Evaluation of the Effects of Airflow Patterns on Human Thermal Perception

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Abstract. Recently, greenhouse gas emissions have led to irreversible climate change, and in order to mitigate the changes, more and more research is focusing on energy efficiency and environmental protection in the building sector. Improving indoor ventilation airflow as a feasible solution for energy conservation as well as improving human thermal comfort. This study aims to provide reference for optimizing the thermal perception of occupants in indoor ventilation design. This research evaluates the effect of heat perception on students in a stable indoor environment (28 ℃, RH 50%) under two airflow patterns (dynamic and constant). The use of airflow was found to have a positive impact on thermal sensation vote (TSV) and thermal pleasure vote (TPV). There was non-significant difference in the effects of heat perception between airflow modes. This finding is consistent with the findings of Parkinson and de Dear's study. It is worth noting that differences in experimental results may be due to other personal factors (e.g., gender, age, and weight). Further studies are therefore needed to demonstrate the influence of these factors on the thermal perception effect of air movement.

Keywords: Airflow pattern; Thermal comfort; TSV; TPV.

1. Introduction

1.1. Background

The rapid growth of air conditioning usage in recent years has led to alarming greenhouse gas emissions. The use of air movement (such as personal fans and natural ventilation) has been suggested as having the potential to reduce greenhouse gas emissions and indoor temperatures in the construction industry.

Numerous studies support that thermal comfort in warmed environments can be improved by using cooling effects of air movement [1]. The thermal comfort and impression of air movement, however, may fluctuate significantly depending on several physical air movement characteristics (such as air velocity and air turbulence strength). The results of numerous studies have shown that the level of thermal discomfort will peak when the air velocity varies between particular frequencies [2].

1.2. Literature Review

ASHARE 55-2020, which is an international thermal comfort standard, has defined thermal comfort zones under two different clothing insulation (clo) (0.5 clo & 1.0 clo) as a guide for achieving thermal comfort through air movement. In accordance with section 5.3.2.4 of the standard, the upper limit to the air velocity of elevated air speed is 0.8m/s, which can avoid thermal discomfort due to temperature rise in a warm environment (Fig. 1).

In addition to the thermal comfort standards, numerous studies have been carried out to investigate the relation of air temperature to the upper limit of air velocity. These studies suggested that the subject preferred a broader range of mean air speed than the standards recommendation (above 0.8m/s). For example, the upper limit of air velocity was 1.35 m/s and 1.85 m/s at 28 ℃and 29.5 ℃, and 1.6m/s under 31 ℃ [3]. In addition, many studies have been conducted to investigate the relationship between airflow patterns and thermal effects (Table 1).

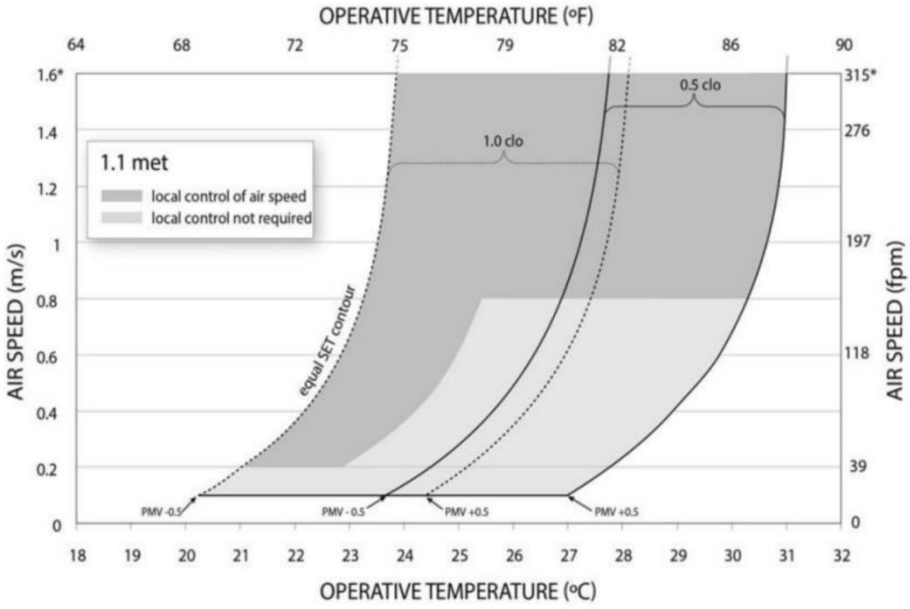


Fig. 1 Elevated air speed model [4]

Fig. 1 shows the elevated air speed model, the dark grey zone means the comfort zone.

Table 1. Summary of related literature

Airflow pattern	Air temperature (℃)	Clothing insulation (clo)	Air speed (m/s)	Thermal perception
Three turbulence intensity levels	23	Depends on subjects	Six levels	TSV decreased with raised air velocity fluctuation
Various fluctuated airflow	27.8 - 31.1	0.6	1.0 - 1.6	TSV decreased with raised air velocity fluctuation
Simulated airflow	26, 30	Depends on subjects	0.8	TSV lower under fluctuating flow
Pulsed mode	28	0.5	0.9	TSV was not significantly different
Simulated airflow (dynamic & constant)	26, 28, 30	0.57	0.86	Lower TSV under dynamic airflow

1.3. Motivation and framework

To investigate the differences in human thermal perception and thermal comfort under the action of different airflow patterns, relevant experiments are needed. The purpose of this study was to assess the differences in human perception of different airflow patterns, including air movement preference, thermal pleasure, thermal sensation, and thermal preference. Experiments were carried out to study the effects of different airflow modes in indoor environments on the psychological and thermal comfort of study subjects. The results and findings from the experiments are compared with the literature review to identify similarities and differences.

2. Methodology

2.1. Participants

Forty-four university students took part in the experiments. Their data and are listed in Table 2.

Table 2. Data of participants

Gender	Male (19)		Female (24)		Prefer not to say (1)
	Mean ± s.d.	Min - max	Mean ± s.d.	Min - max	
Age	27.368 ± 5.325	22 - 45	25.667 ± 3.212	23 - 36	25
Height (m)	174.947 ± 7.261	160 – 185	160.583 ± 7.587	145 - 176	165
Weight (kg)	78.268 ± 8.485	64 – 94	59.667 ± 9.770	41 - 75	70
Clothing insulation (clo)	0.492 ± 0.162	0.22 – 0.95	0.477 ± 0.139	0.24 – 0.84	0.42

2.2. Procedure

This experiment was conducted in the IEQ laboratory. The experiment consisted of five phases with a total duration of approximately 45 minutes (Fig. 2). After entering the chamber, subjects were required to complete the corresponding surveys in each stage, including a background survey and four thermal comfort surveys. Each thermal comfort survey needed to be completed 2 minutes prior to the end of the current phase.

The Pre-adaptation stage was designed to ensure that subjects were acclimated to the experimental environment, and they were asked to sit still for 15 minutes in these warm conditions (28°C). During the experiment, subjects were required to remain as still as possible to ensure that the metabolic rate remained at 1.0 (sedentary MET).

The airflow in the experiment was divided into two modes, one in which the air underwent dynamic flow followed by constant flow, and the other in the opposite direction. Subjects were randomly divided into two groups to experience the two airflow patterns. This was done to counteract the order effects on the experimental results.

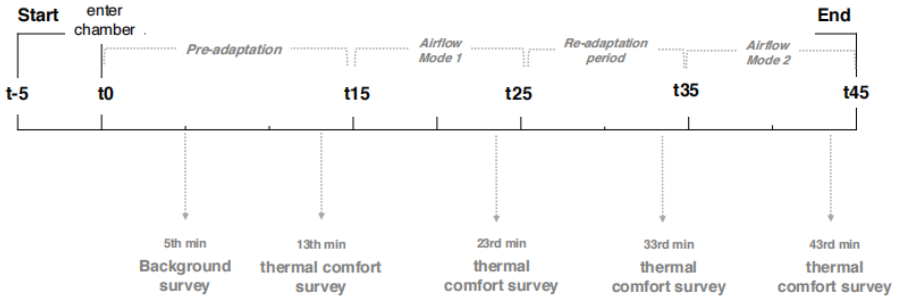


Fig. 2 Experiment timeline

Fig. 2 shows the whole flow of the experiment. It consists of four main phases: two pre-adaptation phases as well as two phases exposed to air flow, in each of which the corresponding survey needs to be completed. The entire experimental procedure lasted 45 minutes.

2.3. Experiment environment and measurement

The environment of the experiment was controlled through the Building Management and Control System (BMCS) in the IEQ lab, where the air temperature and relative humidity were controlled at

28°C and 50%. Vertical fans, which were fixed at 1.1m from the subject, were used to generate air movement (Fig. 3). The fan was connected to the Microcontroller board to create a constant or dynamic airflow by emitting an infrared signal. The two air movement patterns maintain the same average velocity of 0.7 m/s during a 10-minute exposure time (Fig. 4).

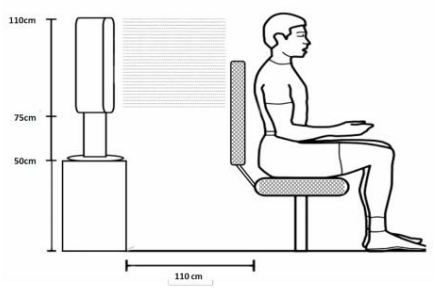


Fig. 3 Experiment facility

Fig. 3 shows the Fig. 3 shows the setup of the experimental setup. The fan was set up at a distance of 1.1 m behind the subject and at a height of 1.1 m. The width of the area where the airflow was generated was 35 cm.

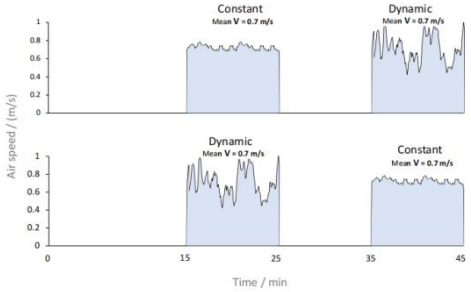


Fig. 4 Air movement patterns

Fig. 4 shows the airflow during the experiment.

2.4. Questionnaires

During the experiment, participants were asked to complete a background survey and four thermal comfort surveys. The background survey consisted mainly of the subject's physical parameters (age, height, weight) as well as Clothing insulation (clo). The thermal comfort survey consisted of three simple questions. The first question is a survey of thermal sensation vote (7-point) and thermal pleasure vote (7-point). The second question is a survey of environment temperature preference (3-point). The last question is a survey of air movement preference (3-point). The results were compiled with the support of laboratory staff.

3. Result

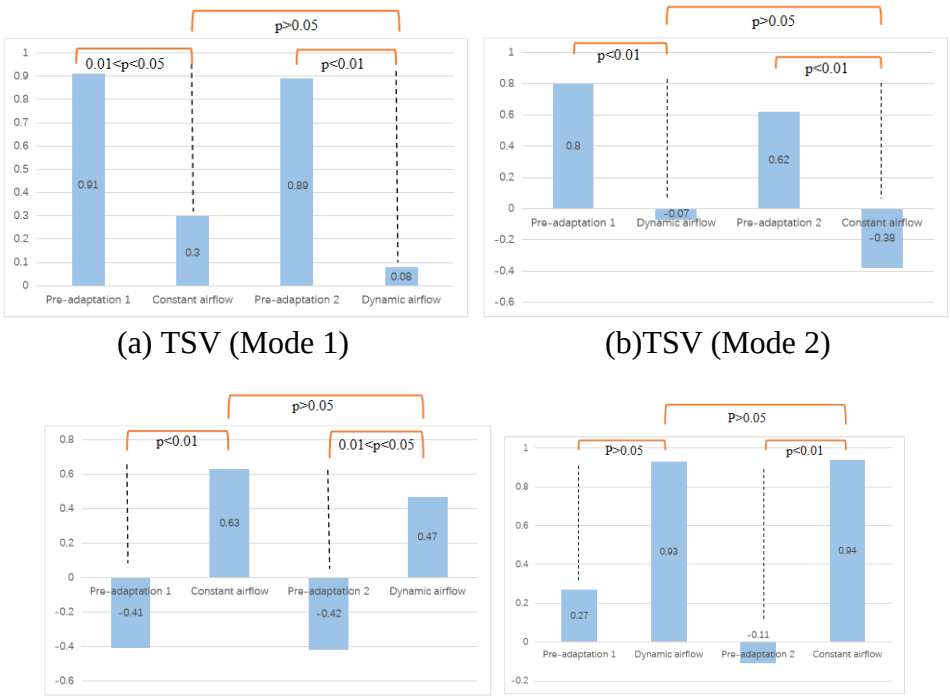
3.1. Thermal sensation vote and Thermal pleasure vote

In accordance with the results in Table 3, constant airflow and dynamic airflow in all phases lead to a significant decrease in TSV and a significant increase in TPV compared to the values in the pre-adaptation phase. This suggests that air movement has a positive effect on thermal sensation and pleasure.

Table 3. Summary of TSV and TPV survey results

Phases	Mode 1		Mode 2	
	TSV	TPV	TSV	TPV
Pre-adaptation 1	0.91 ± 0.73	-0.41 ± 1.12	0.8 ± 0.75	0.27 ± 1.34
Airflow mode 1	0.31 ±0.86	0.62 ± 1.17	-0.08 ± 0.63	0.94 ± 1.32
Pre-adaptation 2	0.89 ±0.96	-0.42 ± 1.13	0.62 ± 0.61	-0.11 ± 1.12
Airflow mode 2	0.08 ± 0.89	0.47 ± 1.38	-0.38 ± 0.52	0.94 ± 0.97

To quantify the effect of constant and dynamic airflow on thermal perception and thermal pleasure, an Analysis of Variance (ANOVA) method has been implemented to support the data analysis (Fig. 5). The value of p in ANOVA indicates the extent of deviation between the two parameters. It was found that comparing the effects between the two airflows on TSV and TPV resulted in p values greater than 0.05, indicating that there was no significant difference between the effects of constant and dynamic airflow on thermal sensation vote and thermal pleasure vote. The results of the ANOVA test showed that dynamic airflow had a more significant effect ($p < 0.01$) on thermal sensation vote than constant airflow compared to the pre-adaptation phase (In mode 1: $0.01 < p < 0.05$; In mode 2: $p < 0.01$). In accordance with part (c) and (d) from figure 5, it shows that TPV has extremely significant differences ($p < 0.01$) between the pre-adaptation and constant airflow phase. Notably, the order of experiencing airflow did influence thermal sensation and pleasure. This can be seen in the significant changes in p values between airflow phase and pre-adaptation phase from the results of TSV and TPV compared to different modes (see Discussion for further analysis).



(a) TSV (Mode 1) (b)TSV (Mode 2)

(c) TPV (Mode 1) (d)TPV (Mode 2)

Fig. 5 ANOVA test result of TSV and TPV of two airflow modes

In Fig. 5, (a)shows the TSV results under airflow mode 1; (b)shows the TSV results under airflow mode 2; (c)shows the TPV results under airflow mode 1; (d) shows the TPV results under airflow mode 2; ($0.01 < p < 0.05$: significant difference; $p < 0.01$: extremely significant difference; $p > 0.05$: no significant difference).

3.2. Thermal preference

There was no significant difference in the frequency distribution of thermal preferences between constant and dynamic airflow. The number of subjects exposed to a dynamic airflow that preferred to be warmer was equal to the number of subjects exposed to a constant airflow, both at 4.3%. Subjects exposed to constant airflow had a greater expectation of maintaining the stability of their current environment compared to subjects exposed to dynamic airflow (constant: 57.4%, dynamic: 52.2%). The potential reason for this is that the skin is more sensitive to transient temperature changes when subjects are exposed to dynamic airflow due to the shallow location of cold receptors in the skin [10]. In addition, about 40% of the subjects wanted lower temperatures. Slightly more subjects were exposed to dynamic airflow than to constant airflow. This is due to the continuous airflow that constantly compensates for the effects of high temperatures, the current temperature and the steady flow of air that continues to cool the skin [10].

As a whole, these results are consistent with the increased air speed model mentioned in section 1.2. As the operating temperature (28°C) approaches the upper limit of thermal comfort operating temperature (31°C), the temperature needs to be kept constant or reduced.

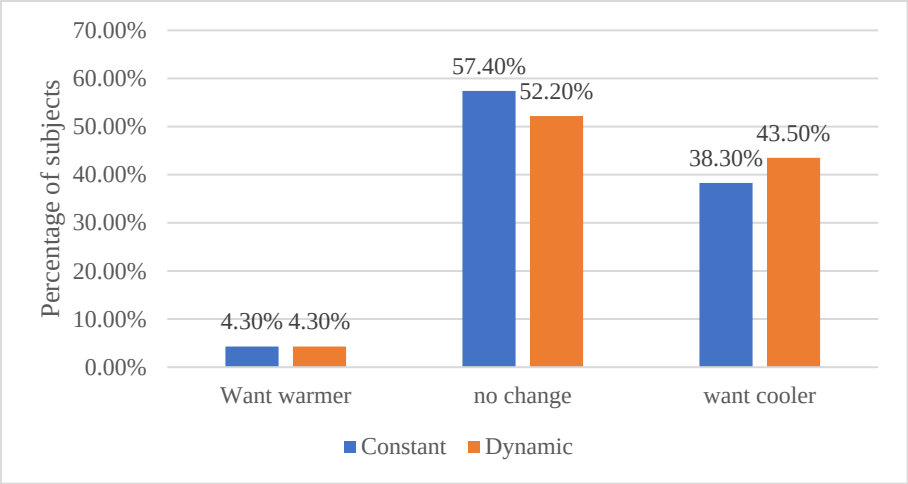


Fig. 6 Frequency distribution of thermal preference

Fig. 6 shows the frequency distribution of the preferred thermal results under constant and dynamic airflow. The results are approximately the same for both airflow modes.

3.3. Air movement preference

The majority of subjects tended to maintain their current air motion or more. About 40% of subjects wanted more air movement (constant: 39.1%, dynamic: 43.5%). Among those who wanted to maintain the status quo, 50% of subjects were exposed to constant airflow and 41% to dynamic airflow. Only about 15% of the subjects wished for less air movement. The results indicate that for such warm conditions (28°C operating temperature), subjects need an air velocity of 0.7 m/s or even higher, which is compatible with the upper limits of air velocity and temperature in the thermal comfort zone presented in section 1.2 [3].

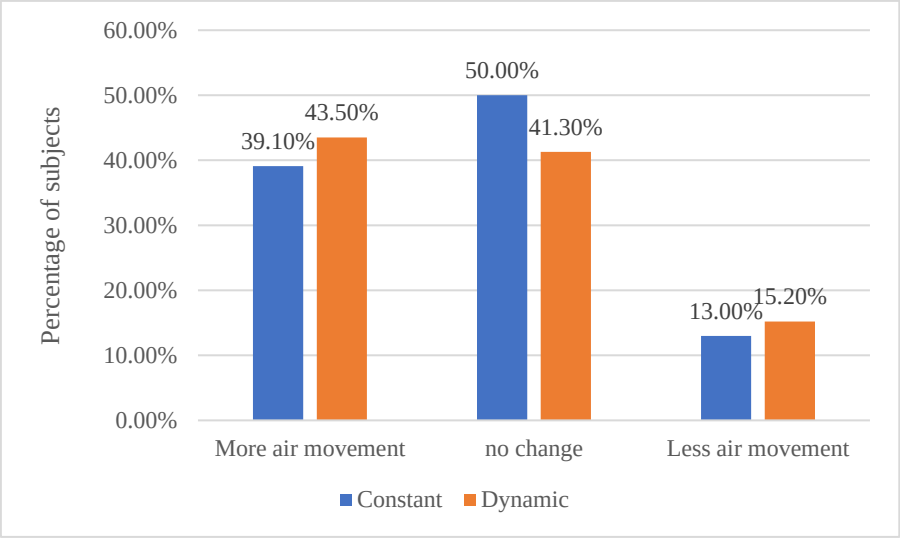


Fig. 7 Frequency distribution of preferred air movement

Fig. 7 shows the frequency distribution of preferred air movement results. Of which 'more air movement' and 'no change' account for the major part.

4. Disccusion

4.1. Differences in airflow perception

In the present experiment, there was no significant difference between the two airflow modes in terms of thermal sensory voting and thermal pleasure voting (section 3.1). This finding is consistent with previous studies [1, 8], but conflicts with the finding of reduced TSV in dynamic airflow modes [5-7, 9]. In comparison with literature review studies, it should be noted that this inconsistency can be due to different research methods. For instance, different thermal parameters values were chosen (e.g., different operating temperatures, clothing insulation, target perception areas, and experimental durations), and these factors may have led to different results for thermal sensation and thermal pleasure experiments.

4.2. Difference caused by airflow sequence

The experimental results (section 3.1) showed that the order of airflow did influence thermal sensation vote and thermal pleasure vote. The difference in TSV was smaller for those who experienced constant airflow first (mode 1, $0.01 < p < 0.05$) compared to those who experienced constant airflow later (mode 2, $p < 0.01$). Similarly, the difference in TPV was smaller for those experiencing dynamic airflow (mode 2) first ($p > 0.05$) compared to those experiencing dynamic airflow later (mode 1, $0.01 < p < 0.05$).

However, the difference caused by the sequence of airflow may be related to the thermal perception of the pre-adaptation phase of the experiment. If subjects felt warm during the pre-adaptation phase (no fan), then their TSV would have changed significantly during the experiment. Similarly, in terms of TPV, those subjects who reported slightly unpleasant would have a greater positive change after the ventilation device was turned on [1].

4.3. Built environment

Thermal perception surveys are primarily based on the subjective perceptions of the subjects, making it difficult to establish a linear relationship between airflow patterns and perceived patterns. Most air conditioning systems can only provide a fixed thermal environment for a space, i.e., all occupants live or work in a uniform environment. If the occupants are allowed to control the airflow according to their preferences, according to the elevated air speed model mentioned in section 1.2,

the occupants can adjust the surroundings to reach the comfort zone (dark gray area), which means that the upper limits of air velocity and operating temperature are also increased.

4.4. Limitation

The air flow pattern is not the only factor that affects thermal perception. Subject data (e.g., gender, age, height and weight) and other parameters (e.g., airflow velocity, air temperature) can also lead to differences in results. This needs to be demonstrated by further studies and analyses.

The sample size capacity will likewise limit the precision of the experimental results, and most of the data obtained in the experiments are subjective perceptions of the subjects, which makes it difficult for the conclusions to guide the whole population.

5. Conclusion

In accordance to the results of the experiment, it shows that the effect of airflow patterns on thermal sensation and thermal pleasure has no significant difference. This conclusion is contrary to the results of some studies due to differences in study methodology and parameter settings. Furthermore, it has been found that thermal sensation and thermal pleasure can indeed be improved by air movement. The order of airflow experienced by subjects was also found to affect TSV and TPV. It is noteworthy that the differences in the perceived effects of the two airflow patterns should be further demonstrated, as individual factors of subject and some other parameters also influence the results. To further investigate and eliminate the effect of subjective perception as much as possible, greater sample size is recommended for the experiment to enhance the accuracy of the results and the generalizability of the experimental findings. To improve occupant thermal comfort, it is recommended to use devices such as Underfloor Air Distribution (UFAD) and fans that allow occupants to adjust according to their personal preferences to make the indoor environment more comfortable.

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