrated a significant physical activity *sleep opportunity interaction for total sleep time (p < 0.001), sleep onset latency (p < 0.001), time spent in N2 (p < 0.001) and N3 (p = 0.03). Post-hoc analyses revealed that participants in the 9 h sleep opportunity conditions had longer total sleep time, shorter sleep onset latency, and more slow-wave sleep (N3) during sleep opportunities 1–4 but not sleep opportunity 5. There were no significant differences in sleep architecture between physical activity condition for the nightshift conditions. Better sleep quality was seen in the 9 h condition compared to the 5 h condition, and breaking up sitting did not affect sleep. Given the benefits of breaking up sitting on health, our findings suggest a breaking up sitting intervention can be promoted without detrimental impacts on sleep.

Keywords Shift work, Sedentary behaviour, Breaking up sitting, Physical activity

Inadequate sleep is a global health concern and has been linked to seven of the fifteen leading causes of death[1–5]. It is highly prevalent with up to 45% of Australian [1–5] and 33% of American adults not obtaining the recommended

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sleep quality or sleep quantity of 7–9 h of sleep per night[6]. Inadequate sleep impairs cognition, psychomotor function, and mood[7]in addition to impacting health by increasing the risk of cardiovascular disease, obesity, metabolic disease, depression, and mortality[8–11]. These health consequences contribute to the global cost of inadequate sleep—$45.32 billion in Australia in 2016–207[12], and forecast to be up to US$718 billion in 2025 in five countries (USA, UK, Japan, Germany, and Canada). Given the health and safety consequences and economic costs of inadequate sleep, strategies to improve sleep are important. Sleep co-occurs with other health behaviours, including physical activity, with both sleep and physical activity considered to be modifiable risk factors for long-term health problems[13].

Physical activity decreases the risk of developing long-term health problems, including cardiovascular disease, diabetes, and obesity[14,15]. Public health guidelines recommend adults participate at least 150 min per week of moderate-intensity physical activity[16]however, many adults do not meet the guidelines, with physical inactivity a global health problem[14]. Physical inactivity is expected to cost healthcare systems approximately INT$520 billion worldwide between 2020 and 2030[17]. Importantly, a bi-directional relationship exists between sleep and physical activity[18,19]. For example, days with increased physical activity are associated with improved sleep quality and quantity, and poorer sleep quality and quantity are associated with physical inactivity the following day[18,20]. Therefore, in addition to having direct health benefits, increasing physical activity could also be a promising intervention to improve sleep[21].

While increased physical activity has positive effects on sleep quality[22–25]research has only just begun to account for the impact of sedentary time[26]. As with inadequate sleep and physical inactivity, sedentary behaviour (such as sitting) is a global health issue, with population estimates suggesting that, worldwide, adults spend approximately 8.2 h/day sedentary[27]. It is possible to meet physical activity guidelines but still be highly sedentary[28]and previous research has highlighted the benefits of replacing sedentary time with physical activity to improve health[29,30]. Given that sedentary behaviour is prevalent in office workers (80% of work hours), breaking up or reducing sedentary time using physical activity at work (e.g., sit-to-stand desks, walking meetings) has been researched as a promising intervention[31,32]. A meta-analysis of 24 workplace physical activity interventions found that physical activity interventions led to reductions in body weight, BMI and waist circumference, which are all markers of cardiometabolic risk[33]. However, the impact of workplace interventions for physical activity and sedentary time, on sleep is less understood.

A laboratory-based study conducted by our team investigated sleep architecture after an intervention during simulated work shifts to reduce sedentary time with physical activity[34]. In this pilot study, 12 participants completed three simulated work shifts and were allocated to a breaking up sitting condition (breaking up sitting with three-minute periods of light intensity physical activity) or a sedentary condition. We found a small increase in slow-wave sleep (average 9.7 ± 0.6 min increase across three sleep periods) in the breaking up sitting condition. While this was a pilot study and only included male participants, participants were restricted to a 5 h sleep opportunity and findings demonstrate the potential benefit of a physical activity intervention on sleep quality at night.

For a workplace intervention for physical activity and sedentary behaviour on sleep to be widely effective, there must also be consideration for those who may sleep during the day. While many people live diurnal schedules and sleep at night, globally, approximately 20% of workers undertake night shifts[35]. Inadequate sleep during the daytime hours is common in those working nonstandard hours (e.g., nightshift), with previous research identifying disrupted sleep stages[36]and less time spent in slow wave sleep[37] and deep sleep[38] when workers sleep during the day compared to at night. Further, sedentary behaviour and physical inactivity are higher in those working non-standard hours compared to those working day hours[39,40]. To date, no research has investigated whether reducing sitting time and increasing physical activity at night impacts daytime sleep.

Given the substantial impacts of inadequate sleep for both day and night workers, and the associations between sleep, physical activity, and sedentary time, research is needed addressing all three of these behaviours. Therefore, this study aimed to investigate the effects of breaking up prolonged sitting with physical activity during the day or night, compared to not breaking up sitting, on sleep architecture during a 9–5 h sleep opportunity.

Results

Sample characteristics

Sample characteristics of the final 125 participants can be seen in Table 1. As expected based on the study design, for dayshift conditions step count averaged across the experimental days significantly differed between breaking up sitting and sedentary conditions, but not sleep conditions (Sit9D 1086 ± 369, Break9D 6905 ± 728, Sit5D 1408 ± 1142, Break5D 6808 ± 1585; $p < 0.001$). For nightshift conditions step count averaged across the experimental days was significantly different ($p < 0.001$) between Break9N (6481 ± 546) and Sit9N (1305 ± 1034).

		Dayshift ($n = 84$)				**Nightshift ($n = 41$)**	
	Total ($n = 125$)	**Sit9D ($n = 22$)**	**Break9D ($n = 20$)**	**Sit5D ($n = 22$)**	**Break5D ($n = 20$)**	**Sit9N ($n = 20$)**	**Break9N ($n = 21$)**
Age (years)	23.45 ± 4.77	23.82 ± 4.66	24.6 ± 4.84	22.41 ± 4.27	23.05 ± 5.36	24.30 ± 3.81	24.48 ± 5.38
Sex (female n: male n)	62:63	10:12	10:10	11:11	10:10	11:9	10:11
Body Mass Index (kg/m^2)	22.75 ± 3.34	23.73 ± 4.04	23.26 ± 2.78	21.56 ± 2.58	22.48 ± 3.41	23.73 ± 3.50	23.17 ± 2.57

Table 1. Sample characteristics of participants by condition (mean ± standard deviation).

Sleep architecture

There were no significant differences between dayshift conditions (Sit9D, Break9D, Sit5D, Break5D) or between nightshift conditions (Sit9N, Break9N) for sleep variables on the arrival night for the dayshift condition (TST $p < 0.88$; WASO $p < 0.97$; SE $p < 0.89$; SOL $p < 0.79$; time spent in N1 $p < 0.83$; time spent in N2 $p < 0.0.57$; time spent in N3 $p < 0.27$; time spent in NREM $p < 0.56$; time spent in REM $p < 0.56$) or for the nightshift condition (TST $p < 0.12$; WASO $p < 0.59$; SE $p < 0.20$; SOL $p < 0.10$; time spent in N1 $p < 0.06$; time spent in N2 $p < 0.0.93$; time spent in N3 $p < 0.49$; time spent in NREM $p < 0.74$; time spent in REM $p < 0.74$).

Dayshift

There was a significant condition* sleep opportunity interaction for TST (F = 94.4 (12,256.8), $p < 0.001$;Table 2) such that Sit9D and Break9D had significantly longer TST than Sit5D and Break5D from sleep opportunities 1–4 but not 5. As discussed in the methods section, for the 5 h sleep conditions, sleep opportunity 5 was 9 h). There was also a significant condition* sleep opportunity interaction for SOL (F = 3.11 (12,258.4), $p < 0.001$;Table 2),

		TST (h)	WASO (mins)	Sleep Efficiency (%)	SOL (%)	Time spent in N1 (%)	Time spent in N2 (%)	Time spent in N3 (%)	Time spent in NREM (%)	Time spent in REM (%)
			M ± SD	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD
Dayshift										
All	Sit9D	8.02 ± 0.58	27.23 ± 20.07	89.18 ± 6.51	31.05 ± 26.94	3.11 ± 1.52	46.07 ± 5.89	26.74 ± 6.86	75.92 ± 6.25	24.08 ± 5.84
	Break9D	7.95 ± 0.68	28.69 ± 24.72	88.66 ± 7.47	31.07 ± 29.48	3.04 ± 2.23	47.43 ± 7.02	25.31 ± 7.62	75.79 ± 6.72	24.21 ± 6.72
	Sit5D	5.57 ± 1.48	7.51 ± 12.67	96.77 ± 2.76	4.55 ± 4.64	3.12 ± 1.35	38.93 ± 7.63	33.55 ± 8.62	75.59 ± 7.34	24.23 ± 6.58
	Break5D	5.55 ± 1.44	8.35 ± 9.56	96.45 ± 2.58	5.02 ± 6.72	2.36 ± 1.53	35.06 ± 9.98	38.41 ± 10.27	75.79 ± 6.72	24.17 ± 6.25
Sleep 1	Sit9D	8.25 ± 0.42	20.69 ± 12.49	91.8 ± 4.61	23.46 ± 24.76	2.75 ± 1.60	45.4 ± 5.98	26.6 ± 6.71	74.7 ± 6.61	25.3 ± 6.61
	Break9D	8.28 ± 0.30	23.83 ± 11.83	92.3 ± 3.13	17.44 ± 11.67	2.82 ± 2.38	46.4 ± 6.85	27.5 ± 8.62	76.7 ± 7.05	23.3 ± 7.05
	Sit5D	4.83 ± 0.09	5.25 ± 3.50	96.6 ± 1.82	4.86 ± 4.67	3.08 ± 1.21	37.3 ± 6.22	37.8 ± 7.04	78.2 ± 5.60	21.8 ± 5.60
	Break5D	4.83 ± 0.13	5.42 ± 3.28	96.9 ± 2.55	3.88 ± 5.15	2.17 ± 1.30	35.8 ± 11.52	42.3 ± 9.96	80.2 ± 6.81	19.8 ± 6.81
Sleep 2	Sit9D	8.18 ± 0.57	24.15 ± 15.96	91.2 ± 6.38	23.35 ± 22.85	3.36 ± 1.69	47.3 ± 6.25	25.3 ± 6.31	75.9 ± 5.66	24.1 ± 5.66
	Break9D	8.07 ± 0.50	25.11 ± 18.44	89.9 ± 5.65	27.61 ± 25.80	2.86 ± 1.85	48.7 ± 6.97	25.2 ± 6.74	76.8 ± 6.55	23.2 ± 6.65
	Sit5D	4.85 ± 0.12	5.29 ± 2.71	96.9 ± 2.38	4.03 ± 4.91	2.82 ± 1.07	38.6 ± 6.66	36.2 ± 8.09	77.6 ± 8.04	22.4 ± 8.01
	Break5D	4.87 ± 0.10	4.88 ± 4.55	97.5 ± 1.92	2.65 ± 1.99	1.98 ± 1.24	33.3 ± 9.52	39.8 ± 8.44	75.0 ± 5.76	25.0 ± 5.76
Sleep 3	Sit9D	8.02 ± 0.70	32.58 ± 29.10	89.2 ± 7.85	25.73 ± 20.62	3.02 ± 1.46	45.3 ± 4.89	27.9 ± 6.78	76.1 ± 7.94	23.9 ± 7.94
	Break9D	7.97 ± 0.76	25.22 ± 18.34	88.7 ± 8.24	31.75 ± 31.11	2.76 ± 1.82	49.1 ± 8.46	23.9 ± 7.53	75.7 ± 7.58	24.3 ± 7.58
	Sit5D	4.88 ± 0.05	3.79 ± 1.47	97.7 ± 0.95	3.03 ± 2.52	3.15 ± 1.31	36.3 ± 6.83	35.5 ± 6.95	74.9 ± 6.86	25.1 ± 6.86
	Break5D	4.82 ± 0.09	6.72 ± 4.35	96.5 ± 1.84	3.80 ± 3.30	2.71 ± 1.86	32.4 ± 9.47	40.1 ± 10.49	75.2 ± 7.27	24.8 ± 7.27
Sleep 4	Sit9D	8.00 ± 0.38	23.88 ± 14.06	89.2 ± 4.15	34.21 ± 22.23	3.40 ± 1.48	47.9 ± 6.18	25.0 ± 7.39	76.3 ± 4.82	23.7 ± 4.82
	Break9D	7.82 ± 0.66	32.00 ± 21.71	87.2 ± 7.28	37.09 ± 35.57	3.22 ± 2.37	46.8 ± 6.38	24.2 ± 8.09	74.2 ± 6.57	25.8 ± 6.57
	Sit5D	4.88 ± 0.03	4.47 ± 1.67	97.6 ± 0.70	2.75 ± 1.73	2.60 ± 0.75	35.3 ± 7.49	35.3 ± 7.38	73.2 ± 9.37	26.8 ± 9.37
	Break5D	4.85 ± 0.06	5.58 ± 2.22	97.1 ± 1.25	3.00 ± 2.64	2.13 ± 1.27	32.6 ± 8.70	40.1 ± 8.81	74.7 ± 5.75	25.3 ± 5.75
Sleep 5	Sit9D	7.62 ± 0.62	34.58 ± 22.76	84.5 ± 6.92	48.73 ± 35.94	3.61 ± 1.50	44.6 ± 6.32	28.8 ± 7.40	76.5 ± 4.07	23.5 ± 4.07
	Break9D	7.62 ± 0.92	38.00 ± 42.73	85.0 ± 10.05	42.44 ± 34.37	3.61 ± 2.80	45.9 ± 6.38	25.9 ± 7.33	75.4 ± 6.06	24.6 ± 6.06
	Sit5D	8.35 ± 0.94	18.34 ± 25.29	95.1 ± 4.92	8.00 ± 6.14	3.93 ± 1.87	46.9 ± 5.25	23.2 ± 4.84	74.1 ± 5.65	25.9 ± 5.65
	Break5D	8.28 ± 0.86	19.02 ± 16.24	94.3 ± 3.56	11.55 ± 11.29	2.82 ± 1.80	41.1 ± 8.54	30.0 ± 9.58	73.9 ± 3.34	26.1 ± 3.34
Nightshift										
All	Sit9N	7.66 ± 1.03	70.3 ± 62.9	85.5 ± 11.2	5.91 ± 8.43	5.77 ± 3.16	46.0 ± 41.3	26.8 ± 6.93	78.6 ± 5.99	21.4 ± 5.99
	Break9N	7.38 ± 1.05	91.5 ± 56.2	82.0 ± 11.7	5.91 ± 6.75	5.49 ± 2.52	41.3 ± 7.99	30.1 ± 7.82	76.9 ± 5.82	23.1 ± 5.82
Sleep 1	Sit9N	7.83 ± 0.85	66.6 ± 48.9	87.1 ± 9.44	2.71 ± 1.77	5.84 ± 3.38	44.6 ± 6.67	27.7 ± 6.92	78.2 ± 6.07	21.8 ± 6.07
	Break9N	7.22 ± 1.42	104.5 ± 84.9	80.2 ± 15.77	2.33 ± 1.78	6.51 ± 3.44	40.7 ± 8.20	30.8 ± 7.57	78.0 ± 6.15	22.0 ± 6.15
Sleep 2	Sit9N	7.72 ± 1.19	70.2 ± 59.7	85.8 ± 13.22	2.95 ± 3.48	6.03 ± 3.28	45.8 ± 5.49	27.1 ± 6.34	78.9 ± 4.75	21.1 ± 4.75
	Break9N	7.63 ± 0.88	79.8 ± 52.4	84.8 ± 9.81	2.61 ± 1.92	5.03 ± 2.27	41.4 ± 7.53	30.1 ± 9.19	76.5 ± 5.26	23.5 ± 5.26
Sleep 3	Sit9N	7.68 ± 1.01	73.8 ± 59.1	85.3 ± 11.24	5.47 ± 4.58	5.72 ± 3.07	45.8 ± 7.97	25.8 ± 7.26	77.3 ± 7.08	22.7 ± 7.08
	Break9N	7.33 ± 0.96	94.8 ± 57.1	81.5 ± 10.62	4.83 ± 2.74	5.26 ± 2.21	41.3 ± 7.25	29.4 ± 6.44	75.9 ± 5.60	24.1 ± 5.60
Sleep4	Sit9N	7.85 ± 0.71	61.7 ± 41.6	87.2 ± 7.84	7.39 ± 5.49	5.25 ± 1.90	47.1 ± 5.48	26.2 ± 5.37	78.5 ± 5.85	21.5 ± 5.85
	Break9N	7.47 ± 0.96	84.8 ± 54.6	83.0 ± 10.15	6.88 ± 4.61	5.20 ± 1.77	41.1 ± 9.55	31.0 ± 7.88	77.3 ± 6.07	22.7 ± 6.07
Sleep 5	Sit9N	7.22 ± 1.26	78.9 ± 71.0	82.1 ± 13.57	17.32 ± 12.28	6.02 ± 4.00	46.8 ± 7.25	27.0 ± 8.80	79.9 ± 6.29	20.1 ± 6.29
	Break9N	7.23 ± 1.06	92.7 ± 63.6	80.4 ± 11.73	13.3 ± 10.93	5.42 ± 2.50	42.2 ± 8.29	29.5 ± 8.54	77.0 ± 6.44	23.0 ± 6.44

Table 2. Sleep variables by condition and sleep opportunity. TST = total sleep time, WASO = wake after sleep onset, SOL = sleep onset latency. Sleep stages = N1, N2, N3, NREM (Non-Rapid Eye Movement), REM (Rapid Eye Movement).

such that Break9D and Sit9D had significantly longer SOL than Break5D and Sit5D across 1–4, and Break9D and Sit9D had an increase in SOL across sleep opportunities 1–4 that was not seen in Break5D or Sit5D. SOL was significantly higher in Break9D than in Sit9D in sleep opportunity 5, but otherwise there were no differences between Break9D and Sit9D or Break5D and Sit5D in any of the other four sleep opportunities. There was a significant condition* sleep opportunity interaction for time spent in N2 ($F = 5.63$ (12,258.1), $p < 0.001$), such that Break9D and Sit9D had more time spent in N2 than Break5D and Sit5D for sleep opportunity 1–4, with no difference for sleep opportunity 5. There was also a significant condition* sleep opportunity interaction for time spent in N3 ($F = 9.55$ (12,258.2), $p < 0.001$), with Break9D and Sit9D having less time in N3 than Break5D and Sit5D across sleep opportunities 1–4 but not sleep opportunity 5. There was no significant interaction between condition*sleep opportunity for SE, WASO, or time spent in N1, NREM, or REM.

There were significant main effects of condition for TST ($F = 288.0$ (3,64.0), $p < 0.001$; longer TST in Sit9D and Break9D compared to Sit5D and Break5D), WASO ($F = 20.60$ (3,66.4), $p < 0.001$; less in Sit5D and Break5D compared to Sit9D and Break9D), sleep efficiency ($F = 28.35$ (3,65.7), $p < 0.001$; higher in Sit5D and Break5D compared to Sit9D and Break9D), SOL ($F = 17.90$ (3,66.0), $p < 0.001$; higher in Sit9D and Break9D compared to Sit5D and Break5D), time spent in N2 ($F = 17.82$ (3,65.7), $p < 0.001$; more time in N2 in Sit9D and Break9D compared to Sit5D and Break5D), and time spent in N3 ($F = 14.55$ (3,65.9), $p < 0.001$, more time in N3 in Sit5D and Break5D compared to Break9D and Sit9D). There were significant main effects of sleep opportunity for TST ($F = 166.8$ (4,256.8), $p < 0.001$; longer TST for sleep opportunity 5), sleep efficiency ($F = 15.39$ (4,258.3), $p < 0.001$; less SE for sleep opportunity 5), WASO ($F = 9.32$ (4,259.3), $p < 0.001$; higher WASO for sleep opportunity 5), SOL ($F = 15.60$ (4,258.4), $p < 0.001$; higher SOL for sleep opportunity 5), time spent in N2 (6.23 (4,258.1), $p = 0.015$; more time spent in N2 for sleep opportunity 5), and time spent in N3 (18.22 (4,258.2), $p < 0.001$; less time spent in N3 for sleep opportunity 5).

Nightshift

There were no significant interactions between condition (Sit9N vs. Break9N and sleep opportunity for any of the sleep variables (TST $p = 0.43$, WASO $p = 0.64$; sleep efficiency $p = 0.58$; sleep onset latency $p = 0.43$; time spent in N1 $p = 0.47$; time spent in N2 $p = 0.98$; time spent in N3 $p = 0.91$; time spent in REM $p = 0.71$; time spent in NREM $p = 0.71$; Table 2). There was a significant main effect of sleep opportunity for sleep onset latency ($F = 35.42$ (4,137.8), $p < 0.001$; with higher sleep onset latency for sleep opportunity 5).

Subjective sleepiness pre- and post-sleep

Dayshift

There was a significant condition*timepoint interaction for sleepiness ($F = 7.21$ (3,634), $p < 0.001$; Fig. 1), such that Break5D was the only condition to show a change in sleepiness pre-sleep compared to post-sleep. There was no difference in pre- and post-sleep sleepiness in the other conditions. Further, Break5D had higher sleepiness than Break9D, Sit9D, and Sit5D pre-sleep but not post-sleep. There were no significant interactions between condition*sleep opportunity, or condition*sleep opportunity*timepoint. There was a significant main effect of condition ($F = 12.98$ (3,183), $p < 0.001$) such that Break5D had the highest sleepiness, a significant main effect of sleep opportunity ($F = 4.10$ (4,525), $p = 0.003$) such that the highest sleepiness was reported for sleep opportunity 4. There was no significant main effect of timepoint.

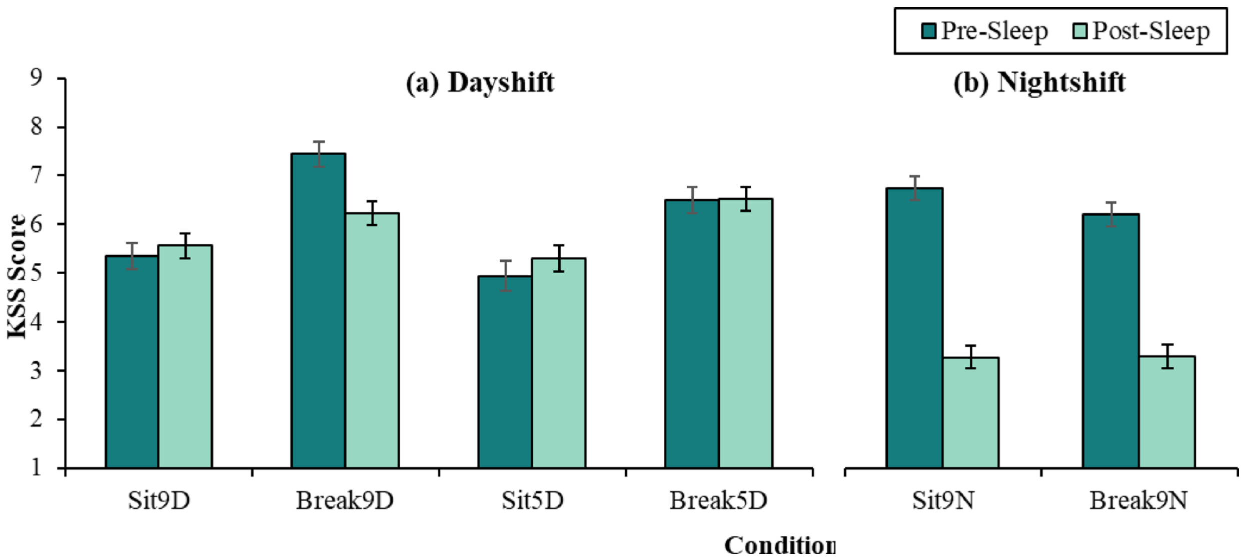

Fig. 1. Subjective sleepiness results from the condition*timepoint interaction for all conditions. Panel a shows the Dayshift conditions and panel b shows the nightshift conditions. Darker shade indicates pre-sleep ratings of sleepiness and lighter shade indicate post-sleep ratings of sleepiness. Means presented are estimated marginal means, and error bars indicate standard errors from model estimates.

Nightshift
There were no significant three-way or two-way interactions between condition, sleep opportunity, and timepoint for the nightshift condition (Fig. 1). There was a significant main effect of sleep opportunity (F = 11.12 (4,305.3), $p < 0.001$) such that participants reported higher sleepiness for sleep opportunity 1, and there was a main effect of timepoint (F = 494.25 (1. 307.3), $p < 0.001$) such that in both conditions, sleepiness was higher pre-sleep than post-sleep.

Discussion
This study was the first to investigate the impact of breaking up sitting with physical activity during simulated dayshifts and nightshifts on sleep architecture, adding to the limited literature on the relationships between sleep, physical activity, and sedentary behaviour. The differences in sleep architecture found between conditions during a dayshift schedule demonstrate the impact of a 5 h sleep opportunity compared to a 9 h sleep opportunity on subsequent sleep quality. After simulated nightshifts, there were no differences in sleep architecture between those that were breaking up sitting and those who were sedentary during their shift.

For simulated dayshifts we found differences in sleep architecture (sleep onset latency, and time spent in stages N2, N3, NREM, and REM), but these differences were between the 5 h and 9 h sleep opportunity rather than between the sitting and breaking up sitting conditions. The absence of an effect of breaking up sitting with physical activity on sleep contrasts with previous research on moderate to high-intensity physical activity, which resulted in greater slow wave sleep[41,42]. It is important to consider the type, duration, and frequency of the physical activity intervention used in this study compared to prior research. The current study includes a light-intensity physical activity intervention, with much of this previous work focussing on regular moderate- to high-intensity physical activity or acute high-intensity activity[43–46]. Higher intensity physical activity may produce greater physiological effects, such as increased heart rate, thermoregulation, and increased release of hormones[47] which may have a larger impact on sleep compared to the effects of lower intensity activity. It has been previously argued that research is needed on the attributes of physical activity that lead to the greatest impacts on sleep, and the exact physiological mechanisms underlying this effect[21].

For nightshifts, there was no difference in sleep architecture between those who were sedentary and those breaking up sitting with physical activity. Moreover, participants in both conditions had a sleep efficiency of over 80%, indicating good sleep[21,48]. Sleeping well in the sleep laboratory is consistent with previous laboratory sleep studies with day sleep periods following nightshifts[49,50] and is likely due to the increase in homeostatic sleep pressure experienced across the nightshift and increased sleep need by the start of the sleep period. Increasing sleep pressure across the nightshift is reflected in the subjective sleepiness results, with significantly more sleepiness pre-sleep than post-sleep, regardless of physical activity condition. Further, participants slept well in the laboratory, likely due to the control over external factors that influence sleep (such as light, sound, temperature) that create an ideal sleeping environment, in addition to controlled lighting during. This good sleep contrasts with results from field-based studies, in which shiftworkers report poor quality sleep during the day[51]often due to the external factors that are controlled for in the laboratory. The ability to obtain good quality sleep each day in the laboratory may have masked any improvements in sleep seen after breaking up sitting. That is, if participants are already sleeping well (e.g., over 80% sleep efficiency) despite a short sleep opportunity, breaking up sitting may not have an added impact. In real-world settings with poor quality daytime sleep in addition to shorter sleep opportunities, a breaking up sitting intervention may act differently on sleep architecture. Additionally, as discussed for the dayshift results, it is also important to consider the type, duration, and frequency of the physical activity at night. However, alternate physical activity interventions need to be considered alongside the potential feasibility challenges of using higher intensity or longer duration physical activity during nightshifts when workers may be engaged in safety-critical tasks[52]. This is the first study to investigate a physical activity intervention during consecutive simulated nightshifts, and more research is needed to assess the feasibility of other physical activity interventions.

We found less time spent in N3 (slow wave sleep) for those in the sitting and breaking up sitting conditions with a 9 h sleep opportunity compared to a 5 h sleep opportunity each night. This finding suggests that time spent in N3 is sensitive to the prior amount of sleep and any subsequent increased sleep pressure from short sleep. This is consistent with previous research on sleep restriction, with increased time spent in slow wave sleep found following periods of sleep restriction[53]. This is thought to be due to the increasing homeostatic pressure for sleep. For example, in previous work[54] analyses predicted a 10–20% increase in slow wave activity over the first few days of sleep restricted to 4 h[55]. Our findings confirm this, as the increased time spent in N3 was seen during sleep periods 1–4, with no difference between the 9 h and 5 h sleep opportunities for the last sleep opportunity (9 h for all participants). The lack of difference in sleep architecture between the dayshift 5 h sleep conditions could be due to the low-intensity physical activity intervention not having enough of an effect to overcome the impact of the increased homeostatic drive for sleep on subsequent sleep architecture.

The subjective sleepiness findings are also consistent with increasing homeostatic pressure for sleep following a 5 h sleep opportunity, as subjective sleepiness pre-sleep was significantly higher in the 5 h sleep opportunity conditions compared to the 9 h sleep opportunity conditions. Of note, participants in the breaking up sitting condition who had a 5 h sleep opportunity reported the highest level of sleepiness pre-sleep, compared to the 9 and 5 h sleep opportunity sedentary conditions. This may be due to energy expenditure, with previous research finding increased energy expenditure under conditions of sleep loss[56,57]. If participants in the breaking up sitting 5 h sleep opportunity condition were experiencing greater energy expenditure than the sedentary participants in the 5 h sleep opportunity condition, this would explain higher subjective sleepiness pre-bed. This may suggest that workers who are sleep restricted should be cautious when adopting a breaking up sitting intervention, as they may experience increased sleepiness towards the end of the shift. Future research should focus on longerterm physical activity interventions (e.g., a month-long intervention) to potentially allow time for participants to adjust to the increased activity.

This is the first study to investigate whether a breaking up sitting intervention during the day and night impacts subsequent sleep. A strength of the current study is the controlled, in-laboratory environment with control over confounding factors such as light and sound[58,59]. However, when interpreting the findings, there are limitations to consider. For instance, an in-laboratory protocol, although well-controlled, may be considered less ecologically valid than a design that collects data in a naturalistic environment[32]. The study was also across five shifts and as such, we cannot comment on the long-term effectiveness of the intervention on sleep[32,60,61]. While the participant age range encompasses working age young adults, results cannot be generalised to adolescents or older populations. Given research indicates SWS decreases as humans age reductions in SWS may be expected in older participants[62] and physical activity may differentially impact SWS compared to in younger adults. Further, participants with sleep disorders were excluded from the current study which limits our findings to 'healthy' sleepers. Given that many shiftworkers are diagnosed with or suffer symptoms of sleep disorders[63,64] (insomnia obstructive sleep apnea), it is important to investigate whether breaking up sitting differentially impacts the sleep of those with sleep disorders. Future research should focus on the pragmatic questions on feasibility and use of an intervention to break up sitting with light-intensity walking. For example, do workplaces have space or access to space for a light-intensity walk, or should treadmills or treadmill desks be supplied. As discussed, workplace interventions for increasing physical activity have been implemented successfully in workplaces for day work[31,32]however there is no research on the feasibility of workplace interventions for physical activity in nightwork. This is an important focus for future research, as the efficacy and feasibility of such an intervention may differ at night. Factors such as break opportunities, resourcing levels, access to facilities, and work tasks need to be taken into account. A first step for this future research is to engage those with lived experience of night work to understand the feasibility of breaking up sitting interventions in workplaces at night.

While we did not find impacts on sleep architecture based on breaking up sitting compared to sedentary behaviour, this research still has important implications for the health of the workforce. Over the past 15 years, sedentary behaviour at work has increased[65–67]. Breaking up sitting is a strategy recommended for mitigating health risks attributed to extended sedentary behaviour[62,68–71]. For example, research has demonstrated the benefits of reducing sedentary time with breaking up sitting on insulin sensitivity, cardiometabolic health, individual metabolic profile, and mortality risk[34,62,68–70]. Our findings contribute to the argument for implementing breaking up sitting interventions, as there were no adverse effects of breaking up sitting on sleep architecture. This is important for implementing breaking up sitting interventions in workplaces for day and night shift workers to improve overall health.

Methods

Study design

The study was an unblinded, parallel (1:1) in-laboratory randomised controlled trial, with an experimental repeated measure, between-subjects factorial design with six conditions (Table 5). Study method and results are reported following the Consolidated Standards of Reporting Trails (CONSORT) Statement. In the principal study[72] two additional conditions were planned (sedentary or breaking up sitting and 5 h sleep), however due to COVID-19 restrictions, the principal study was terminated early and no participants were recruited for the remaining two conditions. No other changes to the study method or outcomes for this study occurred after trial commencement.

These analyses are for secondary outcomes as part of a larger study, with the complete protocol[72]and secondary outcomes to date published elsewhere[73–76]. This study was approved by the Central Queensland University Human Research Ethics Committee (0000021914) and registered with the Australian New Zealand Clinical Trials Registry on 04/11/2019 (ACTRN12619001516178). The authors declare that all procedures performed were in accordance with the ethical standards of the relevant national and institutional committees on human experimentation and with the 1975 Declaration of Helsinki (as revised 2008). Participants provided written consent and were compensated financially for their time after the study on a pro rata basis (AUD$780 total for all days).

Participant recruitment and screening

Participants were recruited via word of mouth, online advertisements, and flyers. Participants were required to meet the following criteria: (1) between 18 and 35 years, (2) no medical, psychiatric, or sleep disorders, (3) no previous shiftwork, (4) no travel across time zones within three months prior to laboratory admission, (5) no prescription medication, (6) non-smoker, (7) habitual bedtime 22:00–00:00 and wake time 06:00–08:00, (8)

Condition	**Sleep opportunity**	
Dayshift	**9 h (10:00–07:00)**	**5 h (02:00–07:00)**
Sedentary	Sit9D	Sit5D
Breaking up sitting	Break9D	Break5D
Nightshift	**9 h (08:00–17:00)**	
Sedentary	Sit9N	
Breaking up Sitting	Break9N	

Table 5. Condition names and sleep opportunity.

consumption of < 10 standard alcoholic drinks per week and < 3 caffeinated beverages per day, (9), fluent in English, (10) low physical activity levels, (11) no contraindications to exercise, (12) body mass index between 18 and 30 kg/m2. Female participants commenced the laboratory protocol during the follicular phase of their menstrual cycle (self-reported). Randomisation was stratified by sex, BMI, and age. Random allocation sequence and group assignment was managed by a researcher who was not involved in the screening of participants. The allocation sequence was concealed to both participants and the remaining research team members until interventions were assigned. Given the nature of experimental conditions (prolonged sitting or breaking up prolonged sitting), participants and assessors were not blinded post-randomisation. Data analysts were also not blinded to the group allocation. Based on the time when participants were admitted into the study, they were allocated into the dayshift or nightshift condition. Participants were randomised at the group level (6 participants per group, consistent with the 6 bedrooms in the laboratory environment) to either the 9 h–5 h sleep condition. Within each group, 3 participants were randomised to the sedentary or breaking up sitting condition. For detailed screening criteria and the sample size calculations based on the primary outcome of the larger study (daily and postprandial glucose response), refer to the study protocol[72]. The screening process for the present analyses is shown in Fig. 2.

Procedure

The study consisted of 6-nights and 7-days in-laboratory at the Appleton Institute Sleep Laboratory at Central Queensland University Adelaide Campus. The facility has six sound-attenuated and temperature-controlled (21˚C ± 2˚C) bedrooms with king-single beds and individual ensuites, and two living/kitchen areas. Light levels were maintained at > 300 lx during wake periods and were negligible (< 0.3 lx) during sleep periods. An overview of the protocol is shown in Fig. 3.

In all conditions, participants entered the laboratory on arrival day (AR) and had a 9 h baseline sleep opportunity (22:00–07:00). On Adaptation Day (AD) participants were familiarised with all relevant questionnaires and components of the cognitive and self-perceived testing battery that are part of the larger study. Participants in the nightshift condition (Sit9N, Break9N) had a nap opportunity from 15:00–17:00 on AD to prepare for the first nightshift. On experimental days E1 to E5 participants completed a simulated workshift (8 h in duration). For the dayshift conditions (Sit9D, Break9D, Sit5D, Break5D) the shift was from 09:00–17:00 and in the nightshift conditions (Sit9N, Break9N) the shift was from 22:00–06:00. During dayshifts or nightshifts, participants in the Break conditions spent 3-minutes every 30-minutes performing light-intensity physical activity. This consisted of walking at a speed of 3.2 km/h on a motorised treadmill (Healthrider H95T; Icon Health & Fitness Inc, Utah, USA) with a level incline (0% gradient). In total, participants in all Break conditions performed 17 × 3 min bouts of walking per experimental day. All participants in the Sit conditions remained seated for the entire study, aside

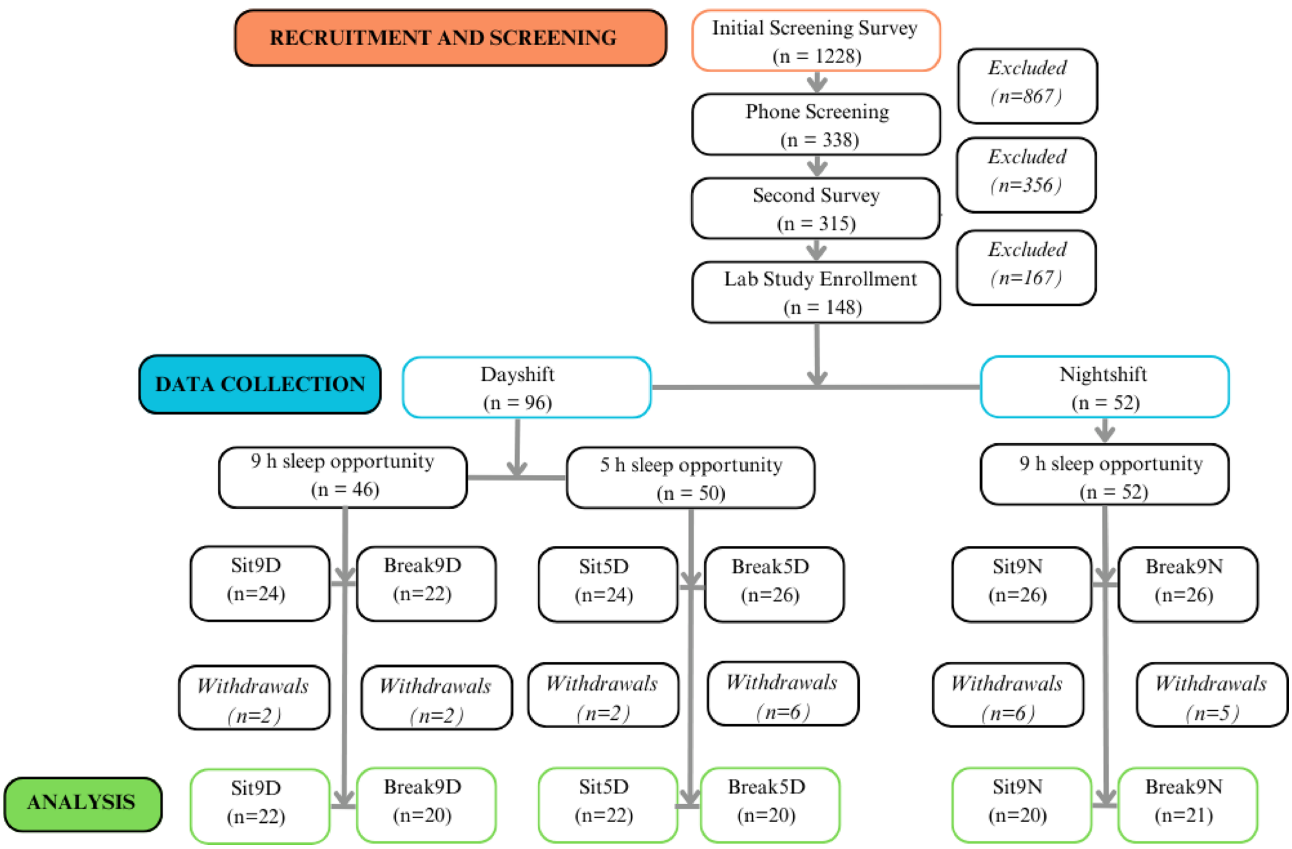

Fig. 2. Flow diagram of recruitment and screening process.

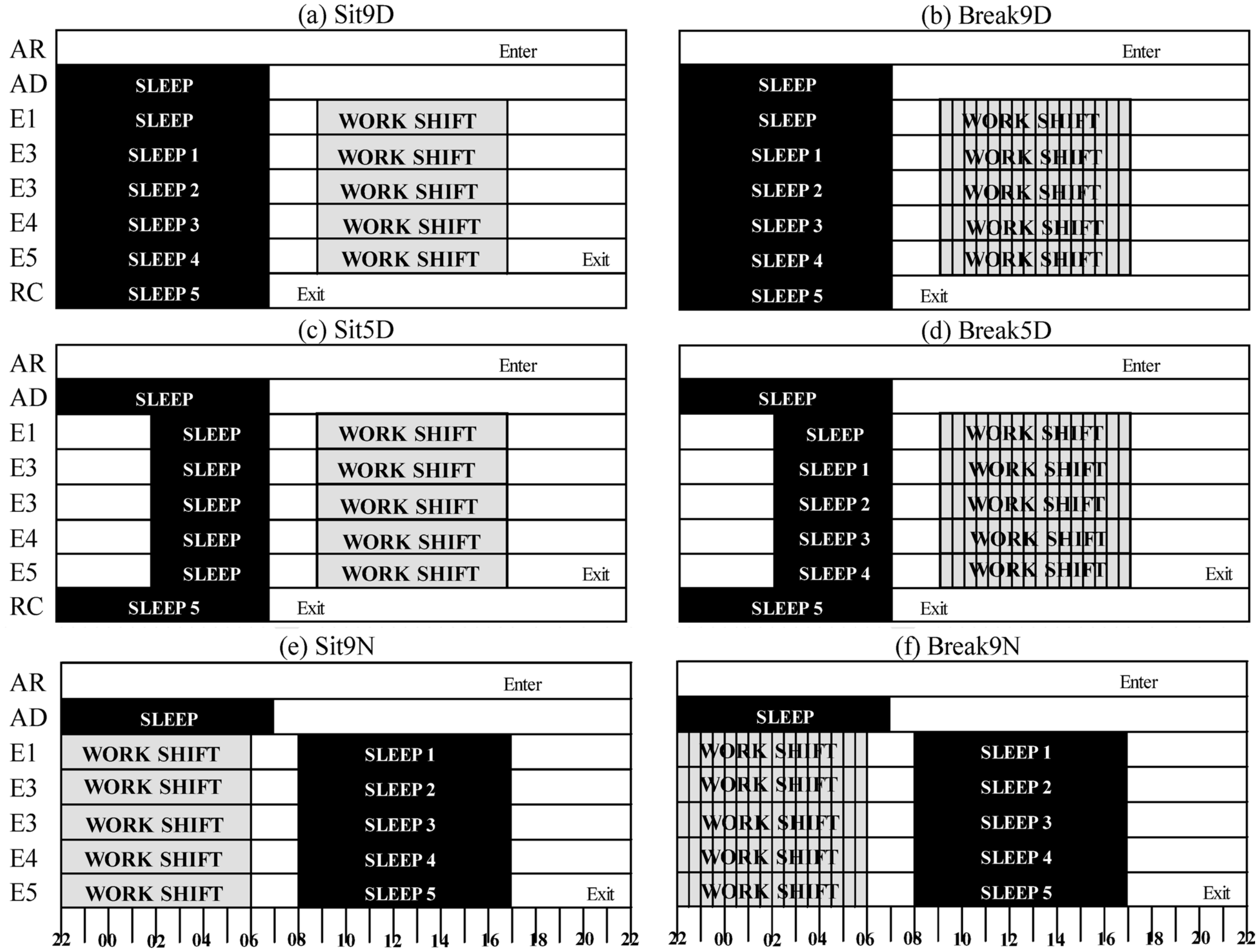

Fig. 3. Protocol diagram for the six study conditions: **a** Sit9D, **b** Break9D, **c** Sit5D, **d** Break5D, **e** Sit9N, **f** Break9N. Y-axis represents day of the study (AR = arrival, AD = adaptation day, E1-E5 = experimental days, RC = Recovery). X-axis represents time of day (24 h). Black bars are sleep opportunities (1–5), grey bars are shift periods, vertical lines indicate the breaking up sitting periods.

from all participants were walking to and from the dining room at meal-time (distance:~32 m) or walking to their ensuites (distance:~8 m). During sitting periods, participants were engaged in activities such as reading, watching television, or completing cognitive testing as part of the larger study. Sleep opportunity opportunities after each workshift were 9 h–5 h depending on the condition, with the exception of the fifth workshift (E5), after which all participants had a 9 h sleep opportunity as a recovery sleep prior to exiting the laboratory. For the Sit5D and Break5D, this means that the fifth sleep opportunity was 9 h. This sleep opportunity is included in analyses. Immediately before and after each sleep period, participants completed a Karolinska Sleepiness Scale presented via Qualtrics (Qualtrics, Provo, Utah, USA) on an Apple iPad (Apple Inc, Cupertino, California, USA).

Measures

Sleep architecture

All sleep periods were measured using polysomnography (PSG), which is a comprehensive sleep measurement that involves monitoring various physiological parameters during sleep[77]. Recordings (Compumedics Ltd, Melbourne, Australia) were taken from the three standard electrode channels, C3/M2, F4/M1 and O2/M1116 in addition to electromyography recordings, from the left, right and middle of the jawline and electrooculography recordings (left and right outer canthi). Sleep was scored by a trained sleep technician in 30-s epochs, according to standard criteria[78]. Variables included total sleep time (TST; min), sleep efficiency (SE; %), sleep onset latency (SOL; min), wake after sleep onset (WASO; min) and percentage of time spent in stage N1, stage N2, stage N3, stage NREM and stage REM (expressed as a percentage of total sleep time). This is considered standard practice in sleep research[34,79].

Subjective sleepiness pre-sleep and post-sleep

The Karolinska Sleepiness Scale (KSS)[80] was used to measure an individual's subjective level of sleepiness immediately pre-sleep and post-sleep. The KSS is a well validated[81] 1-item questionnaire requiring participants to rate their current level of sleepiness on a 9-item scale. This scale ranges from 1('extremely alert') to 9 ('very sleepy, great effort to keep awake, fighting sleep').

Step count

Step count was measured via ActivPAL Micro 4 monitor (PAL Technologies, Glasgow, Scotland), a tri-axial accelerometer. This device was worn continuously throughout the 7-day protocol attached to the midline on the right thigh via an adhesive dressing. Data was sampled at 20 Hz and analysed in 15-s epochs using ActivPAL software-PAL analysis (V8.10.8.76) The daily step count of each participant was calculated using the ActivPAL PAL analysis software.

Statistical analysis

Analyses were conducted to verify that the randomisation strategy to strategy by sex, age, and BMI had achieved equal distributions between the breaking up sitting and sedentary conditions. For the dayshift analyses, separate ANOVA were conducted to compare the means of each group (Sit9D, Break9D, Sit5D, Break5D,) for sex, age, and BMI. For the nightshift analyses, separate independent *t*-tests were conducted for the Break9N and Sit9N groups for sex, age, and BMI. No significant differences were found for these analyses and so these variables were not included as covariates in the linear mixed-effect models.

Linear mixed-effects models were conducted for all PSG outcome variables (TST, WASO, SE, SOL, time spent in N1, time spent in N2, time spent in N3, time spent in NREM, time spent in REM). For dayshift conditions, there were fixed effects of condition (Break9D, Sit9D, Break5D, Sit5D) and sleep opportunity (1–5) and a random effect of participant ID. For nightshift conditions, there were fixed effects of condition (Break9N, Sit9N) and sleep opportunity opportunity (1–5), with a random effect of participant ID. Main effects of condition and sleep opportunity, along with the 2-way interaction between condition*sleep opportunity were analysed.

Linear mixed-effects models were also conducted for KSS. For dayshift there were fixed conditions of condition (Break9D, Sit9D, Break5D, Sit5D), sleep opportunity (1–5), and timepoint (pre-sleep or post-sleep). For nightshift conditions, there were fixed effects of condition (Break9N, Sit9N), sleep opportunity (1–5), and timepoint (pre-sleep or post-sleep) with a random effect of participant ID. Main effects of condition, sleep opportunity, timepoint, along with the 2-way interactions between condition*sleep opportunity, condition*timepoint, and 3-way interaction of condition*timepoint*sleep opportunity were analysed. Linear mixed-effects analyses were chosen as they are suited to repeated measures data and account individual variability at baseline[82]. Significant effects were further investigated by post hoc Bonferroni comparisons. Residuals were checked for normality. For all sleep variables a Bonferroni corrected alpha of $p < 0.006$ was used (to account for the multiple comparisons of 8 sleep variables). Data is reported as mean ± standard deviation (SD), unless otherwise stated. Statistical analyses were conducted using Jamovi software (Version 2.2.5.0). Results are presented by dayshift and nightshift, separately.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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