Optimizing the temperature of the bed microenvironment to enhance sleep quality

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Introduction

Sleep initiation is bidirectionally associated with the circadian rhythms of core body temperature (CBT) and skin temperature, with habitual sleep onset coinciding with CBT decline and increased skin temperature (Van Someren, 2006). The CBT decline during sleep is facilitated by peripheral vasodilation which increases cutaneous blood flow such that internal heat from the body's core is dissipated into the micro-environment surrounding the sleeper's body.

Under the controlled conditions of a constant routine protocol, (Krauchi, et al., 2000) identified the gradient between the distal and proximal skin temperature to be the best predictor for sleep onset latency. A causative role of warming the feet which increases distal skin temperature on shortening the sleep onset latency was validated in (Kräuchi, et al. 1999). (Ko & Lee, 2018) found that sleep onset latency was on average 7.5 minutes shorter when wearing feet-warming bed socks.

(Herberger, et al., 2024) investigated the impact of sleeping on a high heat capacity mattress (HHCM). HHCMs promote body cooling by facilitating the heat transfer from the body's core to the mattress. The main findings in the study were an increase in slow wave sleep (7.5 minutes on average), and a decrease in heart rate (-2.36 beat/min on average) associated with sleeping on a HHCM.

Leveraging the ability of the Sleep Number Climate 360 bed to actively control the temperature of the in-bed microclimate, a study was conducted in collaboration with the Sleep Center at Northwestern University to test the effect of temperature programs on objective and subjective sleep metrics.

Materials and Methods

Sleep Number's sensing technology uses a pressure signal from a sensor positioned inside an inflatable air bladder within a smart bed. Ballistocardiography (BCG) signals, which reflect movement, cardiac, and respiratory activity, are obtained from the pressure signal (see Figure 1). The smart bed's embedded software relies on machine learning methods to determine breathing rate (BR), heart rate (HR), heart rate variability (HRV), sleep duration, restful sleep (i.e., sleep with low movement level), and sleep quality (Siyahjani, et. al. 2022). The latter is a score that aggregates sleep duration, level of movement during sleep, bed exit count, and resting heart rate.

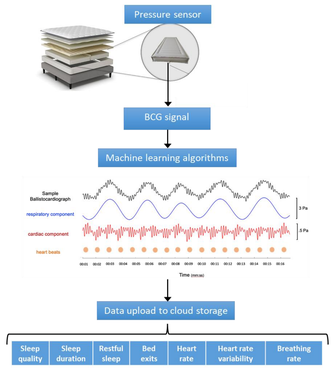

Figure 1. Data from the Sleep Number platform.

The Sleep Number Climate 360 smart bed provides customers the ability to independently control temperature on each side of the bed. The seven possible temperature settings include OFF, high (HH), medium (MH) and low (LH) heat, and high (HC), medium (MC) and low cooling (LC). All these settings but the high heating one were used in the study.

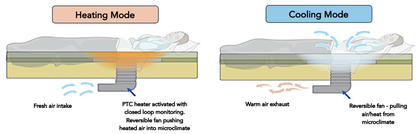

Figure 2. Heating and cooling modes in the smart bed.

Study design

Thirty-one participants (12F/19M); mean age 48.5 (SD: 11.2) years old, recruited among smart bed owners, enrolled in a study consisting of 14 nights within their homes.

Each participant experienced 10 session with temperature programs and 4 baseline sessions. A program is a sequence of four temperature settings each applied to four consecutive 2-hour segments in a sleep session. The programs were timed to start at the participants' self-reported bedtime.

Temperature setting	High cooling	Medium cooling	Low cooling	Off	Low heating	Medium heating
Abbreviation	HC	MC	LC	OF	LH	MH
Numerical encoding	−3	−2	−1	0	+1	+2

Temperature programs

Night 1	OF	LC	MC	HC
Night 2	LC	MC	OF	OF
Night 3	LH	LC	MC	LH
Night 4	OF	OF	OF	OF
Night 5	LH	MH	OF	OF
Night 6	LC	LC	LH	LH
Night 7	OF	OF	OF	OF
Night 8	MH	LH	LH	MH
Night 9	OF	OF	MH	LH
Night 10	OF	OF	OF	OF
Night 11	OF	OF	HC	LC
Night 12	LC	MC	HC	LC
Night 13	OF	OF	OF	OF
Night 14	LH	MH	MH	LH
	2h	2h	2h	2h

Analysis Methods

The data collected in the study were organized in a matrix form to quantify the effect of the encoded temperature setting on a given metric (see Figure 3).

Linear mixed effect models were used for this purpose.

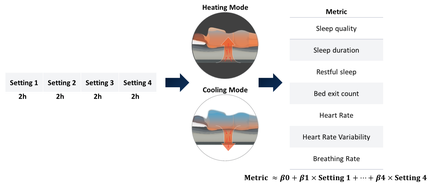

Figure 3. Linear mixed effect model to understand the effect of the encoded temperature setting on a given metric.

Results and Discussion

Sleep sessions with bedtime at least 1-hour before the end of the first temperature setting were selected for analysis. The data from 304 sleep sessions (~10 sessions/per participant on average) were available for analysis. The results of the linear mixed models for sleep quality, sleep duration, and restful sleep are shown on Table 1. The results for bed exits, HR, HRV, and BR are shown on Table 2.

Rows with significant values are indicated with a green background.

Table 1. Linear mixed effect model results for sleep quality, sleep duration, and restful sleep.

	Coefficients	Std Err.	P
Sleep quality score (1-100)			
Intercept	75.65	1.342	0
1st temp. setting	2.798	1.363	0.04
2nd temp. setting	-2.719	0.989	0.006
3rd temp. setting	0.828	0.69	0.23
4th temp. setting	-1.489	0.805	0.064
Sleep duration (hours)			
Intercept	7.9	0.184	0
1st temp. setting	-0.257	0.154	0.094
2nd temp. setting	0.256	0.112	0.022
3rd temp. setting	-0.171	0.078	0.028
4th temp. setting	0.197	0.091	0.03
Percent restful sleep (%)			
Intercept	88.328	0.802	0
1st temp. setting	0.292	0.501	0.56
2nd temp. setting	-0.765	0.364	0.036
3rd temp. setting	0.276	0.254	0.277
4th temp. setting	-0.028	0.296	0.924

Table 2. Linear mixed effect model results for bed exits, heart rate, heart rate variability, and breathing rate.

	Coefficients	Std Err.	P
Bed exit count			
Intercept	1.94	0.306	0
1st temp. setting	-0.671	0.267	0.012
2nd temp. setting	0.589	0.194	0.002
3rd temp. setting	-0.389	0.135	0.004
4th temp. setting	0.347	0.158	0.028
Heart rate (beat/min)			
Intercept	61.764	1.016	0
1st temp. setting	0.263	0.476	0.58
2nd temp. setting	-0.114	0.346	0.742
3rd temp. setting	0.22	0.241	0.362
4th temp. setting	-0.108	0.281	0.701
Heart rate variability (milliseconds)			
Intercept	107.918	8.528	0
1st temp. setting	-1.042	2.494	0.676
2nd temp. setting	0.642	1.807	0.723
3rd temp. setting	1.007	1.259	0.424
4th temp. setting	-0.774	1.488	0.603
Breathing rate (breath/min)			
Intercept	15.251	0.29	0
1st temp. setting	-0.129	0.095	0.174
2nd temp. setting	0.123	0.069	0.075
3rd temp. setting	-0.059	0.048	0.22
4th temp. setting	-0.026	0.056	0.642

The analysis of the effects of the first and second temperature settings on the overall sleep quality was performed using the linear model coefficients and comparing against baseline Off (Figure 4). Heating in the first segment and cooling in the second segment are associated with positive effects on sleep quality.

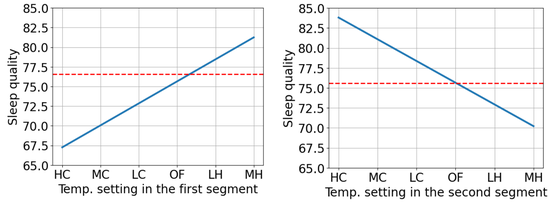

Figure 4. (a) Effect of the first temperature setting on the overall sleep quality (the red dashed horizontal line corresponds to the mean value for sessions with OFF as first temperature setting). (b) Effect of the second temperature setting on the overall sleep quality (the red dashed horizontal line corresponds to the mean value for sessions with OFF as second temperature setting).

The analysis of individual changes (at participant level) in sleep quality between the reference (OFF across all temperature settings) and the program consisting of heating first (including Off first) followed by cooling is shown in Figure 5.

The green diagonal lines show changes resulting in higher than 5 percent gains in sleep quality. The red diagonal lines show changes resulting in lower than 5 percent decrements in sleep quality. The sleep quality associated with heating or off first followed by cooling is significantly better compared to the reference (Wilcoxon test p=0.015).

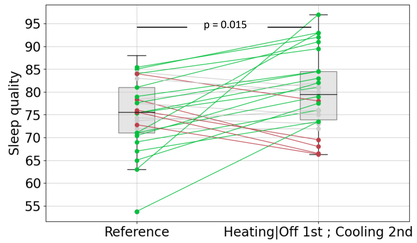

Figure 5. Individual changes in sleep quality between the reference (Off) and the temperature program consisting in heating or Off first and then cooling.

Conclusive remarks

The results in this study suggest that the temperature of the in-bed microclimate can be optimized by initially warming which may help with falling asleep, and then cooling down which may help with sleep maintenance. Indeed, this temperature profile is significantly associated with sleep quality improvements and a reduction in the count of bed exits.

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