

Dynamic thermal sensation and energy consumption during the whole process of showering

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Abstract. The bathroom environment significantly influences individuals' thermal sensation and energy consumption during showering. However, most previous studies only focused on the showering periods. The effects of these factors on occupants' thermal sensations during undressing and dressing periods remain ambiguous. Therefore, this study examines occupants' dynamic thermal sensation (DTS) and energy consumption within bathrooms throughout showering, encompassing undressing and dressing periods. A database including four main environmental parameters, i.e., air temperature, water temperature, water flow rate, and ventilation rate, was generated using the Monte Carlo sampling technique. Taking these parameters as inputs, occupants' DTS and energy consumption during undressing, showering, and dressing periods were calculated using the energy consumption and thermal sensation models adapted from previous studies. The results reveal that most energy was consumed during showering, with water flow rate identified as the primary factor influencing energy use in this period. In contrast, air temperature and ventilation rate are more impactful during undressing and dressing. A reduced water flow rate is recommended to improve energy efficiency, maintaining air temperatures around 27°C and water temperatures at approximately 37°C for a neutral thermal sensation. These suggestions could create thermally comfortable and sustainable bathroom environments, enhancing energy conservation without compromising occupants' well-being.

1. Introduction

Bathroom environmental variables, including air temperature, humidity, and air velocity, substantially influence individuals' thermal perceptions, particularly during showering [1]. Prior investigations have indicated that air temperature is the predominant factor influencing individuals' thermal sensations when subjected to ambient air [2]. Recently, several studies have commenced exploring occupants' thermal sensations in the presence of water, i.e., during showering, revealing that water temperature demonstrates the most significant impact [3], [4]. Nevertheless, the significance of air temperature should not be overlooked in that situation. Both air and water temperatures play a pivotal role in influencing the mean skin temperature (MST) and the dynamic thermal sensations (DTS) during showering [4], [5]. Conversely, the effects of environmental factors on occupants' thermal sensations during undressing and dressing, that is, before and after showering, remain ambiguous. Since these intervals are relatively brief and

atypical, scant attention has been devoted to these transitional periods in existing research. Moreover, most previous studies on thermal comfort focused on average thermal sensation during steady states. Considering occupants' changing states (including activities and clothing insulation) during the undressing and dressing periods, variations in their thermal sensations are to be expected. Consequently, a more comprehensive examination of occupants' dynamic thermal sensations during showering is warranted.

In addition to thermal comfort, the environmental parameters of bathrooms also significantly impact energy consumption, particularly during showering [6]. Statistics indicate that the energy used for domestic hot water has increased considerably during the past decades [7]. Yet, few studies have explored energy consumption during showering, with most of these inquiries concentrating on energy-saving technologies [8]–[10]. For example, Wong et al. [11] proposed a heat recovery measure and estimated its energy-saving potential; Sayegh et al. [12] analyzed the performance of a greywater heat recovery system; Hari et al. [13] compared several energy-saving technologies used in bathrooms and summarized the opportunities and challenges faced by property developers, technology companies and researchers. Despite these extensive investigations, barely any studies have explored the correlations between thermal comfort (or environmental parameters) and bathroom energy consumption. Previous studies on thermal comfort and energy consumption implied that maintaining a thermally comfortable environment might be challenging while simultaneously saving energy [14]. A similar dilemma is expected in bathrooms during showering. Therefore, it is essential to understand the relationship between thermal sensation and energy consumption to identify a relatively balanced configuration that could reconcile thermal comfort and energy consumption in bathrooms.

Therefore, this investigation examines the thermal perception and energy utilization within bathrooms throughout the showering process, encompassing both the periods of undressing and dressing. Through analyzing these two variables under varying conditions, this research attempts to elucidate the relationship between the occupants' dynamic thermal perception and energy consumption across diverse showering contexts, ultimately culminating in recommendations to enhance comfort and efficiency.

2. Methods

2.1 Dynamic thermal sensation calculation

The DTS during showering is influenced by environmental parameters (including water temperature, air temperature, and relative humidity) and individual characteristics of the occupants (such as gender, height, and weight). Using these parameters as inputs, a recent study proposed a mathematical model to calculate the MST and DTS during showering based on equations 1-13 [5].

$$M = C + R + E + Q \quad (1)$$

$$M = \beta \times C_w + (1 - \beta) \times (C + R + E_{evap,max}) + E_{res} + C_{res} + Q \quad (2)$$

$$C_w = \alpha_{cw} \cdot (T_{skin} - T_w) \quad (3)$$

$$C = \alpha_c \times (T_{skin} - T_a) \quad (4)$$

$$R = \alpha_r \times (T_{skin} - T_r) \quad (5)$$

$$E_{evap,max} = 16.5 \times \alpha_c \times (P_{sk,sat} - P_a) \times 10^{-3} \quad (6)$$

$$P_{sk,sat} = 225.24 \times (35.7 - 0.0275 \times M) - 2493.1 = 5114.38 \quad (7)$$

$$E_{res} + C_{res} = 0.0014 \times M \times (34 - T_a) + 0.0017 \times M \times (58.7 - P_a/133.3) \quad (8)$$

$$P_a = RH \times 133.33 \times 10^{(8.07 - 1730.63 / (233.43 + T_a))} \quad (9)$$

$$Q \times A_{sk,seg} = M_{sk,seg} \times c \times \Delta T \quad (10)$$

$$A_{sk,total} = 0.202 \times weight^{0.425} \times height^{0.725} \quad (11)$$

$$T_{sk,mean} = 0.35 \times T_{trunk} + 0.14 \times T_{arm} + 0.32 \times T_{leg} + 0.07 \times T_{head} + 0.07 \times T_{feet} + 0.05 \times T_{hand} \quad (12)$$

$$DTS = -25.119 + 0.746 \times T_{sk,mean} + 2.255 \times dT_{sk,mean} \quad (13)$$

Where M is the metabolic rate, which is 87 W/m² (1.5 MET) during showering; C is the convection heat exchange rate between the human skin and the air (W/m²); C_w is the convection heat exchange rate between the human skin and the water close to the skin (W/m²); β is the ratio of the area that is continuously covered with flowing water to the area of the whole body segment (-); R is the radiation heat exchange rate between human skin and the ambient environment (W/m²); E is the heat exchange rates by evaporation (W/m²) when the skin is covered by water film, the evaporation from the skin surface reaches to its maximum level (E_{max}); E_{res} and C_{res} are the heat transfer via the respiratory tract (W/m²); Q is the net heat gain or loss of the body (W/m²); α_c and α_r are the convective and radiative heat transfer coefficients between the human skin and air (W/(m²·K)); T_{skin}, T_a, and T_r are skin temperature (K), air temperature (K), and radiant temperature (K), respectively; P_a is the ambient vapor pressure (Pa); RH is the relative humidity (%). All of these values were determined according to the study conducted by Mui et al. [5].

However, this study only investigated the undressing and showering periods, neglecting the subsequent dressing period after showering. Therefore, a similar method was adopted in the current study, encompassing the whole showering process, including 7 minutes of undressing, 10 minutes of showering, and 8 minutes of dressing.

2.2 Energy consumption calculation

Given the scarcity of research addressing energy consumption during showering, Zhang et al. [6] adopted the equation (i.e. equation 14) used in fire engineering to establish the correlation between the energy consumption rate and the environmental parameters in bathrooms, as shown in equation 15. However, this equation was explicitly developed for the showering period. Using

a similar approach, an updated equation (i.e., equation 16) was proposed to target the periods of undressing and dressing.

$$\frac{\Delta T_g}{T_\infty} = 0.63 \left(\frac{Q}{m_a c_p T_\infty} \right)^{0.72} \left(\frac{h_k A_T}{m_a c_p} \right)^{-0.36} \quad (14)$$

$$Q_{showering} = m_a \times 291.45 \times \left(\frac{T_a - 17}{182.7} \right)^{1.39} \left(\frac{1.944}{m_a \times 1.005} \right)^{0.5} - m_w \times 15.05 \times 10^{-10} \times T_w^{6.673} \times T_a^{-0.530} + m_w \times 4.18 \times (T_w - 23.65) \quad (15)$$

$$Q_{(un)dressing} = m_a \times 291.45 \times \left(\frac{T_a - 17}{182.7} \right)^{1.39} \times \left(\frac{1.944}{m_a \times 1.005} \right)^{0.5} \quad (16)$$

Where ΔT_g is the air temperature rises above the ambient temperature(K); T_∞ is the ambient air temperature (K) before the heat is released; m_a is the compartment mass ventilation rate ($\text{kg}\cdot\text{s}^{-1}$); m_w is the water flow rate for showering ($\text{kg}\cdot\text{s}^{-1}$).

Therefore, in the current study, equation 15 was applied to calculate the energy consumption during showering, while equation 16 was applied to calculate the energy consumption during the undressing and dressing periods. Similar to the study by Zhang et al. [6], this research also considered winter conditions, as energy consumption tends to be higher during this season, presenting greater potential for energy savings. Based on observatory records in Hong Kong, the ambient outdoor temperature was assumed to be 17°C.

2.3 Monte-Carlo simulation

Since there are numerous possible environmental conditions in the bathroom (i.e., combinations of environmental factors), it seems impractical to measure/simulate the dynamic thermal comfort and energy consumption under all these possibilities. This study employed Monte Carlo simulation—a statistical technique that utilizes repeated random sampling to model and analyze uncertain systems—to address this complexity. This method allows for evaluating of a random subset of all possible scenarios, providing confidence intervals for the predictions. Both DTS and energy consumption were evaluated via Monte-Carlo simulations. The simulation process was as follows. First, the distribution of all the environmental parameters, including air temperature, water supply temperature, ventilation rate, and water flow rate, were assumed to be normally distributed for typical Hong Kong domestic bathrooms. The mean and standard deviation (SD) values were obtained from previous field studies conducted in Hong Kong or related standards. Specifically, the distribution of air temperature was $T_a \in [24.5, 1.5]$ °C; the distribution of water temperature was $T_w \in [38.8, 0.7]$ °C [4]; the distribution of the water flow rate was $WFR \in [0.2, 0.05]$ kg/s (i.e., [12, 3] l/min); the distribution of the ventilation rate was $VR \in [0.02, 0.01]$ kg/s [15], [16]. Considering the different thermal sensations between females and males identified by previous studies, two subjects, i.e. one female and one male, were considered in this study, and their height and weight were obtained as the average values of the subjects from a previous field study [4]. The DTS and energy consumption were calculated for each simulated condition by applying the methods described in sections 2.1 and 2.2, respectively. The procedure was coded and executed with Python.

3. Results and discussion

3.1 Variation of the dynamic thermal sensation during the whole showering process

The variations of subjects' DTS during the whole process of showering are shown in Figure 1. It is clear that the DTS of both female and male subjects decreased a little bit (from 0 to -0.3) during undressing (i.e. 0-7 min), increased remarkably (from -0.3 to 1.4) during showering (i.e., 8-17 min), and decreased again (from 1.4 to 0.5) during dressing (i.e., 18-25 min). Additionally, Figure 1 illustrates the difference in DTS between the female and male subjects, which was also proved by the paired sample t-test result: $t(23)=5.416$; $p<0.001$. The average DTS of the female subject was 0.556, while it was 0.516 for the male subject.

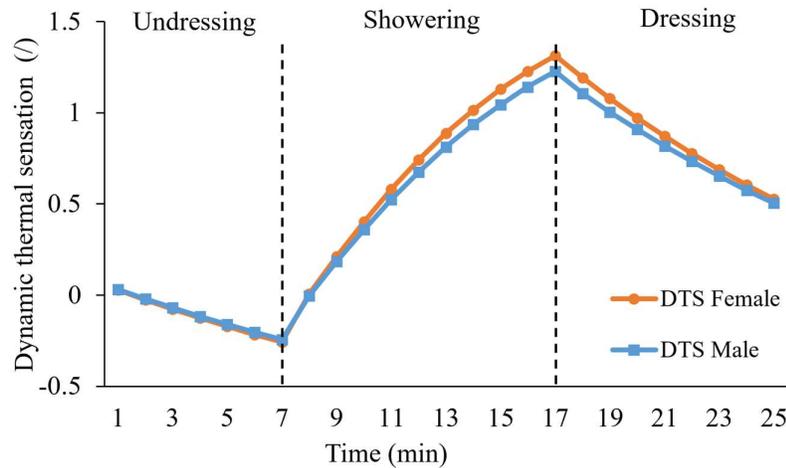


Figure 1. Variation of subjects' DTS during the whole process of showering.

Table 1. Differences in DTS between female and male subjects during showering.

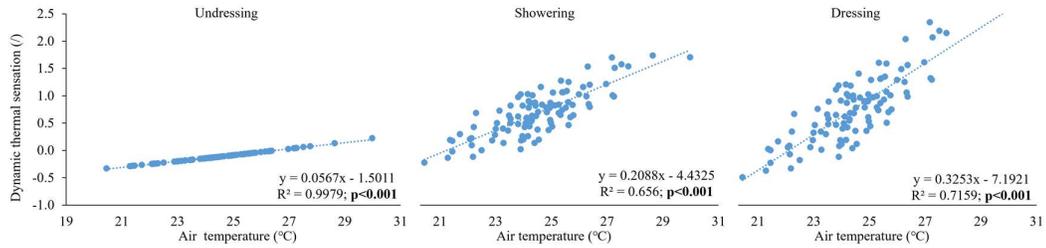
Periods	Female	Male	t	p
Undressing	-0.145	-0.1354	-7.597	<0.001
Showering	0.752	0.690	7.255	<0.001
Dressing	0.839	0.788	6.617	<0.001
Whole	0.556	0.516	5.516	<0.001

Note: all the results were obtained from paired sample t-tests.

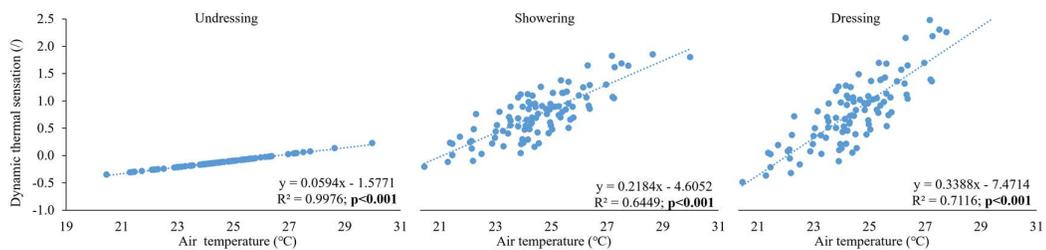
Table 1 presents the comparison results across different periods. The findings indicate that the DTS for female subjects was significantly lower than that of male subjects during the undressing phase, while it was significantly higher during the showering and dressing phases. These results align with previous studies primarily focused on undressing and showering, further highlighting females' sensitivity to thermal sensation [5].

Figure 2 presents the relationships between environmental parameters (i.e., air and water temperatures) and the subjects' DTS during undressing, showering, and dressing periods.

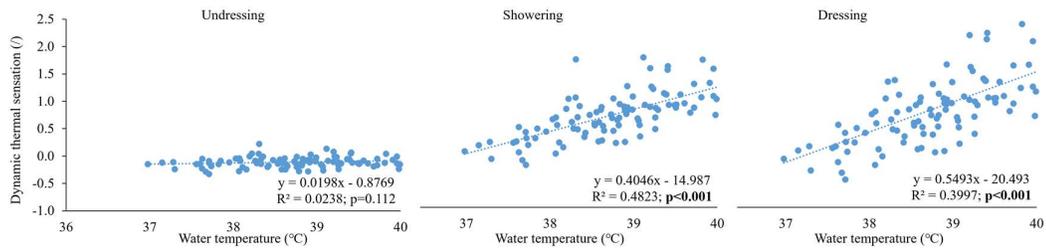
According to the results of the regression analyses, air temperature had a significant positive impact on subjects' DTS during the showering process ($p < 0.05$). During the undressing period, the values of R^2 were the highest (almost 1), while the beta coefficients were the lowest (less than 0.1), compared with the showering and dressing periods, indicating the significant but weak impact of air temperature on subjects' DTS during the undressing period. Besides, the beta coefficients during the three periods showed that the subject's DTS varied more remarkably with the changes in air temperature during the dressing period than during the showering period, while it varied the least during the undressing periods.



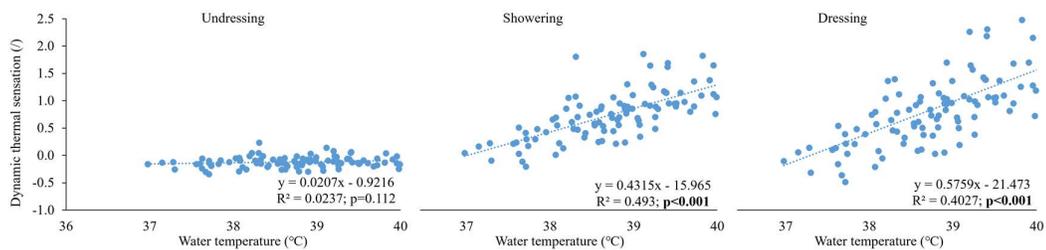
a) between air temperature and male subject's DTS during different periods



b) between air temperature and female subject's DTS during different periods



c) between water temperature and male subject's DTS during different periods



d) between water temperature and female subject's DTS during different periods

Figure 2. Correlations between the environmental parameters and subjects' DTS.

Significant impacts of water temperature were observed during the showering and dressing periods. The R² of the regression analysis between the water temperature and the subject's DTS was higher during showering, while the beta coefficient was higher during dressing. This suggests that the relationship between the water temperature and DTS was more predictable during showering, while the impact of water temperature on DTS was more substantial during the dressing period. In contrast, water temperature did not affect on subjects' dynamic thermal sensation (DTS) during the underdressing period, as there was no water flow then. This weak and

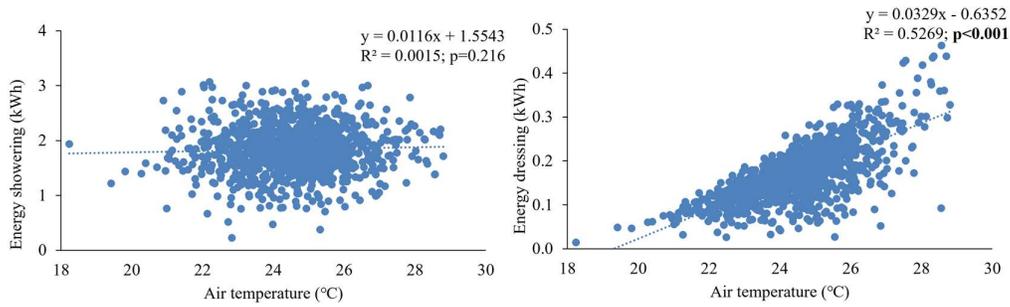
non-significant linear relationship is indicated by the low R^2 value and a large p-value (>0.05) shown in Figures 2(c) and (d).

Regarding the difference between female and male subjects, it appears that female subjects' thermal sensation was more sensitive to the changes in temperature (both water and air), as the higher beta coefficients were overserved in Figures 1b) and d) (for female) than in Figures 1a) and c) (for male). Moreover, the difference was more obvious regarding the impact of water temperature.

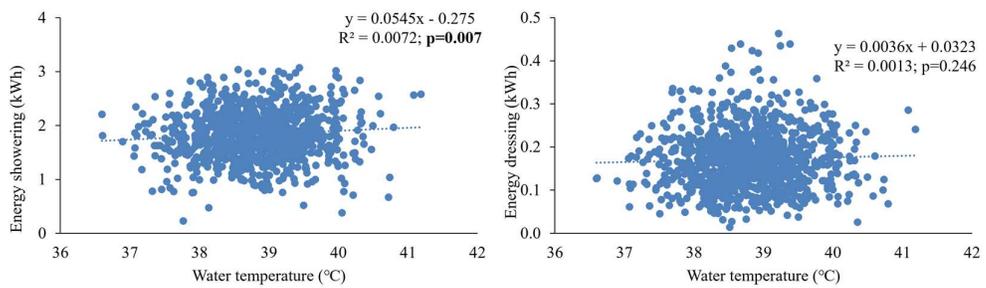
3.2 Energy consumption during showering

Figure 3 illustrates the correlations between various environmental parameters and energy consumption during showering (the left column) and undressing and dressing (the right column). Since the equation used to calculate the energy consumption during dressing and undressing are the same, energy consumption during these two periods was combined and considered. In general, energy consumed during showering was around 10 times the energy consumed during undressing and dressing. According to the results shown in Figure 3, water temperature and water flow rate significantly impacted the energy consumption during showering ($p<0.05$), while air temperature and ventilation rate significantly impacted the energy consumption during the (un)dressing period ($p<0.05$). Specifically, the water flow rate had the predominant impact on energy consumption during showering, as indicated by the high R^2 value of 0.969 in the regression model. In contrast, the effect of water temperature on energy consumption is minimal, with a very low R^2 of 0.007. The results indicated that water temperature explained only a small portion of the variability in energy consumption, and water flow rate played a more important role in determining energy usage during showers. Regarding the energy consumption during dressing and undressing, the impact of air temperature and ventilation rate were competitive since similar R^2 and p values were observed in the related regression models. Based on these results, setting the water flow rate to the minimum level is recommended to save energy effectively. Meanwhile, air and water temperatures can be adjusted according to occupants' thermal sensations to prevent discomfort.

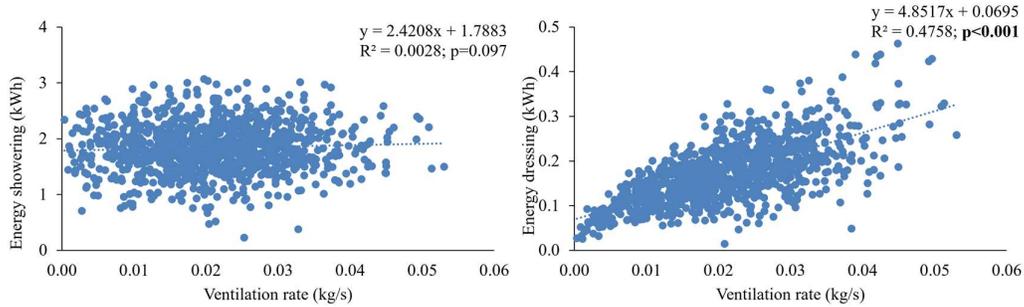
Given that air and water temperatures can influence energy consumption and subjects' DTS, Figure 4 compares their direct relationships to identify optimal settings. Since the trends of DTS were similar for female and male subjects, with female DTS being more sensitive, this section focuses on the DTS of female subjects. As shown in Figure 4a, air temperature was the primary factor affecting DTS and energy consumption during the undressing period. To maintain a neutral thermal sensation, the air temperature was suggested to be set around 27°C . In the showering period (see Figure 4b), air and water temperature were important to subjects' DTS and energy consumption. Since air temperature was relatively higher, a water temperature of 37°C is suggested to achieve a neutral sensation. During the dressing period, air temperature considerably impacted both subjects' DTS and energy consumption, while water temperature only significantly impacted the subject's DTS. Only the air temperature could be adjusted since water use was stopped during this period. Lowering the air temperature is recommended to prevent overheating and conserve energy.



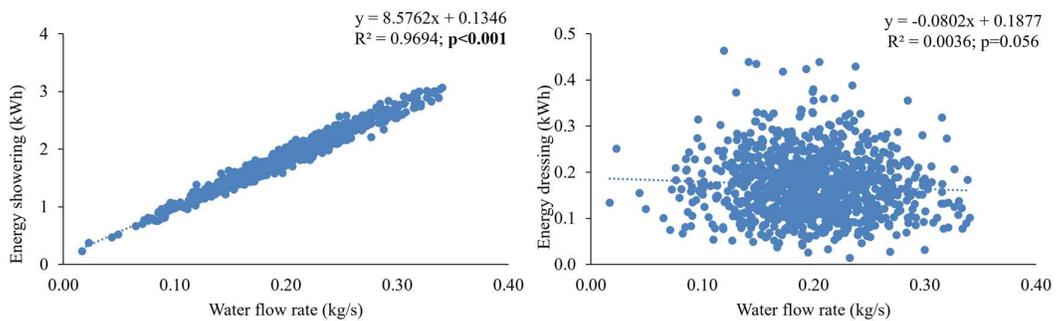
a) between T_a and energy consumption during showering (left) and (un)dressing (right)



b) between T_w and energy consumption during showering (left) and (un)dressing (right)

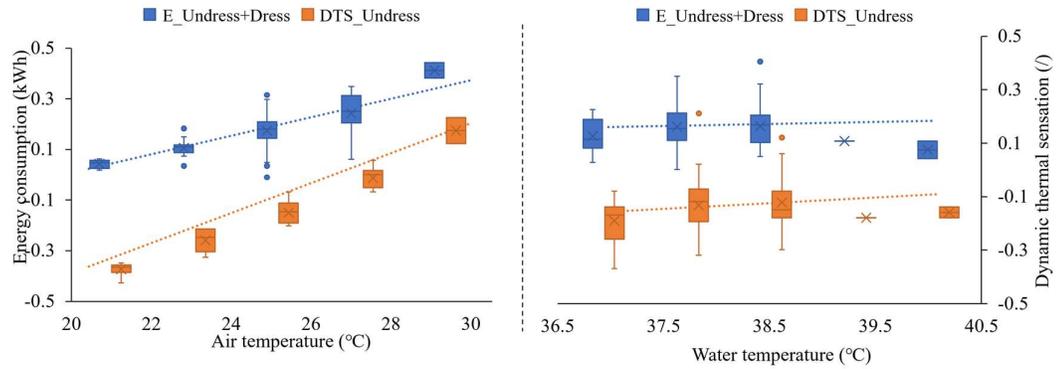


c) between VR and energy consumption during showering (left) and (un)dressing (right)

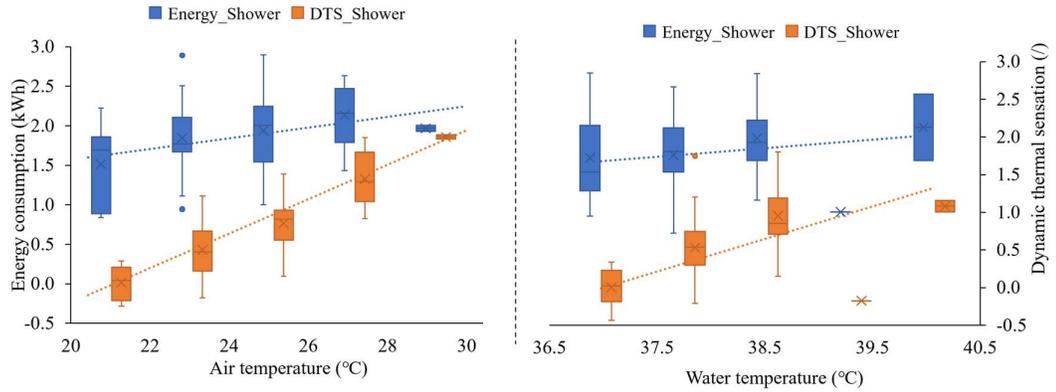


d) between WFR and energy consumption during showering (left) and (un)dressing (right)

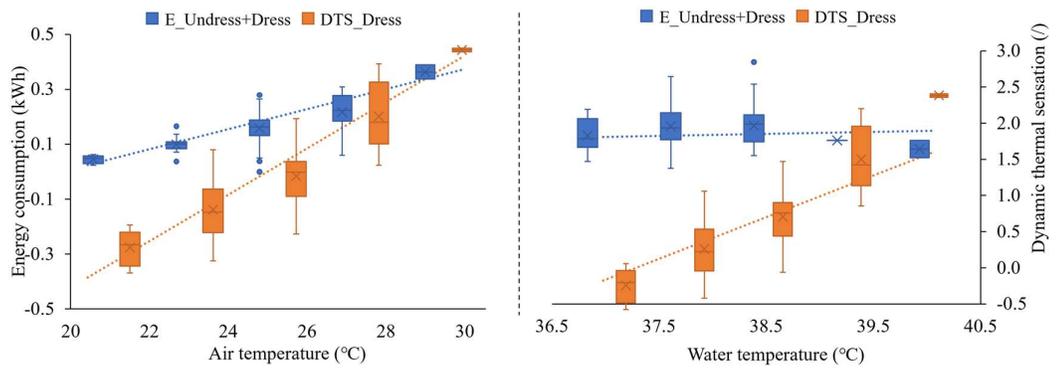
Figure 3. Correlations between the environmental parameters and energy consumption.



a) Undressing



b) Showering



c) Dressing

Figure 4. Impacts of air and water temperature on energy consumption and subjects' DTS.

3.3 Limitation of the current study

The current study is limited by its reliance on the DTS model developed by Mui et al. [5]. As highlighted in their work, "differences were identified by comparing the calculated DTSs during

showering with the thermal sensation votes (TSVs) collected by Luo et al. [1]," leading them to recommend further research to develop a more accurate DTS model. Consequently, the DTS model's accuracy directly impacts this study's findings. Moreover, the DTS model utilized here only accounts for the effects of air and water temperatures, neglecting other influential factors such as water flow rate and ventilation rate. This omission may limit the comprehensiveness of the analysis and the generalizability of the results. Therefore, future studies are recommended to establish a more accurate DTS model by considering more factors.

4. Conclusion

This study investigated the effects of various environmental parameters—specifically air temperature, water temperature, water flow rate, and ventilation rate—on occupants' thermal comfort and energy efficiency in bathrooms throughout the showering process, including undressing and dressing periods. The energy consumption and thermal sensation models developed in previous studies were adapted for this research. Additionally, Monte Carlo simulation was employed to evaluate the impact of the investigated parameters on the energy consumption and the DTS of a female and male subject. The findings revealed that DTS trends were similar for both genders, although female subjects were more sensitive to temperature changes. Furthermore, these results indicated that most energy consumption occurred during showering compared to the undressing and dressing phases. Water flow rate was identified as the predominant factor influencing energy consumption during showering, while air temperature and ventilation rate significantly impacted energy use during undressing and dressing periods. To enhance energy efficiency, a lower water flow rate is recommended. However, it is important to note that reducing the water flow rate may impact subjects' DTS. Therefore, future studies are suggested to investigate this relationship to identify the optimal water flow rate that balances energy efficiency with subjects' comfort. Moreover, air and water temperatures affected energy consumption and subjects' DTS. The study suggests maintaining an air temperature of around 27°C and a water temperature of approximately 37°C for optimal comfort and efficiency. Implementing these recommendations could result in thermally comfortable and sustainable residential bathrooms, promoting occupant well-being and energy conservation.

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