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Publication Date

2025-05-01

DOI

10.1016/j.rser.2025.115474

The effects of personal comfort systems on sleep: A systematic review

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Abstract

Creating a comfortable thermal environment is the necessary measure to safeguard human sleep quality but it requires a substantial amount of energy. Personal comfort systems have the potential to improve sleep while significantly reducing energy consumption compared to typical air conditioning systems. Despite some studies reporting favorable outcomes when using personalized approaches to cooling or heating in bedrooms, a comprehensive summary of the impact of personal comfort systems on sleep is lacking. This systematic review of 25 sleep studies estimates the effect of personal comfort systems on sleep quality, sleep stages and sleeping thermal comfort. Configuration of personal comfort systems and sample characteristics are summarized and compared. Calculated effect sizes show that using personal comfort systems are generally effective in improving sleep quality and sleeping thermal comfort. However, there are potential negative effects of personal heating on slow wave sleep and personal cooling on pre-sleep thermal comfort. Relatively mild contact temperatures for both heating and cooling and steady air velocities below 0.9 m/s in warm environments are preferred. The head and feet are the most frequently targeted body parts for cooling and heating,

 doi.org/10.1016/j.rser.2025.115474
escholarship.org/uc/item/0sz798x5

respectively. Most subjects were aged between 17 and 40 years, suggesting a lack of data for both children and the elderly. Four future research directions are proposed: personal cooling at pre-bed phase, human subject tests with radiant systems, dynamic control strategies, and application of machine learning approaches.

Keywords: Personal comfort systems; Sleep quality; Sleeping thermal comfort; Effect size; System configuration; Sample characteristics.

Highlights

- Systematic review of 25 studies on personal comfort systems (PCS) during sleep.
- PCS can improve sleep while reducing energy use.
- PCS are effective in reducing sleep onset latency and increasing sleep efficiency.
- Thermal parameter settings should be relatively mild to avoid disrupting sleep.
- Four future research directions for PCS in sleep studies are proposed.

Nomenclature

PCS	Personal Comfort Systems
NREM	Non-rapid eye movement sleep, min
N1	NREM stage 1, min
N2	NREM stage 2, min
N3	NREM stage 3, min
REM	Rapid eye movement sleep, min
SOL	Sleep onset latency, min
SE	Sleep efficiency, %
WASO	Wake after sleep onset, min
TCV	Thermal comfort vote
T_a	Ambient temperature, °C
T_c	Contact temperature, °C
V_a	Airflow velocity, m/s

Word account: 7803

1. Introduction

Good sleep quality is imperative for physical, mental, and cognitive health [1, 2]. The thermal environment is one of the pivotal factors influencing sleep quality [3, 4]. Nighttime temperatures are disproportionally increased under climate change and further compounded in large cities by urban heat islands [5, 6]. Increased nighttime temperatures were associated with reduced sleep quality among 765,000 US residents between 2002 and 2011, particularly for lower-income communities and elderly populations [7]. Maintaining the sleeping thermal environment within an appropriate range is a necessary measure to ensure human health.

Common strategies for regulating sleeping thermal environments typically rely on energy-intensive adjustments to the overall room temperature and humidity [8-10]. In contrast, personal comfort systems (PCS) are energy-efficient [11] and may improve the sleep. In contrast to traditional air conditioning systems, PCS are designed to deliver targeted cooling or heating near the body instead of modifying the conditions within the entire space. Some studies have evaluated the efficacy of PCS for sleeping environments, including fans in summer and electric heating blankets in winter [12, 13]. These studies tested several PCS technologies under different settings and personal characteristics as age and sex. However, there is no comprehensive analysis of the sleep features that are specifically affected by PCS, the conditions in which they are affected, and to what extent. This research will therefore review existing studies of PCS and sleep to determine any systematic findings and provide guidance for future research efforts.

The two primary objectives of this review are 1) to quantify the impacts of PCS on sleep in a quantitative manner, and 2) to outline the technologies and configuration of PCS, and subject characteristics in different experiments.

Sleep will be evaluated based on sleep quality and sleeping thermal comfort. The assessment of sleep quality encompasses both subjective and objective methods. Subjective methods involve individuals filling out questionnaires or diaries used then to calculate sleep quality scores [14]. Objective methods entail determining sleep stages and wakefulness based on physiological signals including brain activities from electroencephalogram, eye movements from electrooculogram, muscle tone from electromyogram [15-17]. Sleep duration primarily comprises rapid eye movement (REM) sleep and non-rapid eye movement (NREM) sleep. NREM sleep can be further divided into three stages: N1, N2, and N3. Among these, N1 and N2 are categorized as light sleep, while N3 is classified as deep sleep. Objective indicators of sleep quality such as sleep onset latency (SOL), wakefulness after sleep onset (WASO), and sleep efficiency (SE) – the percentage of time in bed when the individual is actually asleep – are then calculated from those signals [15]. For the evaluation of sleeping thermal comfort, the primary form of occupant feedback is a thermal comfort vote obtained through questionnaires based on ASHRAE 55 [18]. Thermal comfort assessments in sleep studies are typically conducted before falling asleep or after waking up [19, 20], as subjects are unable to provide feedback during sleep. In general, the aforementioned quantitative approaches can be used to evaluate the effect of PCS on sleep quality and sleeping thermal comfort.

The use of PCS in sleeping environments are mainly governed by three key considerations: thermal parameter settings, acting position, and acting duration. Firstly, thermal parameter settings refer to the capabilities of the device to influence the thermal environment experienced by occupants, such as the airflow speed of a fan or the surface temperature of an electric blanket [21, 22]. Secondly, acting position refers to which areas of the body that a PCS is targeting. This is important because local thermal sensitivity varies in different body parts [23]. The impact of the same local temperatures from a PCS on sleep may vary with body region. For instance, Kräuchi et al. pointed out that warming the feet promotes the rapid onset of sleep [24]. Lastly, acting duration refers to how long the PCS continues to work, as studies may control its running strategy to safeguard sleep quality [25]; while position and duration are important factors for achieving a "personal" approach in sleeping scenes. Subject characteristics are another important factor in determining the potential of PCS. For example, sex determines individuals' thermal sensitivity and age affects sleep structure [26, 27]. These factors suggest that PCS may work better for some population compared to others. It is therefore important to summarize the influence of these factors on the efficacy of PCS in sleeping environments.

In summary, this systematic review is centered around the two objectives, while reviewing existing sleep studies involving the application of PCS, it also discusses the characteristics of technologies involved, and further proposes future directions for applying PCS in sleep field.

2. Methods

The literature review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [28]. PRISMA aims to assist reviewers in improving the quality of systematic reviews and meta-analysis reporting. It includes a checklist and a flow chart that outline a standardized four-stage process (Identification, Screening, Eligibility and Inclusion) for identifying and evaluating sources for inclusion in the review. A systematic review can be used to assess interventions [28], which in this case are personal cooling and heating systems introduced to promote sleep.

2.1 Literature search

The literature search included peer-reviewed journal articles in the Web of Science database (1998-2023). Web of Science was chosen as it is the most widely used repository of research publications and citations [29]. The following keywords were used to identify potentially relevant papers: "sleep quality", "sleep stage", "sleeping thermal comfort", "personal cooling", "personal heating", "local cooling", "local heating", "personal airflow", "task ambient conditioning", "personal comfort system", "personalized environmental control system", and "wearable thermal equipment". Additional searches combined keywords using Boolean operators ("AND" and "OR") to produce the most relevant studies. In addition, snowball search techniques, both backward and forward, were applied during the initial database identification.

2.2 Selection criteria

The literature search yielded 682 relevant publications. After adding 14 publications identified through manual searches and removing duplicates, there were a total of 687 publications for further screening. The list of publications was filtered to retain only papers published in English using Web of Science functions, resulting in 436 publications. These publications were then screened based on the objectives of this review. The following criteria were used for screening:

(1) The selected literature should report human-subject tests. While some sleep studies use thermal manikins or modelling to assess thermal comfort, the scope of this review was to focus on understanding the observed impacts of thermal environments on human sleep.
(2) The selected literature should contain real sleep or the pre-bed phase. As this review was intended to focus on the authentic physiological aspects of sleep, therefore some studies related to sleeping posture and bedding system but not involved real human sleep process were excluded. Sleep studies that included the entire bedded sleep process, typically lasting 8 hours were selected; studies that only focused on the period before getting into bed (i.e., pre-bed phase) were also included, because the body temperature during this period have been demonstrated to significantly impact the duration of sleep onset latency [30].
(3) The selected literature should focus on participants who reported having no disability or a health condition that might affect thermoregulation, perceptual responses and sleep processes.
(4) The selected literature should involve quantitative assessment of sleep quality, sleep stages or sleeping thermal comfort.
(5) The selected literature should involve studies of active cooling or heating methods. Here the term "active" denotes the use of energy in generating the heating or cooling provided by the PCS. Studies focused on passive cooling and heating methods, such as varying the coverage or thermal insulation of bedding systems, were excluded.
(6) The selected papers should not be a literature review or conference papers.

Based on the six criteria, 25 publications were retained for analysis. A flowchart of the literature search and screening process, following the PRISMA statement, is presented in Fig. 1.

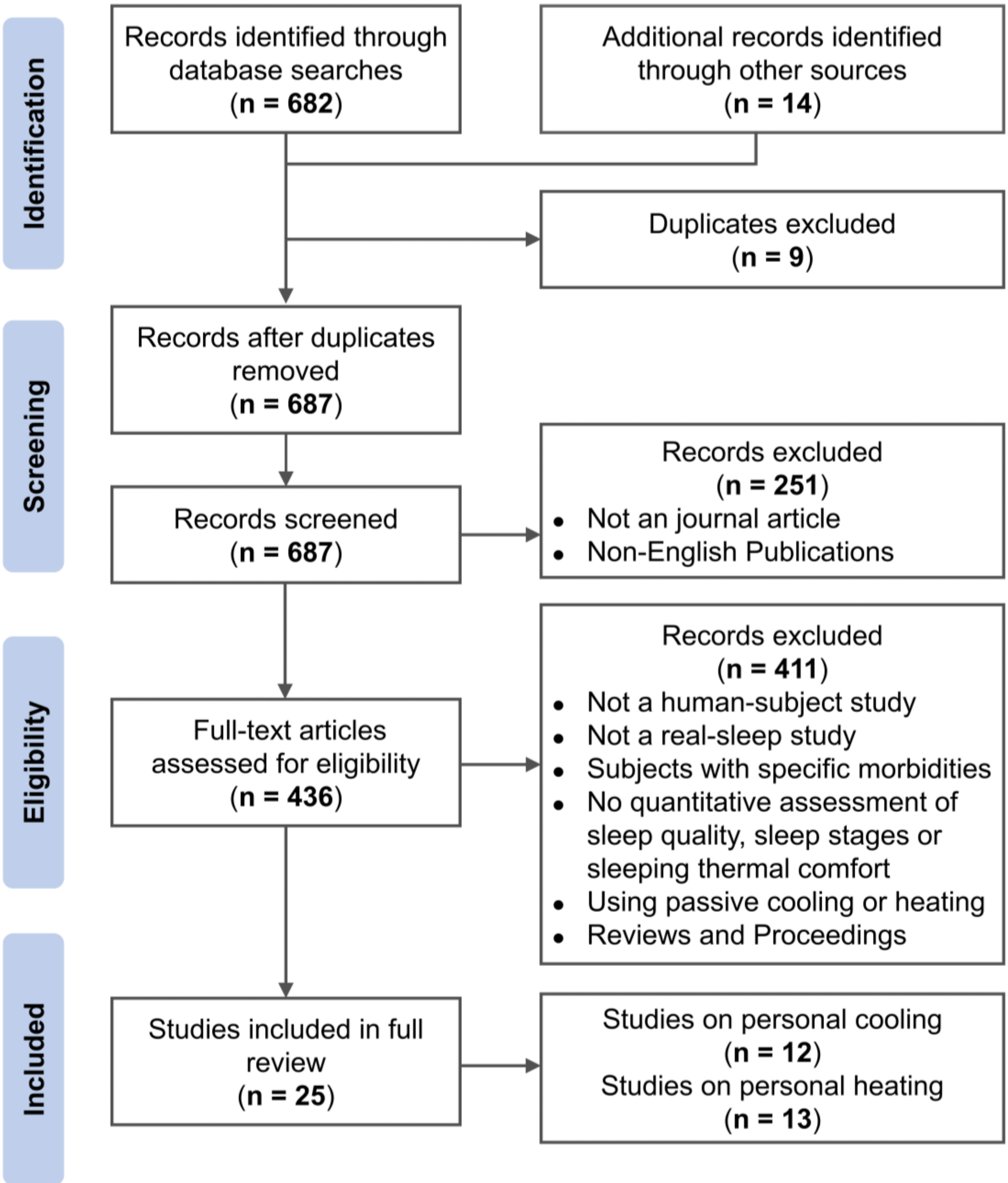

Fig. 1. Flowchart of the publication selection process.

2.3 Analytical framework

The analytical framework used in the literature review is illustrated in Fig. 3. The impact of PCS on sleep process was assessed separately for personal cooling and personal heating systems. Three key dimensions were considered: sleep quality, sleep stages and sleeping thermal comfort. Considering the consistency of metrics across sleep studies, objective sleep quality was chosen for analysis, and its indicators include SOL, SE, and WASO [31]. Shorter SOL and WASO durations, and higher SE indicate better sleep quality [32, 33]. The effects of PCS on the duration of sleep stages were quantified, with the classification of sleep stages primarily following the criteria set by the AASM (American Academy of Sleep Medicine) [15]. The evaluation of sleeping thermal comfort often includes thermal comfort votes obtained before falling asleep (pre-sleep phase, Fig. 2) and/or upon waking (post-sleep phase, Fig. 2). Votes are typically made on a standardized 6-point scale (-2: very uncomfortable, -1: uncomfortable, -0.01: just uncomfortable, 0.01: just comfortable, 1: comfortable, 2: very comfortable) [34].

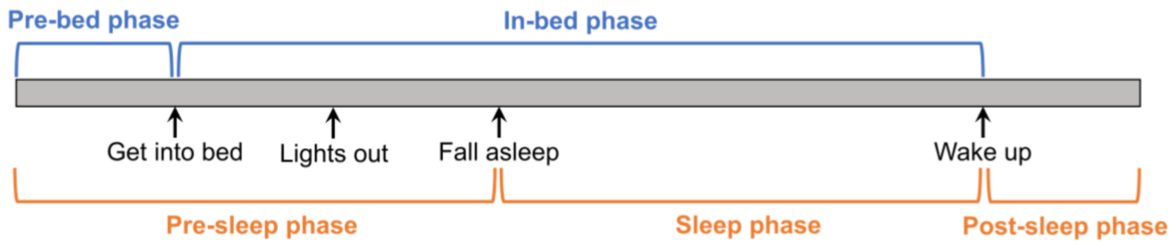

Fig. 2. Definition of research phases for sleep studies.

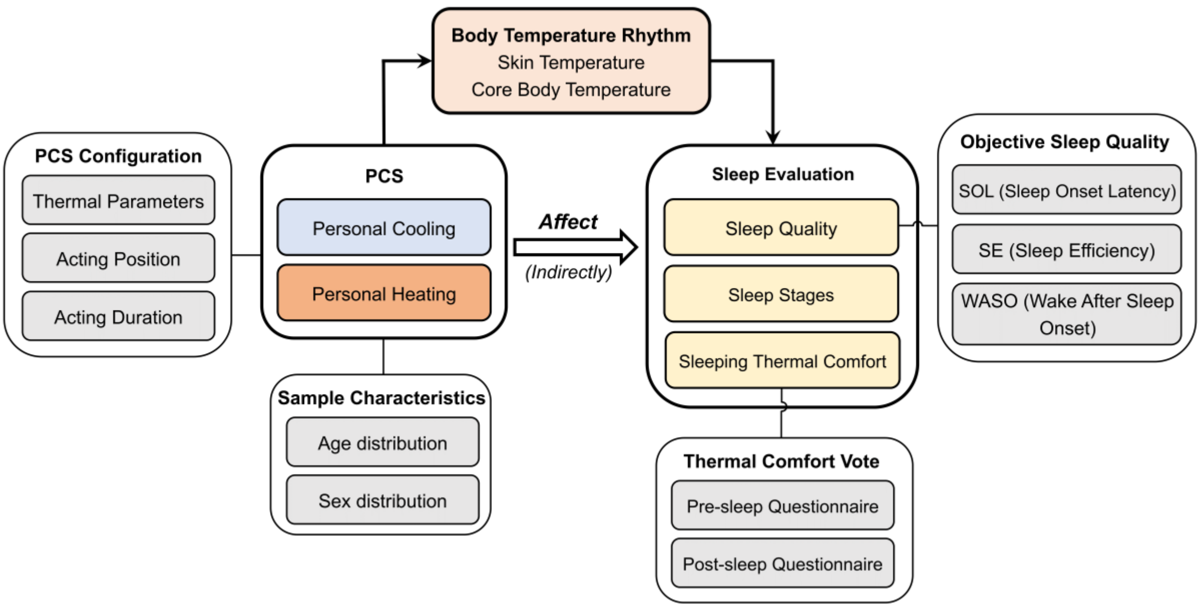

Fig. 3. Analytical framework of systematic review. The main frame shows the effects of adopting PCS on sleep process, with the body temperature rhythm act as a bridge connecting PCS and sleep. The left side shows information related to PCS and experimental setup, and the right side shows the specific metrics involved in the assessment of sleep process.

This systematic review aims to quantify the impacts of PCS on specific indicators of sleep quality, sleep stages and sleeping thermal comfort. Cohen's d was calculated to determine the effect size [35]. A positive Cohen's d indicates that the use of PCS led to an increase in the numerical value of a given indicator. Conversely, a negative Cohen's d indicates that the use of PCS led to a decrease in the numerical value of a given indicator. The thresholds of Cohen's d representing small, medium and large effect size are ±0.2, ±0.5 and ±0.8 respectively [35].

The configuration of PCS and sample characteristics of experiments were classified and analyzed. The PCS configuration [36] including thermal parameters, acting position, and acting duration are summarized and compared. The sample characteristics in the application scenarios of PCS, including age and sex distribution [37, 38], are also summarized and presented.

Furthermore, the physiological responses to PCS were analyzed, such as skin temperatures, as it is considered a bridge connecting external thermal interventions and sleep process [39, 40]. The other consideration is the practical applications of PCS, including the accessibility of devices and the limitations of current technologies.

3. Results

3.1 Overview of included literatures

Table 1 summarizes the basic information of the PCS used in the 25 selected articles. Most of the studies (92%) were published in the last 20 years, with 44% of them published in the last 5 years. Most of the studies were conducted in Asia, with 52% of the studies coming from China and 32% from Japan. There are an almost equal numbers of papers focusing on local cooling (12) and local heating (13). Convection and conduction are the primary forms of heat transfer for personal cooling systems; conduction is nearly the exclusive form of personal heating. In comparison to the reviews by Zhang et al. and Rawal et al. on PCS during wakefulness [41, 42], radiation heat transfer is absent in sleep studies. Some studies have analyzed the impacts of radiant devices on sleeping thermal comfort through numerical simulations [43, 44], but to our knowledge there are no studies with human subjects. An approach of personal heating utilizing warm water to soak the body has emerged in sleep research [45], which fulfills the requirements of screening criteria (2) but notably shifts the active use of PCS from within the 8-hour in-bed period to the pre-bed phase. In addition, almost all of the PCS using at pre-bed phase is via warm water immersion.

Table 1. Basic information of PCS in selected literatures. This includes the year of publication, the country where the study was conducted, and details of PCS and how it was used. Both pre-bed phase and in-bed phase are included.

Authors (year)	Country	Application target	Approach (Device)	Main form of heat transfer
Setokawa et al. (2007) [46]	Japan	Personal cooling	Pillow filled with water and ice	Conduction
Tsuzuki et al. (2008)[47]	Japan	Personal cooling	Fan box	Convection
Zhou et al. (2013)[48]	China	Personal cooling	Bedside personalized ventilation system	Convection
Lan et al. (2013)[49]	China	Personal cooling	Bedside personalized ventilation system	Convection
Morito et al. (2017)[50]	Japan	Personal cooling	Airflow from air conditioner	Convection
Lan et al. (2018)[51]	China	Personal cooling	Hypothermic blanket made of cellular tubes in which water flowed slowly	Conduction
Hamanishi et al. (2019)[52]	Japan	Personal cooling	Temperature-controllable cooling sheet containing tubes filled with circulating water	Conduction
Lan et al. (2019)[53]	China	Personal cooling	Task fan and ceiling fan	Convection
Li et al. (2020)[54]	China	Personal cooling	Temperature-controlled mattresses including circulating water pipes	Conduction
Du et al. (2022)[55]	China	Personal cooling	Fan	Convection
Yu et al. (2022)[12]	China	Personal cooling	Fan	Convection
Hu et al. (2023)[56]	China	Personal cooling	Thermal-conductive bed containing water pipes	Conduction
Fletcher et al. (1999)[13]	Australia	Personal heating	Electric blanket located between the mattress and bottom sheet	Conduction
Sung and Tochihara (2000)[57]	Japan	Personal heating	Hot water in container	Conduction
Okamoto-Mizuno et al.	Japan	Personal heating	Electric blanket placed under	Conduction

(2005)[58]			the bed sheet	
Ebben and Spielman (2006)[59]	USA	Personal heating	Hot water in container	Conduction
Zhang et al. (2016)[60]	China	Personal heating	Electrically heated sleeping bag containing a flexible carbon polymer heating pad	Conduction
Liu et al. (2016)[61]	China	Personal heating	Electric blanket placed under the bed sheet	Conduction
Kim et al. (2016)[62]	South Korea	Personal heating	Hot water in specially designed footbath machine	Conduction
Whitworth-Turner et al. (2017)[63]	UK	Personal heating	Hot water shower	Conduction & Convection
Ichiba et al.(2020)[64]	Japan	Personal heating	Warming eye mask	Conduction
Xia et al. (2020)[65]	China	Personal heating	Electric blanket (covering heating and mattress heating)	Conduction
Song et al. (2020a) [66]	China	Personal heating	Electric blanket placed under the bed sheet	Conduction
Song et al. (2020b)[67]	China	Personal heating	Electrical heating system containing three heating pads	Conduction
Maeda et al. (2023)[45]	Japan	Personal heating	Hot water in bathtub	Conduction & Convection

3.2 Effects of PCS on sleep quality

Fig. 4 shows the effect sizes of PCS on sleep quality (SOL, SE and WASO) from 23 studies. The application of cooling or heating PCS tends to reduce the length of SOL. This is reflected in the calculated effect size, all of which are less than 0, and the average effect size in both cooling and heating aspects could reach the medium range (<-0.5).

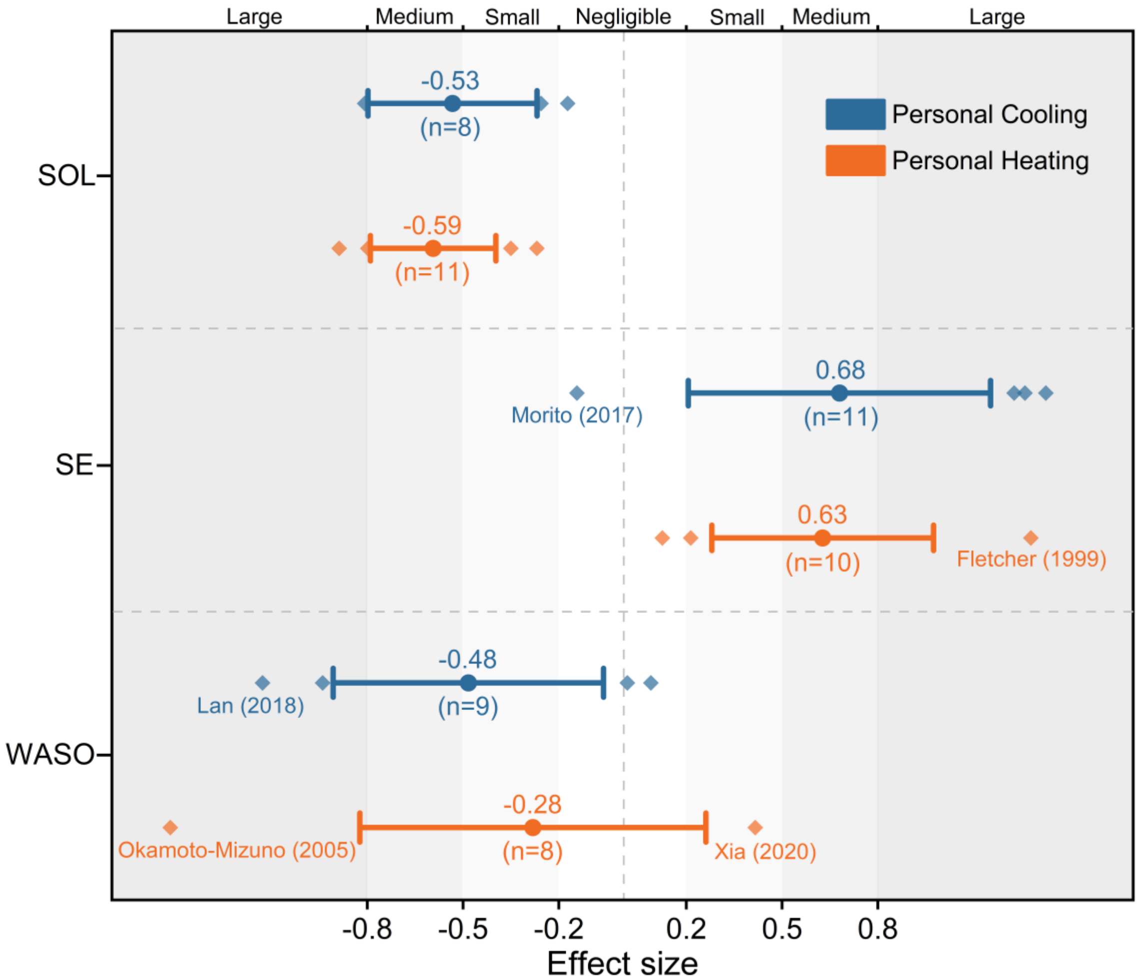

Fig. 4. Effect sizes of PCS on sleep quality indicators. The distribution of effect sizes is presented through the range "mean value ± standard deviation", i.e., the numbers displayed above the center point represent the mean values, and the intervals indicate the standard deviations. Diamond-shaped points represent studies that fall outside the intervals. The values shown after n represent the number of case studies for each indicator.

Studies that measured sleep efficiency generally reported an increase in SE when using PCS. Only one lab study of personal cooling reported a negative effect size [50] due to the potential disruption of sleep from irregular and high velocity air from an air-conditioner. Personal heating led to increases in sleep efficiency, with the average effect size across 10 studies corresponding with a medium effect. Hot water immersion effectively shortens sleep onset latency and increases total sleep time, thereby improving sleep efficiency. While electric blankets may suppress the occurrence of N3 stage (slow-wave sleep), light sleep (N1 and N2 stages) seem to act as substitutes [68], and hence, there was little impact on sleep efficiency.

Studies that measured wake after sleep onset generally reported a decrease in WASO when using PCS. Personal cooling can lead to an average medium effect size, and the most effective method appears in the back and head (neck) cooling of Lan et al.'s study [51]. Additionally, the noise generated by fans at high air velocities can significantly interrupt sleep [69], because awakenings can occur as people tend to reposition themselves to avoid the airflow flow from the air conditioner. Therefore, these negative aspects of high air movement may potentially undermine its positive effects on sleep in warm environments. In addition, personal cooling with conductive heat transfer seems to have fewer drawbacks [51, 52, 54] compared to convective heat exchange using air movement. The absolute value of effect size of personal heating was generally smaller than that of personal cooling, possibly because heating inhibits the decrease in core temperature and thus potentially may interfere with the sleep process.

3.3 Effects of PCS on sleep stages

Fig. 5 shows the effect sizes of PCS on sleep stages from 16 studies. The small effects ($0.2 < |\text{effect size}| < 0.5$) of personal cooling on reducing N1 duration and increasing N2 and REM duration can be seen in Fig. 5. Since REM sleep benefits the consolidation of non-declarative memory (procedural and emotional aspects of memory) [70], personal cooling may contribute to improving daytime cognitive functions, such as enhanced problem-solving abilities, better emotional regulation, and increased creativity.

One interesting finding is that the impact of personal cooling on N3 stage (slow-wave sleep) is the largest, which reports the use of personal cooling systems generally led to a substantial increase in slow-wave sleep with medium to large effect sizes. Since during slow-wave sleep, homeostatic sleep pressure is dissipated, and the consolidation of declarative memory is facilitated [70], personal cooling may be effective in enhancing daytime alertness and cognitive functions, such as improved attention span and better declarative memory recollection. The only negative effect comes from Morito et al.'s study, where reported a negative effect [50] of fluctuating airflow (peak V_a: 1.9 m/s) from an air conditioner on N3 sleep duration. Considering the beneficial effects of local cooling on both REM and N3 stages, local cooling may improve multiple cognitive functions.

Studies of personal heating systems all reported negligible impact in N3 sleep duration (< |0.2|). As explained earlier, the impact of warm water immersion is primarily a reduction in sleep onset latency, with little impact on the later stages of sleep [71]. While electric blankets can prevent cold stress in winter [58], sustained overnight use can increase local heat stress (especially between the back and mattress) [72]. This inhibits the normal decrease in core body temperature and may disrupt deep sleep [73]. For example, Xia et al.'s study of mattress heating reported an overall reduction of slow-wave sleep [65]. In overall, reported findings suggest that personal heating systems should be optimized to avoid warm discomfort after people have fallen asleep.

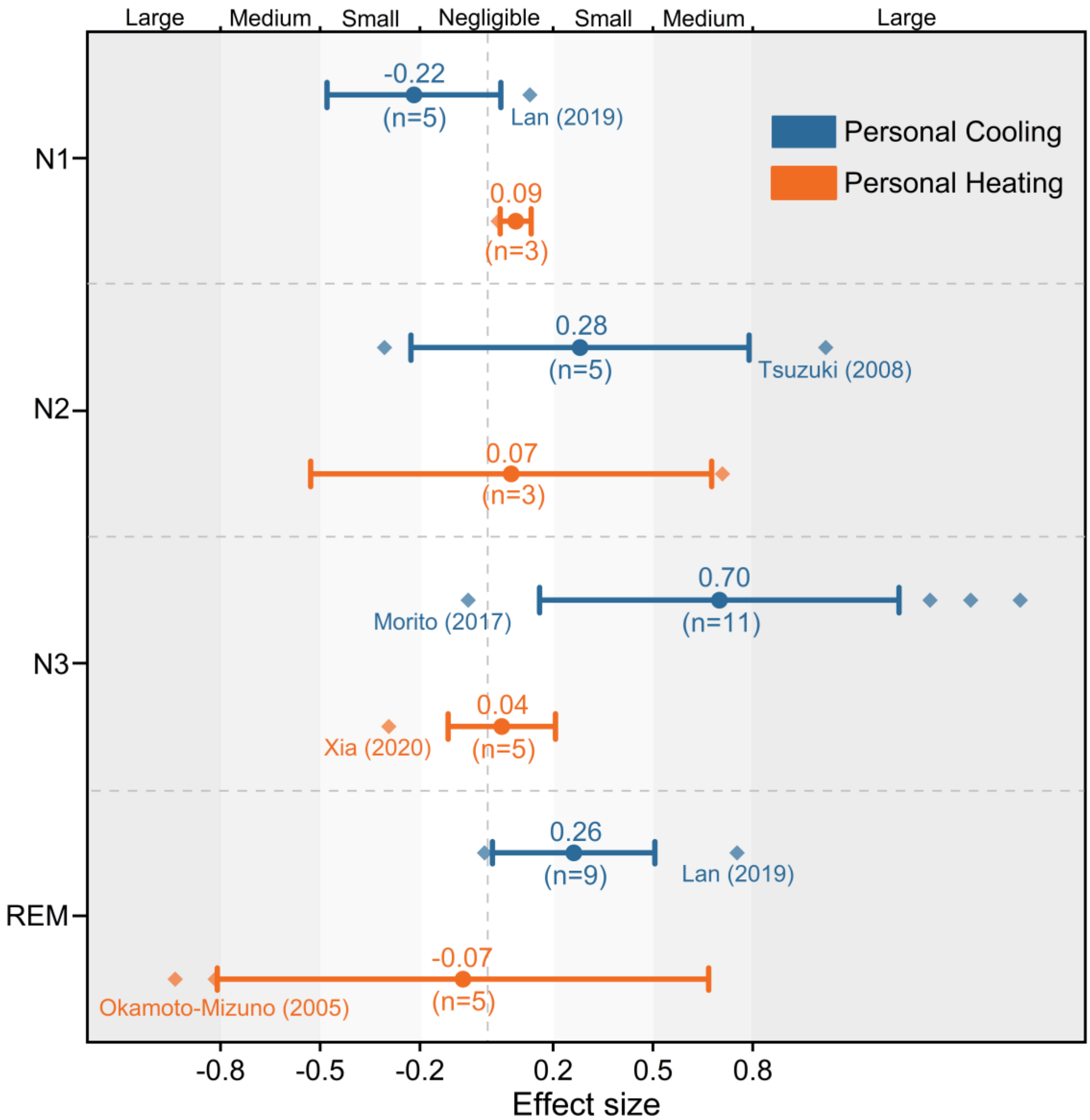

Fig. 5. Effect sizes of PCS on sleep stages. The four sleep stages are REM stage, N1 stage, N2 stage and N3 stage respectively. A few sleep stage 4 determined by Rechtschuffen and Kales criteria are included in the N3 stage [74]. The distribution of effect sizes is presented through the range "mean value ± standard deviation", i.e., the numbers displayed above the center point represent the mean values, and the intervals indicate the standard deviations. Diamond-shaped points represent studies that fall outside the intervals. The values shown after n represent the number of case studies for each indicator.

3.4 Effects of PCS on sleeping thermal comfort

The reported effect sizes of PCS on sleeping thermal comfort indicators from 18 studies are shown in Fig. 6. Personal heating has been found to effectively increase both pre-sleep and post-sleep thermal comfort vote (TCV), i.e., contributing to an increased sense of thermal comfort, while the positive effect of personal cooling is mainly seen at post-sleep time. Both personal cooling and heating are reported to have a more pronounced effect on improving post-sleep thermal comfort compared to pre-sleep thermal comfort. The wider distribution of effect size for personal cooling in the pre-sleep phase suggests there is no consensus on whether they improve thermal comfort.

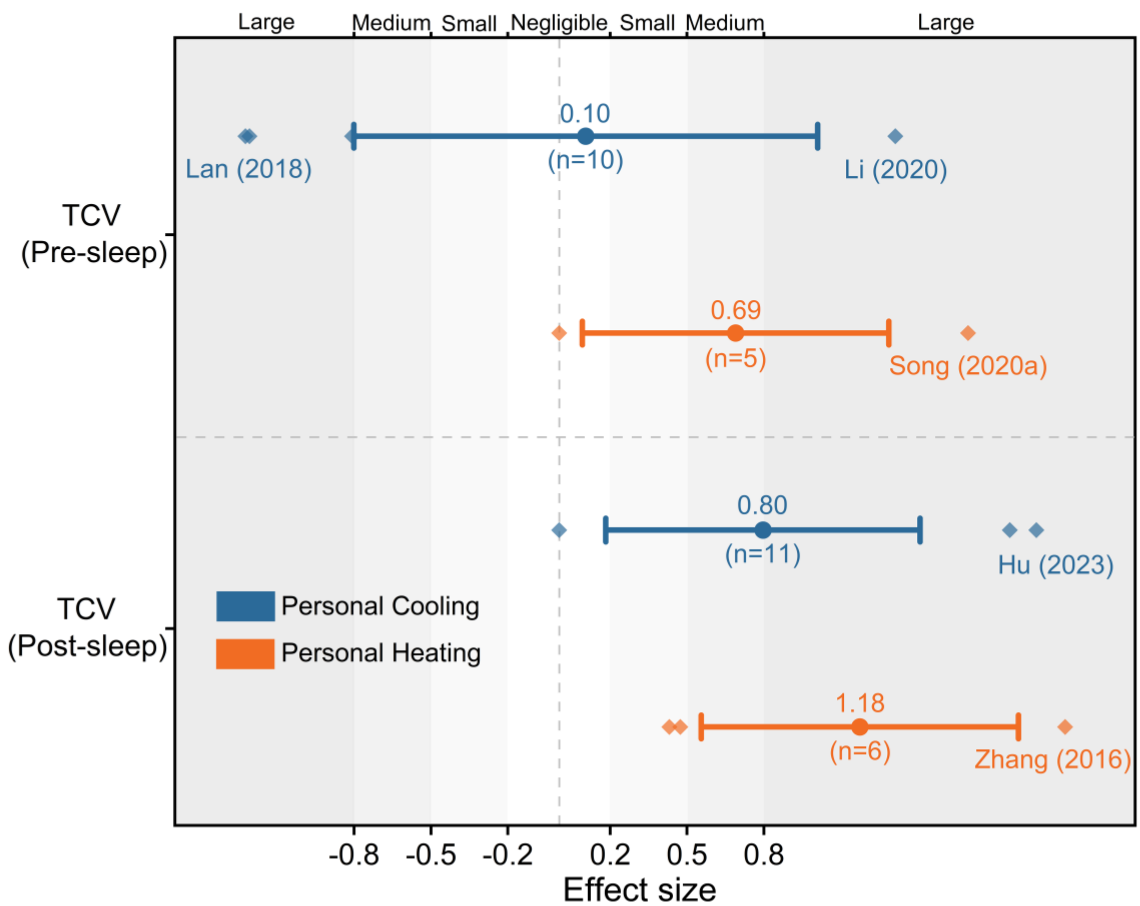

Fig. 6. Effect sizes of PCS on sleeping thermal comfort votes. The distribution of effect sizes is presented through the range "mean value ± standard deviation", i.e., the numbers displayed above the center point represent the mean values, and the intervals indicate the standard deviations. Diamond-shaped points represent outliers that fall outside the intervals. The values shown after n represent the number of case studies for each indicator.

Participants in some studies of personal cooling reported feeling less comfortable in the pre-sleep phase. Participants using a hypothermic blanket filled with 28°C water to cool their neck and back for 30 minutes before sleep at ambient temperature of 31°C to 32°C reported a decrease in pre-sleep thermal comfort compared to the non-cooling condition [51]. The same local cooling contributed to a higher level of post-sleep thermal comfort. This may be attributed to the increased skin temperature of the back [75-77] from the accumulation of heat between the back and mattress. There may therefore be less requirement for cooling in the pre-sleep phase, and cooling at this point may instead lead to cold discomfort. This is supported by other studies that found a detrimental effect on sleep structure from cooling in the first half of the sleeping period [78]. Careful control of the thermal environment to avoid cold discomfort during the pre-sleep and initial sleep phase is crucial to minimize disruptions in sleep structure.

3.5 PCS configuration

3.5.1 Thermal parameters

The summary of PCS in Table 1 shows that the common forms of heat transfer in existing systems is conduction and convection. Conduction typically involves direct contact between the device and the human body to achieve heat transfer for either cooling or heating. The contact temperature of material used in the PCS is therefore a critical design consideration. Contact temperatures used in the reviewed studies are summarized in Fig. 7 for both pre-bed (before going to the bed) and over-night temperatures. The contact temperatures for heating systems at pre-bed phase range between 38 to 42°C to optimize the potential reduction in sleep onset latency [71], as shown in the figure by the unshaded grey region. Such systems are often used in environments with relatively mild temperatures (around 20°C), suggesting they are used to facilitate sleep onset rather than minimizing cold stress overnight.

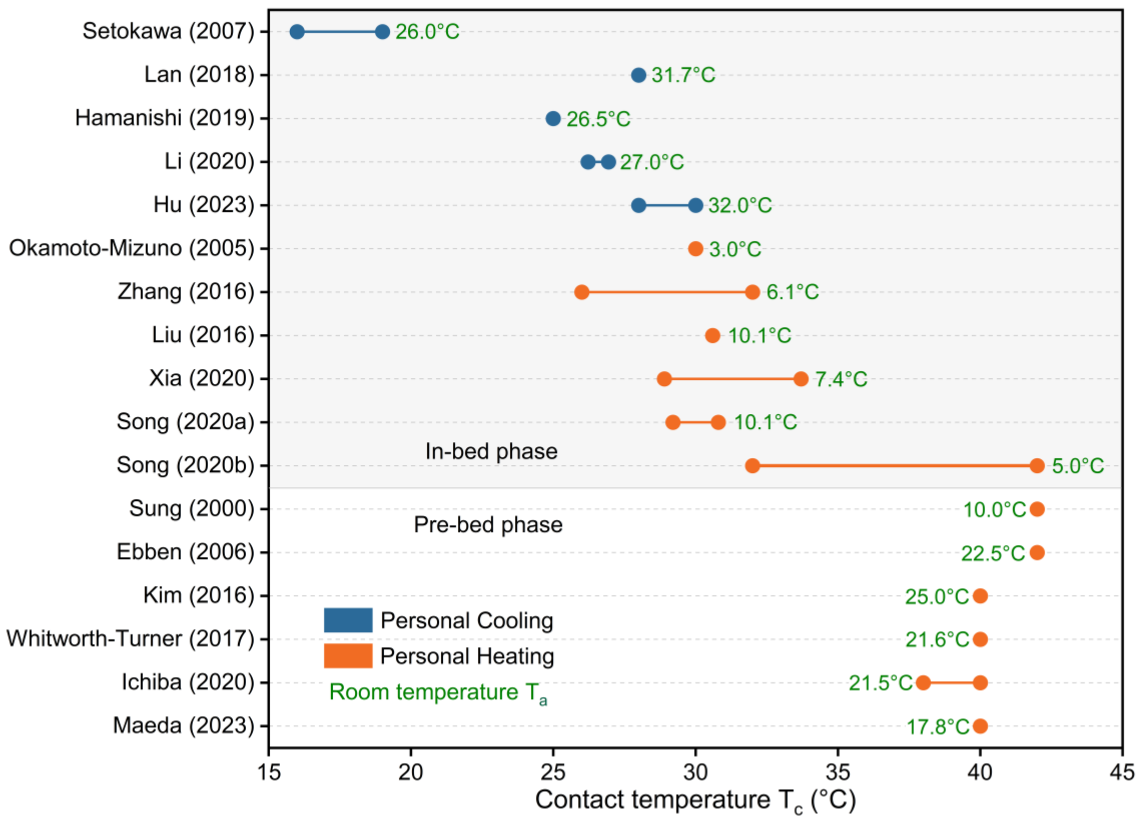

Fig. 7. Thermal parameters for conduction approaches. Systems applied during the pre-bed phase are shown with a white background, while those applied overnight are shown with a grey background. The inset temperatures are the reported room temperatures in the study.

The overnight bed temperature is shown in the grey-shaded area in Fig. 7. The heating contact temperatures used in studies during the in-bed phase is generally lower than those before getting into bed. Most used a surface temperature around 30°C, with the exception of 42°C used in Song et al.'s study [67]. The reason for this is assumed to be the focused heating of the feet, buttocks, and shoulders by pads; other studies applied heating to larger areas such as the entire bed by heated blanket. A smaller contact area requires a larger temperature difference to achieve the same heat transfer effect for conduction heating. For cooling, contact temperatures ranged between 25 and 30°C except in one study that tested 16°C [46]; this may similarly be attributed to a smaller contact area in that study (cool pillow) compared to the other larger area of a cool mattress.

The reviewed studies which use convective PCS devices like fans didn't supply cooled air. The temperature of the airflow is equal to room temperatures, so airflow velocity is the most relevant parameter. The velocities tested in the reviewed studies are summarized in Figure 8. Most studies tested velocities below 0.9 m/s, except for the study by Tsuzuki et al. [47, 50] which had relatively high velocities (<1.9 m/s).

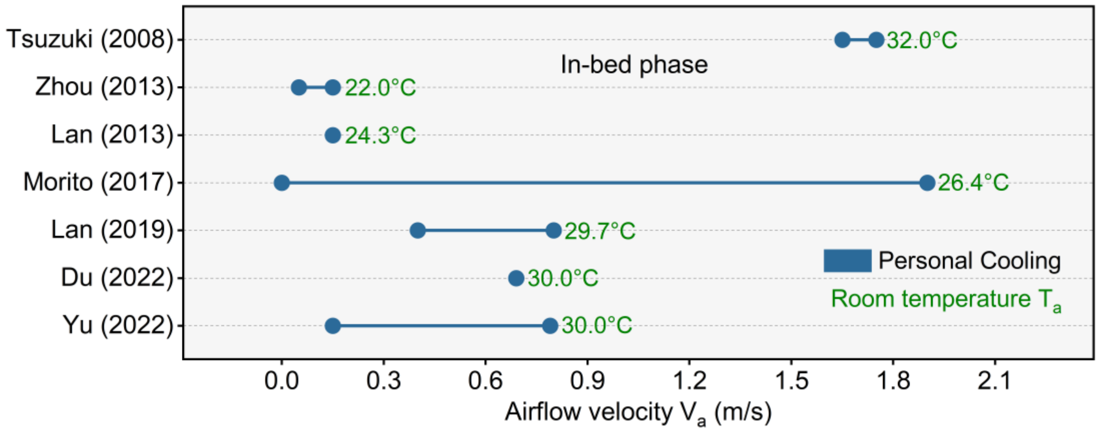

Fig. 8. Thermal parameters for convection approaches. Velocities are measured near the bed or subject, rather than at the outlet of devices. The inset temperatures are the reported room temperatures in the study.

3.5.2 Acting position

The position of the PCS governs where the device/approach will influence the heat transfer across the body's surface. This information is important as the temperature of specific body regions may affect sleep [79]. The position of PCS in the reviewed studies are shown in Table 2. Most devices target similar areas due to the nature of common PCS, such as heating and cooling mattresses. Some exceptions involve tailored approaches that target specific areas, such as personal airflow directed solely at the head [48] or immersing only hands and feet in hot water [59]).

Table 2. Body parts affected by the PCS and the affected times (%) in selected literatures. Target body sites are defined based on the traditional human multi-node models [80-82]. Chest and abdomen were combined into one node denoted as the "Front-trunk".

Ref.	Head	Front-trunk	Back-trunk	Upper arm	Forearm	Hands	Thigh	Calf	Feet

Setokawa (2007)		✓								
Tsuzuki (2008)		✓	✓		✓	✓	✓	✓	✓	✓
Zhou (2013)		✓								
Lan (2013)		✓								
Morito (2017)		✓	✓		✓	✓	✓	✓	✓	✓
Lan (2018)		✓		✓						
Hamanishi (2019)		✓								
Lan (2019)		✓	✓		✓	✓	✓	✓	✓	✓
Li (2020)				✓	✓	✓	✓	✓	✓	✓
Du (2022)		✓	✓		✓	✓	✓	✓	✓	✓
Yu (2022)		✓	✓		✓	✓	✓	✓	✓	✓
Hu (2023)				✓	✓	✓	✓	✓	✓	✓
Fletcher (1999)				✓	✓	✓	✓	✓	✓	✓
Sung (2000)			✓	✓	✓	✓	✓	✓	✓	✓
Okamoto-Mizuno (2005)				✓	✓	✓	✓	✓	✓	✓
Ebben (2006)							✓			✓
Zhang (2016)										✓
Liu (2016)				✓	✓	✓	✓	✓	✓	✓
Kim (2016)										✓
Whitworth-Turner (2017)		✓	✓	✓	✓	✓	✓	✓	✓	✓
Ichiba (2020)		✓								
Xia (2020)			✓	✓	✓	✓	✓	✓	✓	✓
Song (2020a)				✓	✓	✓	✓	✓	✓	✓
Song (2020b)				✓	✓	✓	✓	✓	✓	✓
Maeda (2023)		✓	✓	✓	✓	✓	✓	✓	✓	✓
Occurrence probability of acting positions	Personal cooling at in bed phase	**83%**	42%	25%	58%	58%	58%	58%	58%	58%
	Personal heating at pre-bed phase	50%	50%	50%	50%	50%	**67%**	50%	50%	**83%**
	Personal heating at in-bed phase	0	14%	86%	86%	86%	86%	86%	86%	**100%**

Sleeping subjects mostly maintained a supine sleeping posture where personal cooling with airflow (typically from fans) can generally target the front of most body regions except the back-trunk [12, 47, 50, 53, 55]. Placing the fan at the foot end of the bed resulted in similar velocities at the feet (1.7 m/s) and head (1.4 m/s) ends of the bed [47], indicating whole-body convective cooling rather than a targeted body site. In contrast, personal heating [13, 58, 61, 66] or cooling [54, 56] through the mattress primarily involves heat transfer with the back of most body regions except front-trunk and head, where the thermal insulation of the pillow hinders heat conduction from the mattress to the head.

The occurrence probability (%) of different acting positions was calculated. It is defined as the percent of reviewed studies that have PCS target on each position, and the results are shown in Table 2. It can be observed that the head is the most popular cooling body part (83% at in-bed phase), while feet are the most popular heating body part (83% at pre-bed phase and 100% at in-bed phase). Almost all cooling scheme involve the head, except for a few cases of cooling beds [54, 56]. Heating the head is always avoided even in winter, and the only instances of heating head before sleep occur during showers [45, 63]. Personal heating during the pre-bed phase is often achieved by immersing partial body into warm water; during this phase, special attention is given to the hands and feet, with some studies specifically focusing on immersing only these two body parts [59]. Personal heating during the in-bed phase is primarily achieved through electric blankets/pads/mattresses, which includes both commercially available products and devices designed by researchers; regardless of the device type, heating feet is very important [83].

3.5.3 Acting duration

Most PCS are used during the in-bed phase and function continuously throughout the entire night (approximately 8-hours). However, some studies used PCS during the pre-bed phase to facilitate sleep onset. The duration of use of the personal heating systems in those six studies are summarized in Table 3. Most of the studies used pre-bed heating for about 20 minutes or more. The study with only 5 minutes of heating [59] used the highest contact temperature (42°C) of any of the reviewed studies. While a larger temperature difference may compensate for a shorter duration of use, there is a risk of thermal discomfort due to high temperatures [84, 85].

Table 3. Acting durations of PCS at pre-bed phase in selected literatures.

Ref.	Acting duration (min)
Sung (2000)	20 to 30
Ebben (2006)	5
Kim (2016)	30
Whitworth-Turner (2017)	30
Ichiba (2020)	60
Maeda (2023)	5.2 to 16.1

3.6 Sample characteristics

The participants of most studies (75%) were within the range of 17 to 40 years old (Fig. 9). This suggests there is insufficient evidence to demonstrate the impacts of PCS on sleep for children and the elderly. The only reviewed study focusing on children [49] reported no significant differences between age groups (children aged 6 to 14, young and middle-aged people aged 20 to 55, and elderly aged over 60) when applying cooling to the head. However, both the subjective and physiological responses of children have been shown to be more tolerant of a given thermal environment compared to their parents [86]. Other studies also support the idea that thermoregulation and thermal comfort of children may differ from those of adults [87-89]. There is a need for better understand how to appropriately use PCS to improve children's sleep.

Relevant research is also scarce for people aged over 60. Compared to young adults, this is surprising given the potential for use of PCS in the elderly population is likely to be greater as their thermoregulatory capacity weakens [90, 91]. This is especially true in hot and humid environments where elderly people are more susceptible to heat stress [92]. The use of PCS to help improve sleep in elderly populations holds promise and warrants further research.

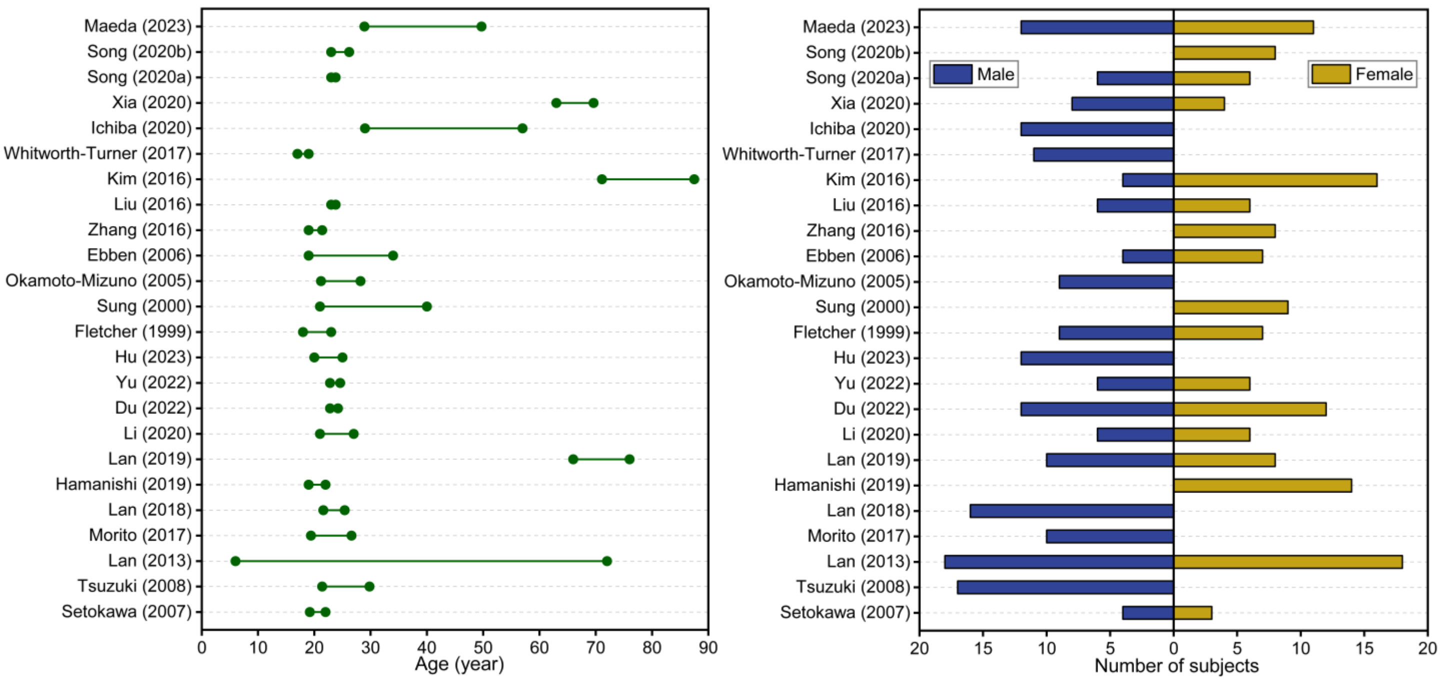

Fig. 9. Sample characteristics in selected publications. On the left is the age distribution of subjects in each study, and on the right is the sex distribution of subjects in each study, i.e., the number of males and females counted.

As shown in Fig. 9, the majority of studies included both male and female participants (54%), while others focused on a single sex (17% female, 29% male). There has been no in-depth analysis of potential differences in the effects of PCS on females and males. Given that females have been shown to prefer a higher temperature during sleep than the males [93], it is possible that PCS settings should vary with sex. Further evidence is needed to address any potential optimizations of PCS for sex.

4. Discussion and future work

4.1 Physiological basis of PCS for sleep

The bedroom thermal environment and the bedding system microenvironment primarily affect sleep by influencing body temperature [94, 95]. PCS fundamentally serve as heat exchangers that provide more energy efficient and optimized modulation of human body temperature (core and skin temperatures) compared to conventional whole room heating and cooling system [96]. The use of personal cooling can decrease mean skin temperature [49], while personal heating can increase mean skin temperature [61]. PCS has also been shown to influence core body temperature through modulation of the thermoregulatory system [97]. In a series of sleep studies by Tsuzuki et al. [47, 78, 98], the use of an electric blanket resulted in a significant increase in rectal temperature compared to conditions without the electric blanket. In the sleep study conducted by Song et al. [67], intestinal temperature measured through swallowable capsule sensors indicated that the use of heating pads slightly increased core body temperature.

The ability of PCS to influence human body temperature is important as the thermoregulatory system is linked to sleep [39, 99, 100]. Body temperature is often considered as an important signal for the transitions between sleep stages [100], as both thermoregulation and sleep regulation are governed by the preoptic/anterior hypothalamus in the brain [101]. The variations in skin temperature of the hands, feet, head have been demonstrated to be useful for predicting the duration of sleep onset latency [75], where a reduction in the temperature gradient between distal and proximal regions serves as a necessary prerequisite for falling asleep [102, 103]. Furthermore, core body temperature serves as the brain's feedback to the temperature signals transmitted from thermoreceptors [104, 105]. Park et al. observed variations in metabolic rates across different sleep stages, with implications for core body temperature changes associated with the metabolic variations [106]. A classification model was recently proposed by Xu and Lian to further illustrate the quantitative relationships between core body temperature and four sleep stages (N1, N2, N3, and REM) [107]. These findings illustrate how PCS can reinforce important physiological functions connected to sleep by first influencing body temperature and then helping regulate sleep rhythm.

4.2 Accessibility of PCS

In this context, the accessibility of PCS refers to easiness for a user to obtain and operate the device. The accessibility is considered high if one can easily purchase and operate the devices, and low if the PCS is a bespoke device used only in research. The accessibility of heating and cooling devices for sleeping is important as it determines the potential of that solution to meaningfully improve sleep quality.

Personal cooling systems in the reviewed literature were fans (42%), cooling conductive materials (42%), or bespoke airflow systems (16%). The accessibility of fans is the highest, as they are commercially available and widely used [11, 108-110]. In contrast, cooling conductive materials and bespoke airflow systems were generally developed and assembled in the laboratory by researchers, and thus are difficult to purchase and operate for everyday use. While Lan et al. claimed that their cooling conductive material was a commercial hypothermic blanket used in hospitals for cryotherapy [51], they did not provide relevant information like the product name or manufacturer. Such products are generally less available for the average consumer and are therefore low accessibility.

Personal heating systems were either electric blankets/mattresses (38.5%), heating conductive materials (23%), or hot water (38.5%). The accessibility of hot water is the highest, and it can be easily implemented using containers or water bottles [111, 112]. The accessibility of electric blanket is also relatively high, and is already widely used and commercially available [113, 114]. The heating conductive materials, however, generally refer to self-made devices like the sleeping bag designed by Zhang et al. [60], and thus with the lowest accessibility.

4.3 Limitations and considerations

While PCS are able to improve sleep while reducing energy use compared to traditional air-conditioning systems, there are practical considerations and challenges that might limit their implementation. The widespread use of fans, hot water, and electric blankets offer useful case studies for the discussion.

Using hot water in direct contact with the body for improving sleep is generally limited to the wake period before falling asleep (such as hot water immersion or shower). This approach can reduce the duration of SOL, but has smaller effects on the overnight 8-hour sleep structure [57, 63]. Therefore, the application of hot water should be combined with in-bed PCS to cover the entire sleep duration.

Electric blankets are commonly used in winter to elevate the temperature of the bedding microenvironment [115]. While electric blankets generally enhance sleeping thermal comfort (Fig. 6), prolonged use can lead to warm discomfort that might interrupt sleep [58]. Sleep onset is typically accompanied by a decrease in core body temperature, which continues to drop until reaching a nadir about 2 hours before habitual wake time [116]. Therefore, the surface temperature of electric blanket should not be excessively high during this period, and it should be used only in low ambient temperatures [58]. It would be beneficial for the surface temperatures to be automatically regulated to gradually decrease during the first half of sleep, aligning with the thermal physiology of the sleeping individual.

Extreme weather events such as heat waves are more likely to occur in the future due to climate change [117]. The associated change in nighttime temperatures makes the application of personal cooling systems highly relevant to bedroom environments. Fans are the most commonly used personal cooling systems; however, their air velocities must be carefully controlled in sleep scenarios. Morito et al. suggested that individuals tend to avoid high speeds (e.g. 1.9 m/s peak) while sleeping [50]. Other studies reported a preference for stable airflow during sleep (0.15 m/s) [49] when compared to intermittent airflow (0.6 m/s) [118]. Noise generated by fans may potentially disrupt the sleep process, particularly when the peak noise level exceeds 45 dB(A) [119]. Fans using direct current brushless motors are more energy efficient and generate less noise [120]. The use of fans during sleep should therefore meet three requirements: the velocity should not be too high; the velocity should not fluctuate, and low operating noise.

Most thermal interventions for sleep environments target the entire bedroom space. As a result, there were only 25 studies that met the inclusion criteria for this review. While this number is adequate for a systematic review [121-123], the limited diversity of PCS tested in the reviewed studies - a significant proportion involved fans and electric blankets/mattresses - may restrict the generalizability of the results in practical applications.

4.4 Future work and perspective

4.4.1 Personal cooling at pre-bed phase

Existing studies of PCS in the pre-bed phase (before going to bed) focused exclusively on personal heating. This implies a gap in our understanding of what individuals should do before going to bed in hot climates to facilitate sleep onset. Personal heating of the distal regions (hands and feet) before sleep is intended to reduce the temperature gradient between distal and proximal body parts [75, 102]. But the same can be achieved by cooling proximal body parts to narrow the distal-proximal temperature gradient. Could it be possible that cooling proximal body parts (chest, head) at pre-bed phase could also be beneficial for promoting sleep onset? Future research should explore this hypothesis to determine whether PCS cooling can be used to expedite the onset of sleep in hot climates.

4.4.2 Radiant cooling and heating

The PCS used in the reviewed studies generally used convective and conductive heat transfer to influence the body temperature of participants. While there are simulation studies about radiative heat transfer devices for sleep environments [43], there is lack of human-subject tests that to provide an understanding of the impact of radiative devices on sleep quality and sleeping thermal comfort. The use of radiative heat transfer devices can efficiently maintain comfort by warming the human body directly [124-126], which proves to be of great potential for applications. Future research should apply radiative devices [43, 44] to studies of human-subject sleep experiments to quantifying their values.

4.4.3 Dynamic PCS control strategy

Most of the reviewed PCS devices were operated with constant settings and positions. The control logic could also be based on personal or cohort comfort models [127, 128]. The only dynamically operated device appears in the study by Yu et al. [12], where the air velocity varies with changes in skin temperature. There are two main reasons why dynamic PCS might be more suitable for sleeping environments. First, the sleep process usually lasts many hours. Constant thermal stimuli applied to local body areas over an extended period is likely to lead to warm or cool discomfort because thermal physiology changes over the course of night. The use of an electric blanket throughout the night leading to excessively high skin temperature of the back [129] is a clear example of this. Second, the thermal physiological state and regulatory capacity changes during sleep. Metabolic rate often experiences a sustained decrease in the first half of an 8-hour sleep period [30]. A PCS device should not suppress the decline of metabolic rate and core body temperature during this phase. In the latter half of the sleep period, which includes the predominant REM sleep, the thermal regulatory capacity weakens [130, 131]. The use of PCS in this phase should be designed to ensure the sleeping person is as close to thermal neutrality as possible. Moreover, a personalized dynamic PCS control strategy should account for individual differences in thermal preferences and thermoregulatory capacities [132, 133], as well as the varying requirements of different sleep stages. Tailoring PCS control strategies for specific target populations and implementing real-time regulation based on user behavior and feedback during operation may be necessary.

4.4.4 Machine learning approach in PCS application

PCS aims to deliver personalized environments tailored to the thermal preferences of individuals. By analyzing databases to interpret physiological and psychological differences, a machine learning approach may enable the design and operation of PCS to achieve smarter control while further reducing energy consumption [134-137]. At present, research on applying machine learning approaches to control PCS in sleep environments is limited. Previous research revealed significant individual differences in both skin temperature and core body temperature during sleep [30, 107]. Moreover, compared to analyzing a comprehensive database that includes all individuals, model accuracy significantly improves when analyzing the database of single subject [107]. Therefore, future research on sleep PCS should consider integrating machine learning methods to analyze data on thermal environment, body temperature, sleep stages, and sleeping thermal comfort, thereby enhancing the understanding of individual differences and improving the effectiveness of personalized control.

5. Conclusions

This systematic review of 25 studies examined the application of PCS in sleep research. The impact of PCS on sleep was evaluated from three dimensions - sleep quality, sleep stages and sleeping thermal comfort. An overview of PCS configurations and sample characteristics were provided to contextualize the findings. The main conclusions were:

(1) Personal cooling is effective in enhancing sleep efficiency, and reducing sleep onset latency and wake after sleep onset. Personal heating significantly shortens sleep onset latency and increases sleep efficiency. However, the impact of personal heating on wake after sleep onset might be consistent, as heating inhibits the decrease in core temperature and may interfere with the sleep process.

(2) Personal cooling generally led to an increase in slow-wave sleep (N3 duration) with medium to large effect sizes. Small effects ($0.2 < |\text{effect size}| < 0.5$) were reported for personal cooling in reducing N1 duration and increasing N2 and REM durations. The impact of personal heating on most sleep stages was negligible.

(3) Both personal cooling and heating systems increased pre-sleep and post-sleep thermal comfort. However, a personal cooling blanket may decrease thermal comfort when subjects initially get into bed. Careful control of PCS is therefore crucial in avoiding initial cold discomfort in the pre-sleep phase and warm discomfort that disrupts sleep throughout the night.

(4) PCS should be configured to deliver relatively mild conditions to avoid disrupting sleep. During the pre-bed phase, the contact temperature for heating devices was typically set between 38 and 42°C. During the in-bed phase, the contact temperature for heating and cooling were generally set around 30°C and from 25 to 30°C, respectively. Air speeds for cooling are usually below 0.9 m/s. Cooling the head and heating the feet are the most common approaches.

(5) The majority of subjects in the reviewed studies were aged between 17 to 40 years, indicating a lack of data for children and the elderly. Different age groups should be given equal attention in sleep research as both body temperature rhythm and sleep patterns undergo significant changes with age. Moreover, the application of PCS for older populations could be

particularly impactful given their vulnerability to adverse thermal environments.

(6) The application of PCS in future sleep studies is expected to develop in four directions: introducing personal cooling into the pre-bed phase to address the research gap in hot climates; conducting practical human trials on radiant cooling and heating; developing and implementing dynamic PCS control strategies to align with human thermal physiological rhythms; integrating machine learning approaches for PCS application.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

Acknowledgements

This research was partly funded by the industry consortium members of the Center for the Built Environment (CBE), University of California, Berkeley and partly funded by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) program.

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