Evaluating the Impact of Fan Design and Air Speed on User and Nearby Occupants' Thermal Comfort in a Shared Office

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Personal Comfort Systems (PCS) are increasingly recognized for their potential to improve individual thermal comfort and reduce building energy demand. ASHRAE Standard 55 defines PCS as a device, under the control of the occupant, intended to heat and/or cool individual occupants without affecting the thermal environment of other occupants. Desk fans are common PCS cooling devices, but their use in shared workspaces raises questions about the differential impact on the primary user and nearby occupants. Limited empirical evidence exists on how local air speed and fan technology jointly influence thermal, airflow, and acoustic domains among occupants.

To address these gaps, a human-subject experiment involving 40 participants was conducted, paired into 20 pairs: P1 as the fan primary user and P2 as a nearby occupant. Two desk fan designs (conventional-blade and bladeless) were tested at high and low-speed settings. Participants provided repeated comfort assessments at each fan speed condition.

The results indicate that both fan technology and operating speed significantly affect the alignment or divergence of comfort between P1 and P2. At low speed, both fan types produced strong convergence, with both occupants reporting neutral thermal sensation, slight satisfaction, and a shared perception of air movement as “just right.” In contrast, at high speed, the bladed fan resulted in divergence: P1 perceived the airflow as “too breezy” and preferred less air movement, while P2 reported no change despite experiencing breezy conditions.

Conversely, the bladeless design reduced this asymmetry. At all speeds, both P1 and P2 reported neutral thermal sensation and consistent satisfaction. For primary users, both fan types enhanced thermal comfort at both speeds. The bladed fan was effective only at low speed, as high speed produced a “too breezy” sensation, whereas both speeds were acceptable for the bladeless fan. Despite these advantages, the bladeless fan introduced acoustic disturbance to the environment. High-speed bladeless was perceived as more annoying than the bladed fan, with the P2 group reporting higher annoyance (85%) than the P1 group (65%). This suggests that the high-frequency profile of the air multiplier technology is intrusive, especially for nearby occupants in shared environments.

For shared workspaces with mechanical cooling, a low-speed fan setting is recommended. This configuration minimizes acoustic annoyance for both fan technologies (0-5% annoyance) while maintaining high thermal satisfaction for primary users and minimal intrusion into the environment of nearby occupants.

Acknowledgements

I would like to express my sincere appreciation to my advisor, Dr. Joyce Kim, for her guidance and support throughout my degree. Her mentorship extended beyond academic matters and contributed significantly to the completion of this work.

I am also grateful to Dr. Moses and Mrs. Adeola Ogun for their support in helping me achieve this goal. I would like to acknowledge my friends at the University of Waterloo (Nengimote Vanessa, Dinah, Aderonke, and Soukaina) for their encouragement and friendship.

Finally, I am thankful to my mother for instilling in me the importance of education, even in circumstances where it was not always considered attainable.

Dedication

I dedicate this thesis to God, who helped me start this journey and directed my path until this moment.

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List of Abbreviations

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

BMI: Body Mass Index

CP: Corrective Power

HVAC: Heating, Ventilation, and Air Conditioning

Icl: Clothing Insulation

IEQ: Indoor Environmental Quality

ISO: International Organization for Standardization

MET: Metabolic Equivalent of Task

P1: Primary User

P2: Nearby Occupant (Non-User)

PCS: Personal Comfort System(s)

PMV: Predicted Mean Vote

REB: Research Ethics Board

RH: Relative Humidity

RQ: Research Question

SD: Standard Deviation

Tsk: Skin Temperature

Va: Average Air Speed

1 Introduction

People spend about 90% of their time in the built environment (Klepeis et al. 2001). For buildings designed for human occupancy, a primary objective is to provide a comfortable environment for their occupants. To meet this objective, thermal comfort is an important criterion, which ASHRAE Standard 55 defines as “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE 2023). Conventionally, this is managed by heating, ventilation, and air conditioning (HVAC) systems designed to achieve at least 80% occupant satisfaction. However, HVAC systems frequently struggle to meet this target due to the inherent limitations of the ‘one-size-fits-all’ approach. According to a longitudinal survey database spanning 20 years, nearly 40% of occupants are dissatisfied with their thermal environment, and temperature remains a primary source of thermal dissatisfaction (Graham et al. 2021) . This performance gap is largely due to the reliance on uniform temperature delivery, which fails to address individual differences, such as age and sex, in thermal comfort needs. Furthermore, the effort to maintain these uniform conditions results in high energy consumption, with HVAC systems accounting for approximately two-thirds of total building energy use (Borodinecs et al. 2024). This creates a fundamental conflict between occupant comfort and sustainability goals.

To address these challenges, there is growing interest in Personal Comfort Systems (PCS). ASHRAE Standard 55 (ASHRAE 2023) defines PCS as devices intended to allow occupants to control their local thermal environment without affecting the environment of those around them. PCS functions as a distributed, decentralized solution that enables individuals to address their own thermal comfort requirements. Among various PCS technologies for cooling, the desk fan is the most widely adopted due to its low cost and effectiveness in enhancing local convective heat loss. While studies (Rawal et al. 2020; Zhang et al. 2015) have shown the effectiveness of desk fans in improving comfort for the primary user across a wide range of ambient temperatures (24-30°C), their use in shared spaces creates a “spillover zone” that can alter the multi-domain environments (thermal, air movement, and acoustic) of nearby occupants.

However, existing research primarily focuses on the user-device relationship and does not account for inter-occupant environmental interactions that arise when these devices are used in close proximity. This study aims to move beyond the single user to understand the impact of fan operation on the environmental interaction and perception of both the users and the nearby occupants.

2 Literature Review

2.1 PCS Effectiveness and Energy Savings

PCS are recognized for their dual capability to improve individual thermal comfort while reducing building energy consumption. Many lab and field studies have demonstrated that PCS achieves high occupant satisfaction by enabling individual control over the local environment(Khovalyg et al. 2025; Al-Assaad et al. 2025; Kim et al. 2019). The effectiveness of these systems is typically evaluated using performance metrics that assess a device's ability to improve thermal comfort when applied to specific body segments (Luo, Kramer, De Kort, et al. 2022) . Most studies (Simone et al. 2014; Luo, Kramer, Kort, et al. 2022; Udayraj et al. 2018) rely on subjective metrics, such as thermal sensation, acceptability, and preference, to assess occupant perception of thermal comfort improvement. For instance,(Tang et al. 2022) evaluated six heating and cooling devices, finding that while most improved individual comfort, only desk and floor fans significantly increased whole-body thermal acceptability to over 80%. This suggests that PCS effectiveness depends strongly on the heat transfer mechanism, with convective systems often providing a superior balance between individual comfort and device efficiency(Arachchi Appuhamilage and Rijal 2025).

The effectiveness of a PCS is closely tied to the physiological sensitivity of the targeted body part(Nakamura et al. 2008). Specifically, local cooling applied to the face and heating applied to the abdomen significantly improve whole-body comfort. In the context of desk fans, this effectiveness is driven by enhancing the local convective heat transfer coefficient at the skin surface, which accelerates heat dissipation. To translate these physiological responses into a standardized metric, (Zhang et al. 2015) proposed the concept of Corrective Power (CP), defined as the “difference in room temperature at which a person maintains the same thermal sensation with the PCS as they would without it.” Their review indicated that cooling devices generally offer a CP range of -1K to -6K, while heating devices provide a more substantial range of +2K to +10 K.

The relaxation of ambient temperatures enabled by high CP values is the primary driver for energy savings. A simulation study (Hoyt et al. 2015) suggests that for every 1°C shift in the central HVAC setpoint, energy consumption can be reduced by approximately 10%. Simulation studies by (Schiavon and Melikov 2008) indicate potential savings of 10–28%, depending on the device's power draw. However, if a device exceeds a power input of 20 W, the energy consumed by the PCS may offset the savings gained from the HVAC setpoint relaxation . Ultimately, the literature suggests that achieving energy savings goals requires a balance between device efficiency, heat transfer mode, and the thermal characteristics of the ambient environment.

2.2 Perception of Air Movement and Multi-Domain Interactions

The desk fan is one of the most common convective PCS used to provide immediate cooling through increased air movement. This works through convective heat loss from the body, which helps reduce the perceived air temperature and improve thermal comfort. Generally, existing studies have focused on how occupants perceive air movement as desirable or undesirable. Fanger's study (Fanger and Christensen 1986) introduced the concept of draft, defined as unintended cooling that causes discomfort. The work revealed that occupants' sensitivity to draft depends on airflow type, with turbulent airflow producing greater discomfort than laminar airflow at the same air velocity. The study also proposed lowering the air-velocity limits in standards to better reflect real-world conditions of turbulent airflow, as the limits in place at the time were based on studies conducted under laminar airflow. Furthermore, (Toftum 2004) suggested that these velocity fluctuations cause draft because the rapid changes in speed may trigger cold receptors on the skin more frequently than steady air.

It is important to note that the distinction between a desirable breeze and an unwanted draft is often moderated by 'perceived control' (Hellwig 2015; Langevin et al. 2012). While the primary user has control over the airflow to mitigate thermal discomfort, the nearby occupant is a passive recipient. This lack of control may lower the physiological and psychological threshold for discomfort, making the physical characteristics of the airflow even more critical for the nearby occupant.

While air movement is predominantly studied as a thermal comfort factor, it is inherently a multi-domain phenomenon. The operation of a fan does not just alter the thermal environment; it simultaneously introduces airflow changes and acoustic signatures. Existing studies often fail to account for these cross-domain interactions. For example, (Hoyt et al. 2009) highlighted that a velocity that causes discomfort in a neutral environment is often welcomed as a desirable cooling source in a warm environment (i.e., thermal alliesthesia); however, this perception may be modulated by the fan's noise annoyance. This multi-sensory experience is not limited to the primary user but extends to nearby occupants in shared spaces. Yet, the interaction effects between thermal, air movement, and acoustic domains in shared environments remain largely uninvestigated.

2.3 Bladed versus Bladeless fan technology

Bladed and bladeless fans both provide cooling via convective heat transfer, yet their physical structures and airflow mechanisms differ significantly. A bladed fan contains visible rotating blades within a mesh enclosure, driven by a motor located in the base. As each blade moves through the air, it generates airflow in intermittent pulses that result in uneven air distribution and increased turbulence (Daiya 2018) . In contrast, the bladeless fan has no visible rotating blades, but it features an impeller in its cylindrical base to pull in and pressurize air, which is then sent as a steady, continuous stream toward a hollow ring. The bladeless fan is also known as an air multiplier because it leverages the Coanda effect – a phenomenon in which high-speed air passing through narrow slits creates a low-pressure region that entrains and amplifies the surrounding air by up to 15 times(Daiya 2018; Li 2013). Because the airflow is guided through smooth internal channels, the resulting output is far more uniform and less turbulent than the airflow produced by rotating blades (Mehmood et al. 2022). The airflow characteristics of the two fan technologies, bladed and bladeless, are visualized in Figure 2.1.

The comparative study by (Daiya 2018) between conventional bladed and bladeless desk fans suggests that bladeless technology produces smoother airflow and generates less noise, while providing an equivalent cooling effect that does not diminish with distance, compared to a conventional bladed fan. In high-density office layouts, these distinctions may significantly alter the environmental perception of both the primary user and nearby occupants. Hence, understanding how these fan technologies influence the shared environment is essential for evaluating the practical implications of convective PCS as a decentralized cooling strategy.

(a) (b)

Figure 2.1: Airflow characteristics of (a) bladed and (b) bladeless fan. Adapted from (Daiya 2018).

2.4 Human Subject Studies on Desktop Fans

Table 2.1 summarizes key human subject studies on desk fans, categorizing them by technology type, participant roles, and the specific perception metrics employed. Existing literature has mainly focused on the device's impact on primary users, considering factors such as the number of blades, air speed, and noise level (André et al. 2021). These studies have established the efficacy of elevated air movement in improving thermal comfort, particularly in warm environments. Despite the prevalence of these devices in shared spaces, very few studies have systematically examined how the airflow from these fans, particularly at varying speeds, affects nearby occupants in a shared office.

Table 2.1: Summary of experimental studies on personal cooling fans and perception metrics

Study (Author, Year)	Subject Type	Fan Technology	Speed Range (m/s)	Primary User (Human subject)	Nearby Occupant (Human subject)	Perception Metrics
(Simone et al. 2014)	Humans/Manikin	Desk fan (bladed)	0.6 – 2.0	Yes	No	Air flow acceptability, thermal acceptability, thermal sensation,
(He et al. 2018)	Humans	Desk fans(bladed)	3.0	Yes	Yes (Shared room)	Thermal sensation, thermal comfort, thermal preference, thermal acceptance
(Udayraj et al. 2018)	Humans	Conventional desk fan and air ventilation clothing (bladed)	1.98	Yes	No	Thermal environment acceptance, thermal comfort, thermal sensation, air movement acceptance
(André et al. 2020)	Humans	Desk fan(bladed)	1.32-1.50	Yes	Yes (Shared office)	Thermal acceptability, thermal sensation, thermal comfort, thermal preference, air movement acceptability, air movement preference
(André et al. 2021)	Humans	Desk fan and evaporative fan (bladed)	0.81 – 2.98	Yes	Yes (Shared office)	Noise perception
(Kent et al. 2023)	Humans	Ceiling fan and desk fan (bladed)	Speed setting 1, 2 for ceiling fan	Yes	Yes (shared office)	Thermal preference, thermal satisfaction, air staleness
(Xie et al. 2023)	Humans	Desk fan (bladed)	Not mentioned	Yes	No	Thermal sensation, thermal comfort, thermal preference
(Ilmiawan et al. 2024)	Humans	Desk fan(bladed)	1.51 - 1.77m/s	Yes	No	Thermal sensation, thermal preference vote, Wind movement acceptability, Overall comfort
(Norouziasl et al. 2025)	Humans	Desk fan (bladed)	0.0 - 1.0	Yes	No	Thermal sensation, thermal acceptability, thermal comfort

As summarized in Table 2.1, the literature shows that personal control over a desk fan significantly enhances individual comfort by allowing occupants to fine-tune their micro-environment (Udayraj et al. 2018; Simone et al. 2014; Xie et al. 2023). Furthermore, (André et al. 2021) showed that ease of operation, fan speed adjustment, and airflow sensation, as well as the perceived noise, were the most important criteria for users. However, (André et al. 2020) suggest that a lack of sufficient vertical adjustment can reduce device efficiency and prevent users from targeting optimal cooling spots. A study has also quantified the cooling potential of different airspeeds, finding that an airspeed of 0.5 m/s can increase the cooling setpoint by 2.8°C while maintaining optimal comfort (Norouziasl et al. 2025). Furthermore, (Ilmiawan et al. 2024) found that different fan configurations improved thermal comfort for users, even in warm conditions of 28.6°C.

Despite these advancements, a review of the literature reveals two fundamental gaps. First, while current studies evaluate the benefits for the primary user, the impact on the nearby occupants remains under-investigated. (He et al. 2018) explored the interaction between two occupants in a shared room, but the study focused on behavioral impacts such as how one person's choices affect collective energy use and comfort, rather than individual perception. Similarly, (Kent et al. 2023) combined the use of ceiling and desk fans in a shared office, but did not account for the spillover impact of the desk fan on nearby occupants. Second, perceptual assessments are predominantly anchored in thermal comfort metrics. There is limited understanding of how different fan technologies and speed settings influence the multi-domain interactions among thermal, airflow, and sound perception.

2.5 Research Objectives

The primary goal of this research is to investigate how local air movement from desk fans affects both primary users and nearby occupants regarding their local environment and multi-domain perception in shared office settings. Specifically, the study addresses the following research questions:

1) How do changes in fan speed (High vs. Low) affect the thermal comfort, air movement perception, and noise annoyance of the primary user (P1) and the nearby occupant (P2)?
2) How do bladed and bladeless fan technologies differ in their effects on the thermal sensation, air movement perception, and noise annoyance of P1 and P2?
3) What are the trade-offs between thermal, air movement, and acoustic domains, and how does the experience of P1 differ from that of P2 based on fan speed and technology?

2.6 Thesis Overview

The remainder of this thesis is organized as follows:

- Chapter 3 details the methodology, including the experimental design and procedure, the fan specifications, instrumentation, and the subjective metrics used in the human subject experiment.
- Chapter 4 presents the results, describing the experimental findings and statistical analysis of the data.
- Chapter 5 presents a discussion of the key findings and their significance.
- Chapter 6 includes the overall conclusions and the limitations of the study, including suggestions for future research.

3 Methodology

3.1 Overview

This study investigates the impact of desk fans on both primary users and nearby occupants (non-users) in a shared office setting. The investigation evaluates occupant thermal comfort, air movement perception, and noise annoyance under fan operation. The methodology comprises experimental design, environmental characterization, and human subject testing protocols designed to determine how variations in fan type and speed affect the perceived comfort of both occupant groups.

3.2 Personal Comfort System (PCS) Devices

Two commercially available personal cooling devices were selected for this experimental study: a Rowenta Turbo Silence Extreme+ (hereafter referred to as the bladed fan) and an ULTTY CR021 Bladeless Tower Fan (hereafter referred to as the bladeless fan). Both devices are commercially available in the Canadian market. The bladed fan was chosen as the baseline for this study due to its high market prevalence and status as the standard personal cooling solution in office environments (Ilmiawan et al. 2024). Its impact on thermal comfort has been extensively investigated in previous studies (Norouziasl et al. 2025; Udayraj et al. 2018; He et al. 2020; Tang et al. 2022; André et al. 2024).

The bladed fan (Figure 3.1a) has dimensions of 28.0 cm (L) × 23 cm (H) × 30 cm (W) and features a five-blade design and a knob for speed adjustment. This device utilizes a standard axial flow mechanism to provide cooling through convective heat loss. The manufacturer-specified noise level is 38 dB for the minimum level of fan speed. The fan offers a 120-degree oscillation and four speed levels. However, this study used a fixed airflow direction and two specific speed levels: level 3 (High) and level 1 (Low). The bladeless fan (Figure 3.1b) measures 25.4 cm (D) x 25.4 cm (W) x 59.7 cm (H) and has a manufacturer-specified noise level of less than 32 dB, but the associated speed was not specified. This device operates by drawing a small volume of air into the base and accelerating it through a narrow slit in the upper hoop, resulting in a uniform airflow profile. While the device includes an integrated air purifier, air quality was not assessed in this study. The device offers nine speed levels controlled via remote, of which only levels 9 and 3 were selected as the high and low-speed settings, respectively. Although this bladeless fan is typically regarded as a floor-standing unit, its compact vertical design allows desktop placement. During the experiment, the fan was tilted vertically to direct airflow toward the primary user's head and upper body.

(a) (b)

Figure 3.1: Personal cooling devices: (a) The conventional bladed desk fan, and (b) The bladeless fan

3.3 Fan Speed Characterization

To accurately measure the airflow experienced by the occupants, air speed was quantified using the method outlined in ASHRAE Standard 55 (ASHRAE 2023). For seated occupants, air speeds were measured at three heights: 0.1 m, 0.6 m, and 1.1 m above the floor level to represent the ankles, mid-body, and head regions. The representative average air speed (Va) is calculated as the mean of these three measurement points.

The two distinct speed levels selected for the experiment were based on these measurements.

- **Low speed:** Selected to fall within speed range (0.36 m/s to 0.8 m/s)
- **High speed:** Selected to exceed 0.8 m/s

Table 3.1 presents the measured Va for each available setting of the two devices, highlighting the specific levels selected to represent “High” and “Low” airspeed conditions used in this study.

Table 3.1: Average air speed (Va) measurement of the bladed and bladeless fans at the user location for discrete fan speed settings

Device	Average Air Speed Levels (m/s)								
	L1	L2	L3	L4	L5	L6	L7	L8	L9
Bladed Fan	0.35*	0.93	1.05*	-	-	-	-	-	-
Bladeless Fan	0.15	0.28	0.34*	0.4	0.52	0.63	0.72	0.92	0.99*

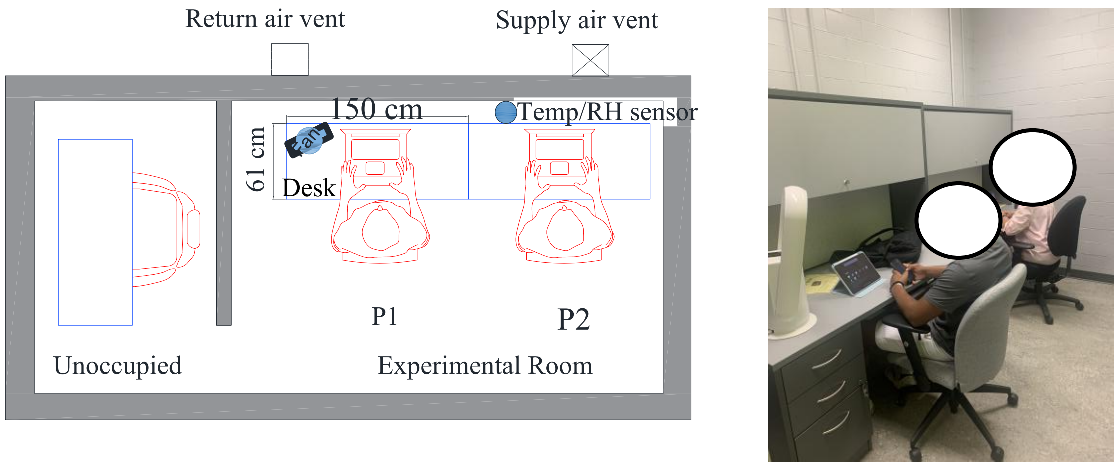
Note: Speed levels marked with an asterisk (*) represent the specific fan settings (L3 and L1 for the bladed fan; L9 and L3 for the bladeless fan) selected for the human subject experiment to represent “High” and “Low” air speed conditions.

For the bladed fan, L3 and L1 were used as high and low settings, respectively. Similarly, for the bladeless fan, L9 and L3 were used as high and low levels, respectively. These levels were chosen to provide a comparable range of air speeds between the two different fan technologies.

3.4 Room Selection and Layout

The study was conducted in the Engineering 2 building at the University of Waterloo, Ontario, Canada, during the summer months from August 7 to 15, 2025. The test site was an existing office room located within the building’s interior zone with representative indoor environmental conditions for a mechanically cooled building during the summer season. Two side-by-side workstations in the room were used to simulate a shared workspace. To replicate the arrangement of an open-plan office, the existing partition between the desks was removed. The desk dimensions were 150 cm x 61 cm, and the occupants were positioned 1.5 m apart, measured from center to center.

Figure 3.2 shows the room floor plan and a photo of the experimental setup. Both fans were placed at the front corners of the desk, angled 45º towards the primary user's center. This setup reflects typical office workstation arrangements, where a laptop or monitor occupies the central desk area, and the fan is placed in the desk's corner. To evaluate the environmental interaction and spillover effects, the nearby occupant (P2) was positioned on the right side of the user (P1), within the fan’s potential aerodynamic and acoustic influence zone. During the experiment, the fans were positioned to direct the air flow specifically toward P1’s head and upper body to evaluate both the cooling effectiveness for the user and the unintended air movement spillover for the nearby occupant.

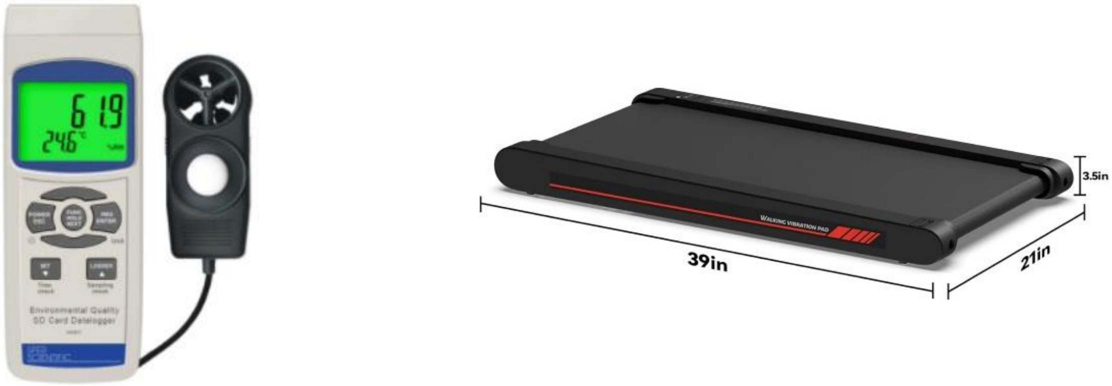


(a) (b)

Figure 3.2: Experimental room (a) floorplan and (b) workstation layout used in the human subject experiment showing the positioning of the desk fan relative to the primary user (P1) and nearby occupants (P2), HVAC supply/exhaust vents, and environmental sensor locations.

3.5 Experimental Equipment and Instrumentation

The ambient room temperature and relative humidity were recorded using the SPER Scientific Environmental Meter (Model 850071), shown in Figure 3.3a, to monitor the room's environmental conditions. Air speed from the fan was measured at multiple heights using the Omega HHF-SD1 Hot Wire Anemometer-Thermometer. Additionally, a Sperax Walking Pad (Figure 3.3b) was used to simulate increased metabolic rates during the pre-test phase. Table 3.2 provides the technical specifications and accuracies for all instrumentation.



(a) (b)

Figure 3.3: Equipment and instruments used in the study. (a) Temperature/Relative Humidity Data Logger (b) Treadmill

Table 3.2: Technical specification of the instrumentation used in the human subject experiment

Category	Instrument	Parameter	Range	Accuracy	Resolution
Environmental	SPER Scientific Environmental Meter (Model 850071)	Temperature	0 to 50 °C	±0.8 °C	0.1 °C
		Relative Humidity (RH)	0% to 95% RH	>70% RH: (3% reading + 1% RH) < 70 % RH: 3% RH	0.1% RH
	Omega HHF-SD1 Hot Wire Anemometer	Air Speed	0.2 to 25 m/s	± (5% of reading + 0.1m/s)	0.01 m/s
Physiological	Sperax Walking Vibration Pad	Belt Speed	0.2 to 3.8 MPH	—	—
	Maxim Integrated iButton	Skin Temperature	-20°C to +85°C	±0.5°C from-10°C to +65°C	0.0625°C

3.6 Human Subjects

A total of forty subjects (N = 40) were recruited for human-subject testing, comprising 22 males and 18 females, all university students aged 18 or older. The participants' backgrounds or ethnicity were not considered during recruitment to ensure broad demographic representation. However, participants with a history of chronic dry eyes were excluded from this study to prevent potential eye irritation from the fan's directed airflow. Table 3.3 summarizes the participant characteristics.

Table 3.3: Summary of participant characteristics and demographics

Participant Group	No of Participants	Female	Male	Age (mean ± SD)	BMI (mean ± SD)
Primary User (P1)	20	8	12	25.4 ± 3.6	24.3 ± 3.8
Nearby Occupant (P2)	20	10	10	26.4 ± 5.7	26.8 ± 8.8
Total	40	18	22	25.9 ± 4.7	25.5 ± 6.8

The participants were organized into 20 pairs, with each pair consisting of a primary user (P1) and a nearby occupant or “non-user” (P2). These roles remained fixed for the duration of the testing session to evaluate the localized cooling effect vs. the unintended spillover effect. To quantify P1's physiological response while on the treadmill and after exposure to airflow from a fan, Maxim Integrated iButton sensors were used to monitor local skin temperature at two locations: the forehead and the wrist. All P1 and P2 participants were required to wear typical summer clothing on the day of the experiment, consisting of walking shorts/skirts and a short-sleeved shirt. Trousers with short-sleeved shirts were permitted as the study focused primarily on upper body cooling. Clothing insulation (Icl) was estimated using the ensemble method outlined in ASHRAE Standard 55, with ensembles of all participants ranging from 0.36 to 0.54 clo. This study was reviewed and received ethics clearance through the University of Waterloo Research Ethics Board (REB 47367).

3.7 Experimental Procedure

To simulate the physiological state of occupants arriving at the office or returning from a break, P1 completed a physical activity prior to each testing session. The P1 participants walked on a treadmill for 10 minutes to raise their metabolic rate from a resting state (~1.0 MET) to 1.8 MET, consistent with walking metabolic rates defined in ASHRAE Standard 55. This activity was conducted in a separate room with slightly warmer ambient conditions than in the test office, and participants were advised to wear comfortable running shoes for the treadmill activity. Immediately after the activity, P1 moved to the test office to begin the fan exposure session. P2 remained in the test office space throughout the session to reflect typical steady-state occupancy. Both participants were instructed to perform office-related tasks on their laptops during the experiment to reflect typical office activities.

The survey was administered during the experiment, and it consisted of two sections, the background and the subjective metrics question. The background survey was conducted once at the beginning of the session to record demographics and physical characteristics (including height and weight for BMI). The clothing insulation of the participants were recorded separately based on observed clothing ensemble. This method was used because participants were not expected to accurately identify their insulation values. A survey was used repeatedly throughout the session to capture instantaneous thermal perception, air movement perception and noise annoyance. In addition to the scheduled surveys, P1 was given the option to express their desire for speed reduction during high-speed exposure or turning off during low-speed exposure. When this was expressed, they were asked to fill out an additional survey.

The order of fan type exposure was fixed across all participant pairs: the bladed fan session (25 minutes) was conducted first, immediately followed by the bladeless fan session (25 minutes), both completed within a single 50-minute testing period. The testing duration for each fan type was 10 minutes, as shown in Figure 3.4, and followed this sequence:

- **Initial without fan (0 minutes):** Both participants completed the initial background survey and answered the ‘right-now’ survey questions on thermal, air movement, and noise level.
- **High-speed exposure (0-5 minutes):** P1 was exposed to the fan at high speed for 5 minutes. The ‘right-now’ surveys were administered to both P1 and P2 at the 1-minute mark to capture immediate comfort perception.
- **Low speed exposure (5-10 minutes):** The fan was set to low speed for the remaining 5 minutes, with follow-up ‘right-now’ surveys administered at the 6-minute mark (one minute after the transition to low speed) and the 10-minute mark.

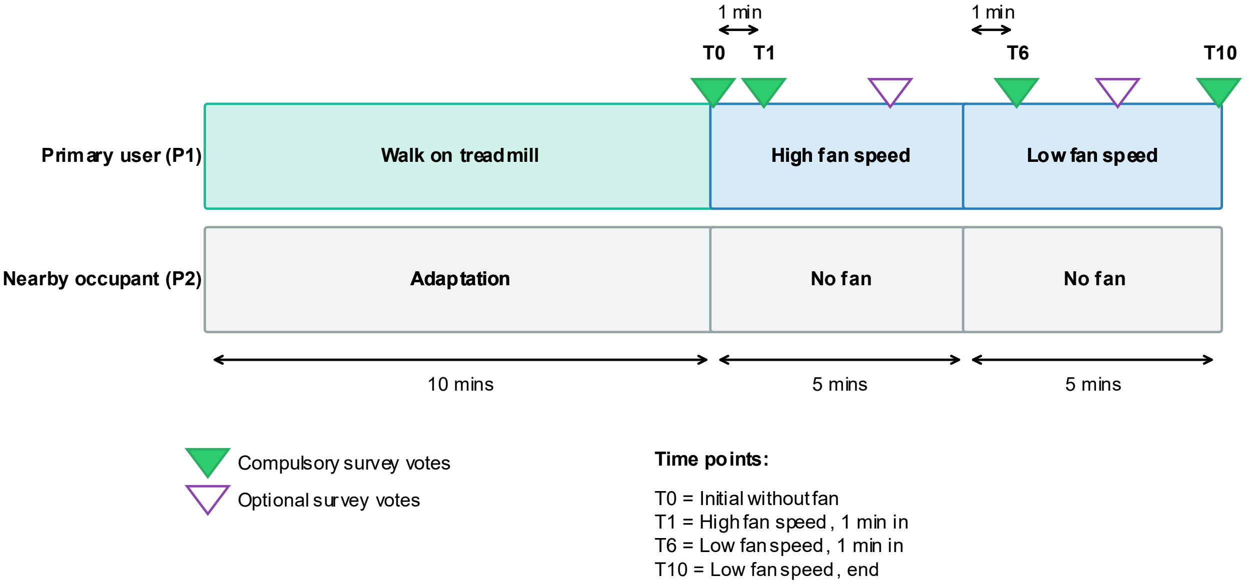
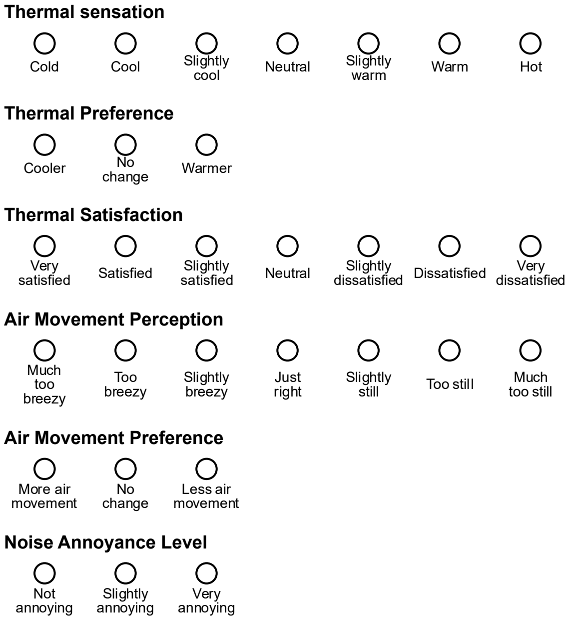


Figure 3.4: Timeline of the human subject experiment for Primary Users (P1) and Nearby Occupants (P2), highlighting the pre-test physical activity, fan speed exposure levels (High and Low), and survey administration points (inverted triangles).

While previous studies typically expose participants to 20-30 minutes of exposure (André et al. 2020, 2021; He et al. 2018), this study employed a 5-minute exposure period for each fan speed setting. This decision was informed by the study's specific ambient temperature context. Unlike previous studies conducted in warm environments (26-30°C) without air conditioning, this study was conducted in a mechanically cooled office with an average ambient temperature of 24°C, which represents a typical office environment in summer. To validate this shortened duration, a pilot study (n = 6) was conducted before the main experiment. Results indicated that, under these conditions (~24°C), participants expressed a desire to switch off the fan within the first 5 minutes of high-speed exposure. This suggests that they were in neutral conditions after a brief period of high-speed fan exposure in representative air-conditioned summer environments and prolonged fan exposure may lead to overcooling.

3.8 Subjective Metrics and Surveys

The background survey was used to record the demographic and physical characteristics of the study participants. It included questions on age, sex, height, weight, and participant role, which were used to characterize the collected data and support the interpretation of thermal comfort responses. The ‘right-now’ survey employed in this study was adapted from the ASHRAE Standard 55 “right-now” survey to assess the immediate impact of fan settings on participant comfort. Thermal sensation, thermal satisfaction, and air movement perception were assessed using 7-point scales, whereas thermal preference and air movement preferences were evaluated using 3-point scales. Additionally, noise annoyance level was included in the survey using a 3-point scale to capture subjective perceptions of fan noise at different speeds (Figure 3.5).



Thermal sensation

○ Cold ○ Cool ○ Slightly cool ○ Neutral ○ Slightly warm ○ Warm ○ Hot

Thermal Preference

○ Cooler ○ No change ○ Warmer

Thermal Satisfaction

○ Very satisfied ○ Satisfied ○ Slightly satisfied ○ Neutral ○ Slightly dissatisfied ○ Dissatisfied ○ Very dissatisfied

Air Movement Perception

○ Much too breezy ○ Too breezy ○ Slightly breezy ○ Just right ○ Slightly still ○ Too still ○ Much too still

Air Movement Preference

○ More air movement ○ No change ○ Less air movement

Noise Annoyance Level

○ Not annoying ○ Slightly annoying ○ Very annoying

Figure 3.5: ‘Right-now’ survey questions

3.9 Data Collection and Analysis

The collected survey responses were consolidated for processing, and the analysis and visualizations were performed using Python. The Pandas library was used for data preprocessing, and Matplotlib for plotting. Given that the subjective responses were collected using Likert-type scales, the data were treated as ordinal rather than continuous. Previous thermal comfort studies often used parametric statistics for analysis, but (Favero et al. 2023) indicate that nonparametric analyses yield more reliable results for ordinal data.

The following nonparametric tests were employed.

- **Mann-Whitney U Test:** for independent comparisons between the P1 and P2 groups.
- **Friedman Test:** for repeated measures to assess changes within groups across fan speeds.
- **Wilcoxon Signed-Rank Test:** for post-hoc pairwise comparisons with **Bonferroni correction** applied to adjust the p-values and control for Type 1 errors.

The effect size (r) for all nonparametric tests was reported as Cohen's r, a standardized measure of effect magnitude. The interpretation of these values followed the correlation-based thresholds originally proposed by (Cohen 1988) which are widely recommended for non-parametric statistics (Tomczak and Tomczak 2014; Fritz et al. 2012) . Based on this, the following categories were used to classify the effect sizes: 0.1 (small), 0.3 (medium), and 0.5 (large).

4 Results

This chapter analyzes indoor environmental conditions and subjective comfort responses of the Primary User (P1) and Nearby Occupant (P2). Occupant comfort is evaluated across thermal, air movement, and acoustic metrics for two fan speeds and two fan technologies (bladed and bladeless). Statistical significance of the results was determined using Friedman (within-subjects) and Mann-Whitney U (between groups) tests, with effect sizes used to assess the magnitude of the observed differences. Detailed statistical outputs, including p-values, Z-scores, and effect sizes (Cohen's *r*), are provided in Appendix A.

4.1 Indoor Environment Conditions and Skin Temperature Response

Table 4.1 summarizes the indoor and outdoor environmental conditions recorded during the experiment period. Outdoor temperatures increased by 5°C during the initial part of the study, peaking at 31°C on the 5th day out of the six-day period. Despite these fluctuations, the indoor temperature within the test room remained relatively stable (23.7 ± 0.6°C) as the room was situated within an interior zone with mechanical cooling. Relative humidity similarly remained consistent at approximately 63.1 ± 4.4% during the study period.

Table 4.1: Summary of indoor environmental conditions in the test room and outdoor environment during the study period. Mean values are presented with standard deviations (± SD). Outdoor data were obtained from a local weather station. Indoor environmental conditions were measured via on-site data loggers at a height of 2 m.

Parameter	Mean ± SD	Min	Max
Indoor temperature	23.7 ± 0.6 °C	22.4 °C	25.1 °C
Indoor relative humidity	63.1 ± 4.4 %	52.4 %	69.9 %
Outdoor temperature	27.6 ± 2.5°C	21.5 °C	32.6 °C

Continuous monitoring of skin temperature (Tsk) was used to quantify the physiological impact of the treadmill activity and subsequent cooling via fan on the Primary User (P1). Figure 4.1 presents the Tsk profile measured from the forehead and wrist iButton sensors. Skin temperature was monitored only for P1, as described in Section 3.6. During the 10-minute treadmill walking phase, forehead and wrist Tsk increased by an average of 3.9°C and 2.3°C, respectively. Upon activation of the fan, both sensors recorded a steady decline. The high-speed interval exhibited a steeper cooling rate compared to the low-speed interval, illustrating the immediate impact of increased air velocity on convective heat loss.

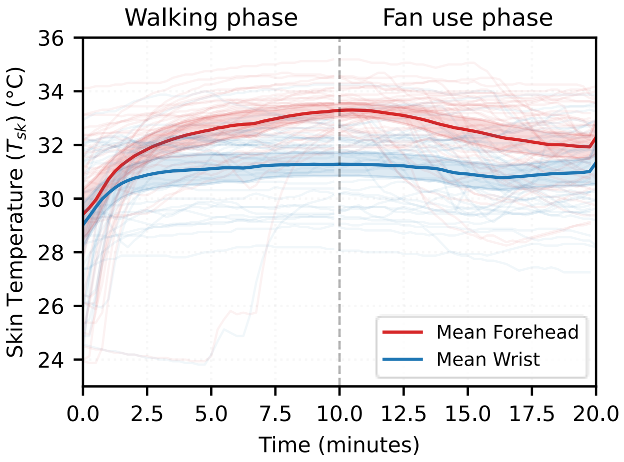


Figure 4.1: Local skin temperature (Tsk) profile for Primary User (P1) during treadmill activity and fan intervention. Bold lines represent the mean response across all participants. Shaded regions indicate the 95% confidence interval. Light gray background lines represent individual participant skin temperature profiles.

4.2 Subjective Thermal Comfort Assessment

Subjective thermal comfort responses (thermal sensation, thermal preference, and thermal satisfaction) were analyzed to evaluate the impact of bladed (Figure 4.2) and bladeless (Figure 4.3) fans on P1 and P2 participant groups across different speed settings.

4.2.1 Bladed Fan

The bladed fan session evaluated the efficacy of the pulsating airflow generated by traditional rotating blades in addressing post-metabolic thermal discomfort and its subsequent impact on the shared environment.

Primary User (P1) Response. The following results characterize the thermal response of the fan user (P1) to air movement within their immediate local environment:

- **Initial Condition (T_0):** This interval established the baseline thermal state following exercise and prior to any convective cooling. All P1 participants reported warm sensations: 35% reported “Slightly Warm,” 50% “Warm,” and 15% “Hot.” Correspondingly, 55% of participants preferred “Cooler” conditions, and 65% reported varying levels of thermal dissatisfaction.
- **High-Speed Exposure (T_1):** At the high-speed fan setting, thermal sensation shifted significantly toward the cool end of the scale (Wilcoxon $Z = -3.95$, $p < 0.001$, $r = 0.62$, $p < 0.001$), with 80% of users reporting sensations between “Slightly Cool” and “Cold,” indicating potential overcooling effects. Thermal preference for “No Change” rose to 65% (from 40% at T_0) ($Z = 4.04$, $p < 0.001$, $r = 0.64$), while thermal satisfaction increased to 60% (inclusive of neutral votes) compared to 35% at T_0. ($Z = 2.28$, $p = 0.023$, $r = 0.36$)

- **Low-Speed Exposure ($T_6 – T_{10}$):** Transitioning to the low-speed setting resulted in a more balanced thermal response. Neutral sensation votes initially rose to 65% at T_6 (up from 20% at T_1, $p < 0.05$), though this shifted to 50% by T_{10}. During this final interval, cool sensations ("Slightly Cool" to "Cool") increased to 45%, up from 35% at T_6, while a small subset (5%) reported feeling "Slightly Warm." Despite these sensation shifts, preference for "No Change" reached 80% by T_{10} ($Z = 4.12$, $p < 0.001$, $r = 0.65$), and thermal satisfaction peaked at 85% ($Z = 3.22$, $p < 0.001$, $r = 0.51$ compared to T_0**)**, suggesting a generally positive response to the low-speed setting.

Nearby Occupant (P2) Response. Subjective thermal responses due to the "spillover" effects within the shared environment are as follows:

- **Initial Condition (T_0):** At baseline, the thermal sensation of the nearby occupant was varied: 50% felt "Neutral," 35% felt "Slightly Warm" or "Warm," and 15% reported feeling "Slightly Cool" to "Cool." Thermal satisfaction was high, with 90% reporting varying levels of satisfaction (inclusive of neutral votes). However, 55% of P2 occupants expressed a preference for cooler conditions.
- **High-Speed Exposure (T_1):** High-speed operation for the primary user resulted in an unintended cooling effect for the nearby occupant. A marked shift toward cooler sensations occurred, with varying cool sensations increasing from 15% at T_0 to 65% at T_1 $Z = -3.24$, $p < 0.001$, $r = 0.51$). The preference for "Cooler" conditions decreased from 55% to 5% ($Z = 3.38$, $p < 0.001$, $r=0.53$), while preference for "No Change" increased from 40% to 65%. Satisfaction among nearby occupants decreased slightly (from 90% to 80%), as 30% of P2 participants reported a preference for warmer conditions – a notable increase from the 5% recorded at T_0.
- **Low-Speed Exposure ($T_6 – T_{10}$):** The reduction in fan speed appeared to restore the nearby occupant's comfort. "Slightly Cool" to "Cold" sensation votes decreased from 65% to 20% by T_{10} ($Z = 2.48$, $p < 0.013$, $r = 0.39$ for T_1 vs T_{10}), while neutral sensation votes increased from 30% to 75% ($Z = -2.28$, $p = 0.023$, $r = 0.36$). Preference for warmer conditions among P2 decreased from 30% at T_1 to 5% at T_{10}, and dissatisfaction dropped to 10% (compared to 15% at high speed).

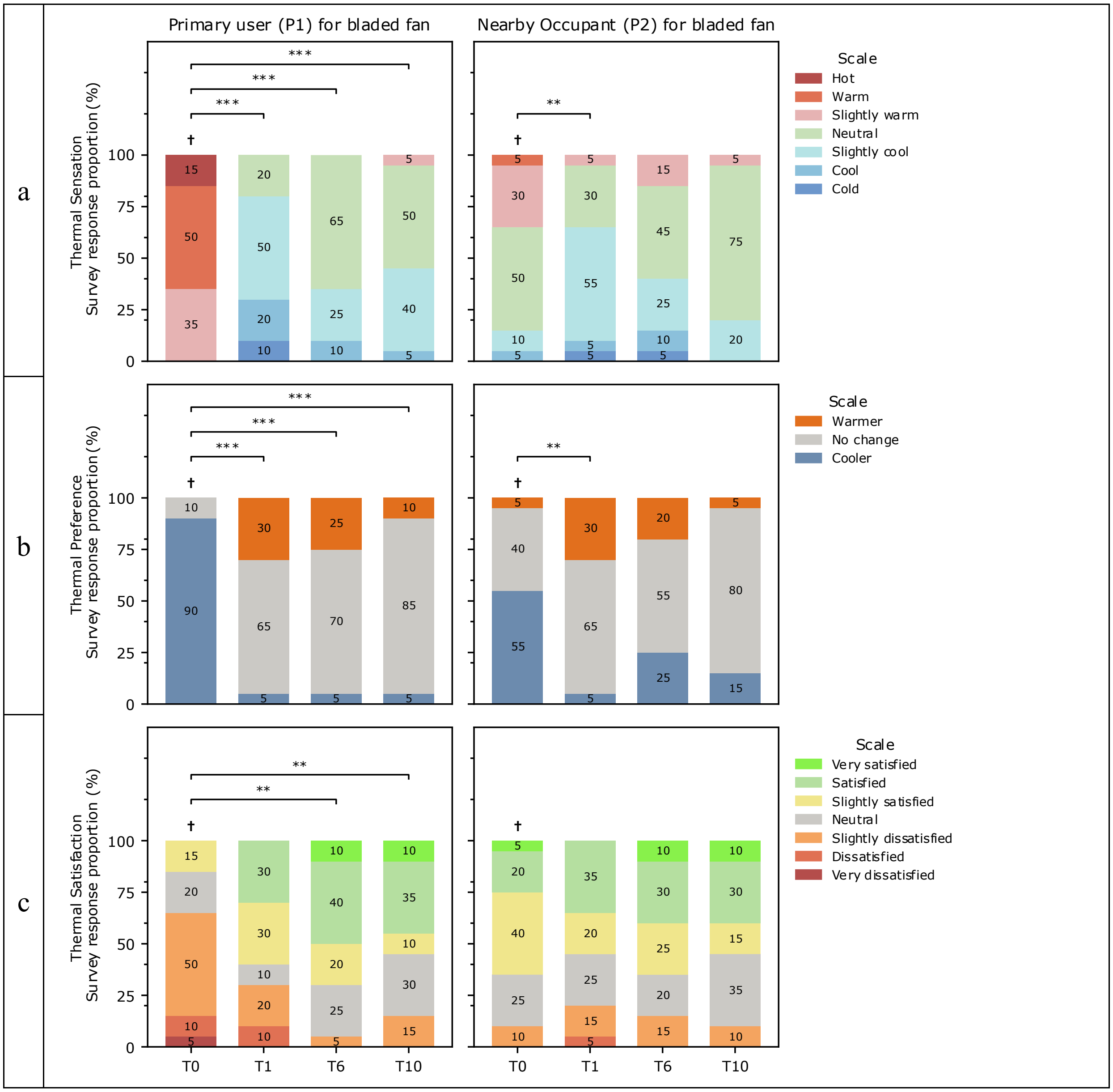


Figure 4.2: Distributions of subjective thermal comfort responses for bladed fan (N=20). Stacked bar charts illustrating (a) thermal sensation, (b) thermal preference, and (c) thermal satisfaction for Primary User (P1) and Nearby Occupant (P2) across the experimental timeline. Note: Asterisks (*) indicate significant differences within a group relative to baseline (T_0) (Wilcoxon test, *p < .05, **p < .01, ***p < .001). Daggers (†) denote significant differences between P1 and P2 at a specific timestamp (Mann-Whitney U, p < .05)

4.2.2 Bladeless Fan

The bladeless fan session investigated whether the uniform airflow produced by air-multiplier technology could provide comparable user cooling while minimizing disruption to the nearby occupant (P2) through a more laminar distribution profile.

Primary User (P1) Response. The following results characterize the thermal response of the fan user (P1) under a uniform and non-fluctuating aerodynamic profile:

- **Initial Condition (T_0):** Consistent with the bladed fan session, the baseline P1 response reflected predominantly warm sensations, with 70% of votes ranging from "Slightly Warm" to "Hot" and 30% reporting "Neutral." 5% preferred "Cooler" air, and 70% reported dissatisfaction (ranging from slightly to very dissatisfied).

- **High-Speed Exposure (T_1):** High-speed operation provided an immediate cooling effect, characterized by an increase in "Neutral" sensations (from 30% to 50%) and "Slightly Cool" sensations from 0% to 35% ($Z = -3.21$, $p = 0.001$, $r = 0.51$). Thermal satisfaction increased significantly from 30% to 95% (inclusive of neutral votes) with the high-speed air movement ($Z = 3.49$, $p < 0.001$, $r = 0.55$), and 75% expressed a preference for "No Change" ($Z = 3.23$, $p = 0.001$, $r = 0.51$)

- **Low-Speed Exposure ($T_6 – T_{10}$):** The transition to low speed further shifted thermal sensations toward neutrality, reaching 65% at T_6 and 75% at T_{10} ($Z = -3.09$, $p = 0.002$, $r = 0.49$ for T_0 vs. T_{10}).. Thermal satisfaction was maintained high at 90% (inclusive of neutral votes) ($Z = 3.40$, $p < 0.001$, $r = 0.54$ for T_0 vs. T_{10}), while the proportion of participants reporting being "Very Satisfied" tripled (from 5% to 15%) by T_{10}. However, preference for cooler conditions slightly increased, reaching 25% at T_{10} compared to 15% at T_1.

Nearby Occupant (P2) Response. Subjective responses regarding the "spillover" effects of a more laminar airflow distribution on the nearby occupant (P2) are as follows:

- **Initial Condition (T_0):** The baseline for the nearby occupant was divided: 75% reported "Neutral," while 20% expressed "Slightly Warm" to "Warm" sensations, and 5% felt "Slightly Cool". 85% were satisfied (inclusive of neutral votes) and 45% preferred "No Change," while 55% expressed a preference for cooler conditions.

- **High-Speed Exposure (T_1):** Under high-speed operation, some of the nearby occupants group (40%) perceived "Slightly Cool" to "Cold" sensations. Neutral sensations decreased from 75% at T_0 to 55% at T_1. ($Z = -3.08$, $p = 0.002$, $r = 0.49$ for T_0 vs. T_1). While P2 satisfaction increased slightly from 85% to 90% (inclusive of neutral votes), the preference for "No Change" increased from 45% to 60%. Notably, 20% of nearby occupants preferred warmer conditions at this interval, compared to only 0% at T_0, indicating potential overcooling effects.

- **Low-Speed Exposure ($T_6 – T_{10}$):** The low-speed interval facilitated a shift back toward neutral sensations, moving from 55% at T_1 to 65% at T_6 and eventually 80% by T_{10} – a level of neutrality higher than the initial baseline (T_0). With the transition to low speed, nearby occupant satisfaction returned to 95% (more than the initial state), and 70% preferred "No Change," representing a marked increase from both T_1 (60%) and T_0 (45%) ($Z = 2.22$, $p = 0.026$, $r = 0.35$. Overall, the spillover effects at low speed were perceived more positively than the baseline state without fan operation.

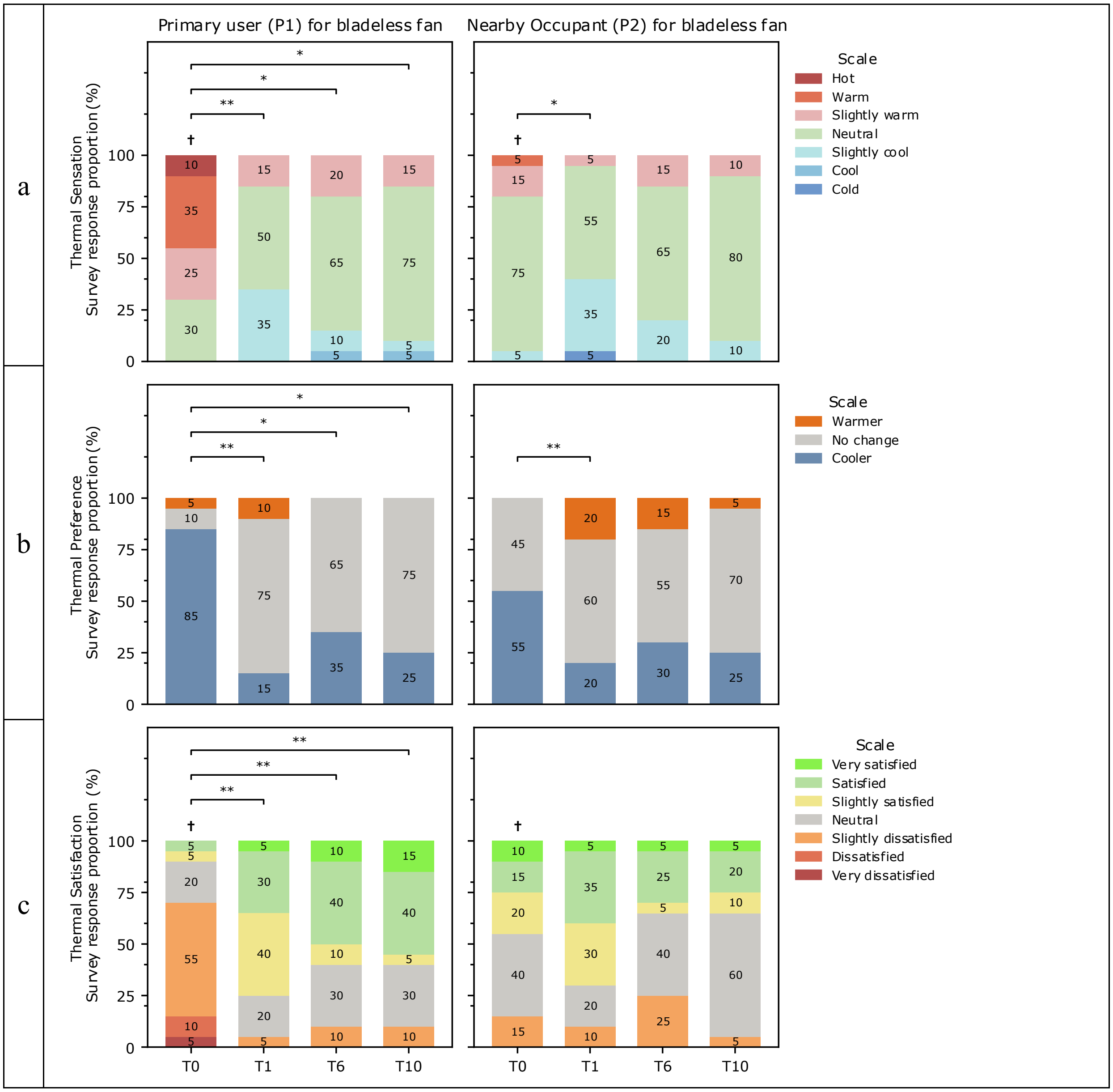


Figure 4.3: Distributions of subjective thermal comfort responses for bladeless fan (N=20). Stacked bar charts illustrating (a) thermal sensation, (b) thermal preference, and (c) thermal satisfaction for Primary User (P1) and Nearby Occupant (P2) across the experimental timeline. Note: Asterisks (*) indicate significant differences within a group relative to baseline (T_0) (Wilcoxon test, *$p < .05$, **$p < .01$, ***$p < .001$). Daggers (†) denote significant differences between P1 and P2 at a specific timestamp (Mann-Whitney U, $p < .05$).

4.3 Air Movement Perception and Preference

Subjective responses regarding air movement (perception and preference) were analyzed to determine the efficacy of airflow distribution for both the bladed (Figure 4.4) and bladeless (Figure 4.5) fans on the P1 and P2 groups across different speed settings.

4.3.1 Bladed Fan

The bladed fan session evaluated how the pulsating and fluctuating patterns of turbulent airflow were perceived within the immediate and peripheral zones of the shared workspace.

P1 Response. Perception for the user group is summarized as follows:

- **Initial Condition (T_0):** In the absence of convective cooling, 95% of participants perceived the air as “Slightly Still” to “Much Too Still”. Consequently, 95% expressed a preference for “More” air movement.
- **High-Speed Exposure (T_1):** The introduction of high-speed turbulent air resulted in a notable shift in perception ($Z = 3.94$, $p < 0.001$, $r = 0.62$); 90% of users categorized the airflow as “Slightly Breezy” to “Too Breezy.” Concurrently, 70% of the P1 user group preferred “Less Air Movement” at high speed ($Z = -3.97$, $p < 0.001$, $r = 0.63$).
- **Low-Speed Exposure ($T_6 – T_{10}$):** Upon transitioning to low speed, the preference for “No Change” in air movement increased significantly to 70% by T_{10} ($Z = -4.04$, $p< 0.001$, $r = 0.64$ for T_0 vs. T_{10}). The perception of air movement also shifted predominantly to “Just Right” (50% at T_{10}) representing a significant increase from 10% at high speed ($Z = -3.55$, $p < 0.001$, $r = 0.56$), as the breezy sensations from high-speed operation were mitigated.

P2 Response. Nearby occupants' perception of air movement indicated the unintended localized spillover of the bladed fan operation into the shared environment:

- **Initial Condition (T_0):** The nearby occupant group reported a predominantly stagnant environment, with 65% characterizing the air as “Slightly Still” to “Much too still” and 65% desiring increased air movement.
- **High-Speed Exposure (T_1):** A marked spillover effect was recorded at the high-speed setting. 50% of P2 participants perceived “Slightly Breezy” to “Too Breezy” conditions, compared to only 5% “Slightly Breezy” at baseline ($Z = 3.26$, $p = 0.001$, $r = 0.52$). Concurrently, 45% of the P2 nearby occupant group expressed a preference for “Less Air Movement” ($Z = -3.85$, $p < 0.001$, $r = 0.61$).
- **Low-Speed Exposure ($T_6 – T_{10}$):** The reduction in speed effectively localized the impact of the airflow to the primary user. 65% of P2 nearby occupants reported a “Just Right” level of air movement ($Z = -3.20$, $p = 0.001$, $r = 0.51$ for T_1 vs. T_{10}) and 75% preferred “No Change” by T_{10}($Z = 3.71$, $p < 0.001$, $r = 0.59$ for T_1 vs. T_{10}) Notably, while 25%

desired more air movement, 0% desired less, confirming the low-speed setting mitigated the disruptive draft for the nearby occupant.

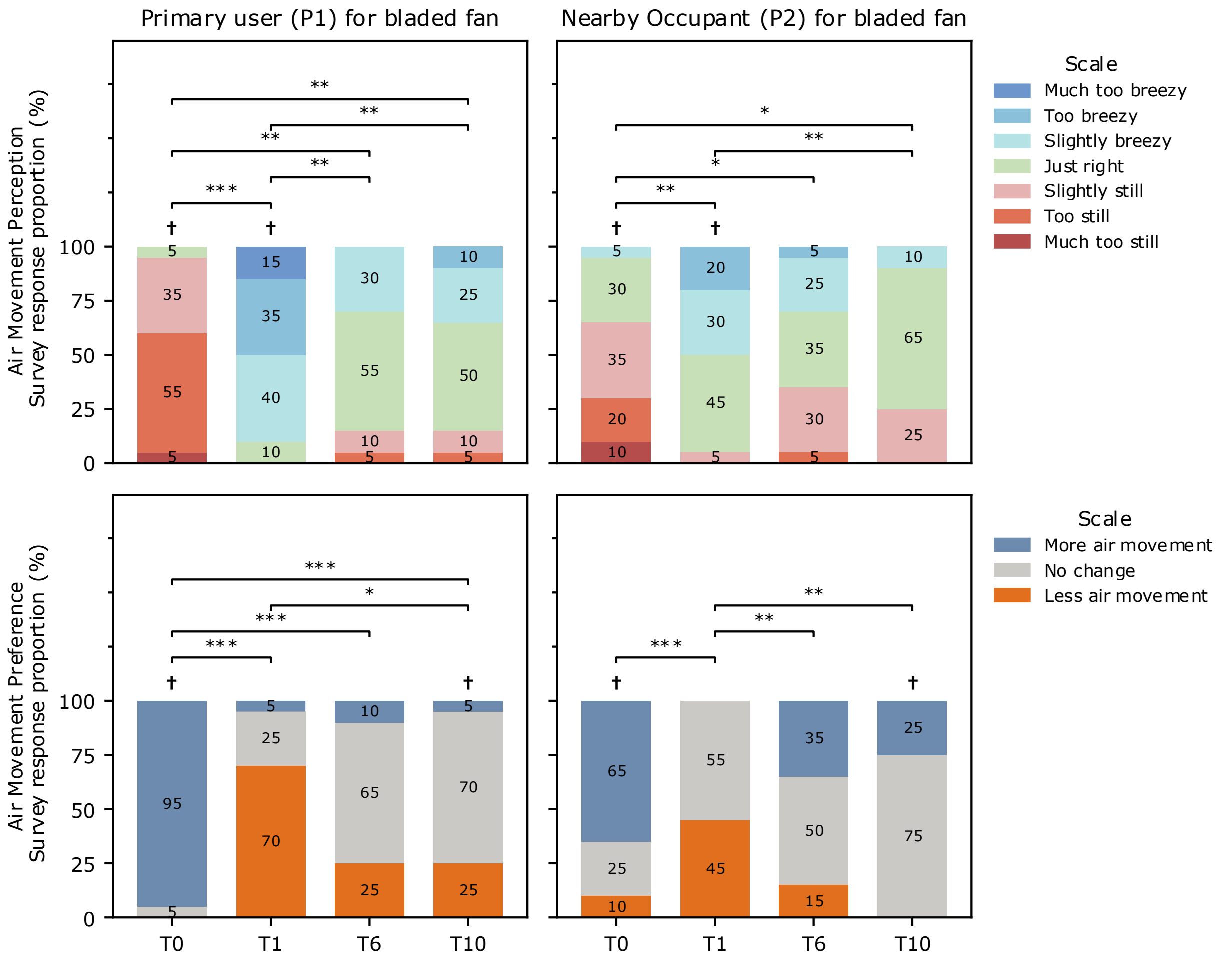


Figure 4.4: Distributions of subjective air movement responses for bladed fan (N=20). Stacked bar charts illustrating (a) air movement perception and (b) air movement preference for Primary User (P1) and Nearby Occupant (P2) across the experimental timeline. Note: Asterisks (*) indicate significant differences within a group relative to baseline (T_0) (Wilcoxon test, *p < .05, **p < .01, ***p < .001). Daggers (†) denote significant differences between P1 and P2 at a specific timestamp (Mann-Whitney U, p < .05).

4.3.2 Bladeless Fan

The bladeless fan session investigated the perception of more uniform and constant airflow produced via air-multiplier technology.

P1 Response. Perception for the user group is summarized as follows:

- **Initial Condition (T_0):** Similar to the bladed fan results, baseline perceptions of air movement for the bladeless fan were stagnant, with 90% characterizing the air as "Slightly Still" to "Much too still" and 80% desiring more air movement.

- **High-Speed Exposure (T_1):** While 60% perceived breezy conditions, the proportion reporting the movement as "Just Right" was 40%, which is a notably higher acceptance rate than the 10% recorded in the bladed session. ($Z = 3.94$, $p < 0.001$, $r = 0.62$). At high speed, the preference for more air movement decreased significantly compared to baseline ($Z = -4.00$, $p < 0.001$, $r = 0.63$).
- **Low-Speed Exposure ($T_6 – T_{10}$):** The bladeless fan maintained high levels of air movement acceptance throughout the low-speed interval. 65-70% of users wished for no change in setting, between T_6 and T_{10} ($Z = -3.57$, $p < 0.001$, $r = 0.56$ for T_0 vs. T_{10} preference), and 65% reported the airflow as "Just Right" ($Z = -3.41$, $p < 0.001$, $r = 0.54$).

P2 Response. Similar to the trends observed in the bladed session, the bladeless spillover was also perceived more as beneficial ventilation than as a disruptive draft:

- **Initial Condition (T_0):** 70% of the nearby occupant group reported "Slightly Still" to "Much too still" air movement. While 65% preferred increased movement, 35% expressed a preference for no change.
- **High-Speed Exposure (T_1):** Perception shifted positively under high-speed operation. The proportion of nearby occupants reporting "Just Right" air movement increased from 25% at baseline to 65% ($Z = 3.32$, $p < 0.001$, $r = 0.52$), and 75% desired no change in the current setting ($Z = -3.46$, $p < 0.001$, $r = 0.55$ for T_0 vs. T_1). Only 25% perceived the air as "Slightly Breezy."
- **Low-Speed Exposure ($T_6 – T_{10}$):** 60% of nearby occupants voted "No Change" in preference. By the end of the session ($Z = -2.09$, $p = 0.037$ for T_0 vs. T_{10}). However, the reduction in velocity caused some participants to perceive the air as stagnant. 50% reported "Slightly Still" to "Too Still" air (compared to only 10% "Slightly Still" at high speed) ($Z = -2.62$, $p = 0.009$ for T_1 vs. T_{10}), while 45% felt it was "Just Right". At the same time, 40% of P2 participants desired more air movement at T_{10}, representing a significant increase from the 10% recorded during high-speed operation ($Z = 2.93$, $p = 0.003$ for T_1 vs. T_{10}).

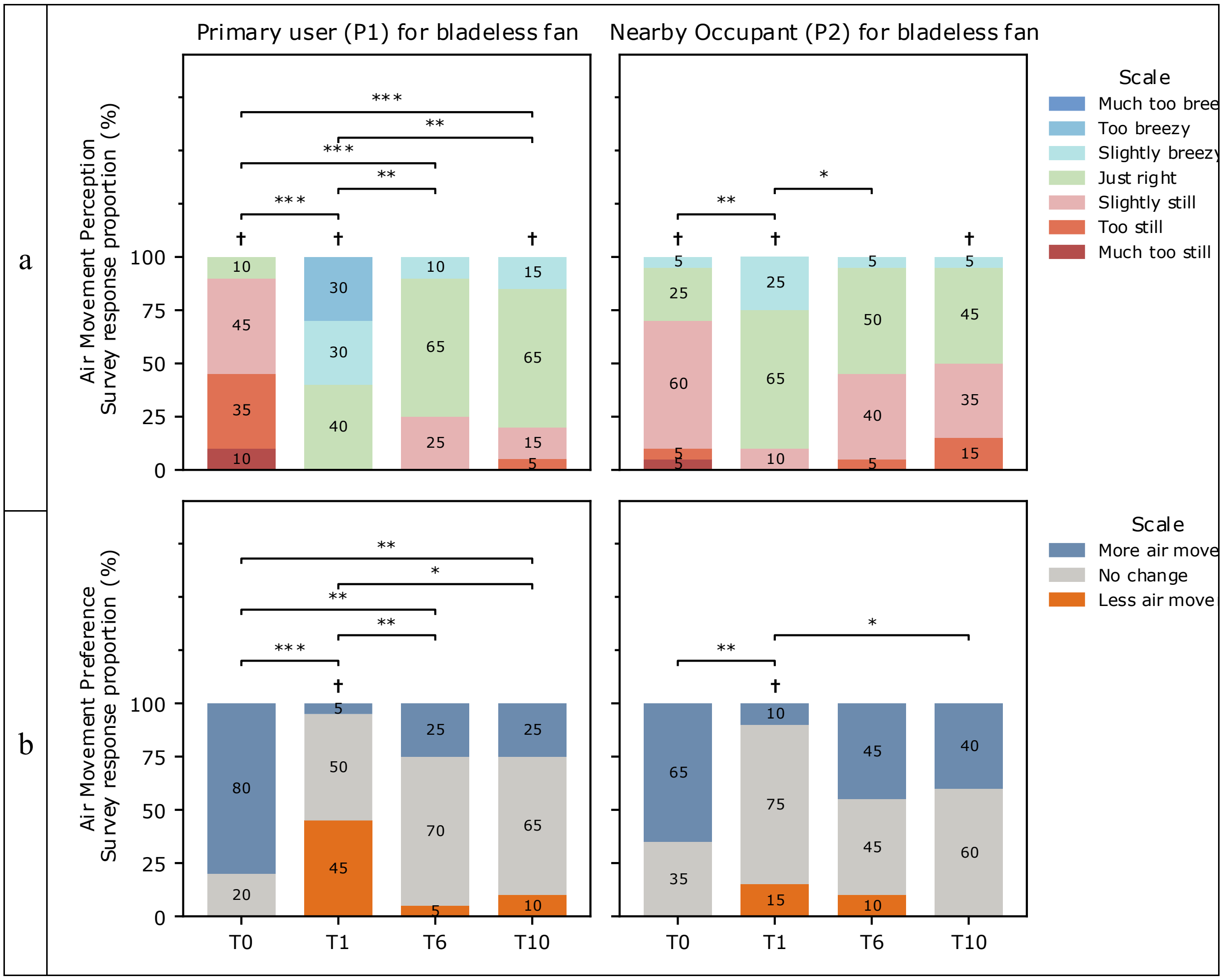


Figure 4.5: Distributions of subjective air movement responses for bladeless fan (N=20). Stacked bar charts illustrating (a) air movement perception and (b) air movement preference for Primary User (P1) and Nearby Occupant (P2) across the experimental timeline. Note: Asterisks (*) indicate significant differences within a group relative to baseline (T_0) (Wilcoxon test, *p < .05, **p < .01, ***p < .001). Daggers (†) denote significant differences between P1 and P2 at a specific timestamp (Mann-Whitney U, p < .05).

Desired Control Adjustments. To evaluate operational air movement acceptability, P1 participants were asked at each interval if they desired to adjust the current fan setting (e.g., reduce speed or turn off the fan) (Figure 4.6). These votes were recorded as a measure of "desired control," representing the threshold at which subjective preference would trigger a change in fan operation had they been given control. The frequency of desired adjustments was notably higher during the high-speed exposure (T_1), particularly in the bladed fan session.

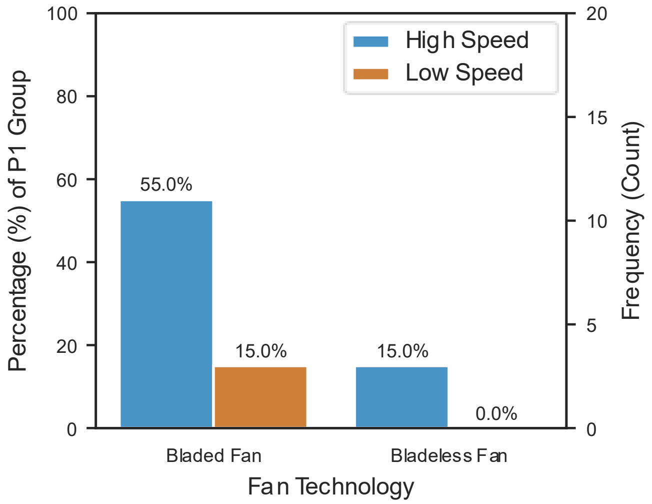


Figure 4.6: Frequency of desired control adjustments. Bar plot illustrating the percentage of participants who indicated a desire to adjust or turn off the fan.

- **Bladed Fan:** The turbulent nature of the bladed airflow appeared to reach occupant tolerance thresholds more rapidly at high speed. 55% of P1 participants expressed a desire to reduce the fan speed within the first five minutes of high-speed exposure, correlating with the high "Too Breezy" perception reported in Section 4.3.1.
- **Bladeless Fan:** In contrast, the more uniform and laminar distribution profile of the bladeless technology resulted in higher operational acceptability. Only 15% of P1 users desired a speed reduction at high speed, aligning with the higher "Just Right" air movement perception recorded for this technology.

Upon the transition to the low-speed interval (T_6–T_{10}), the desire for further adjustment fell to 15% and 0% for bladed and bladeless fan respectively.

4.4 Subjective Noise Annoyance Analysis

Subjective noise annoyance on a 3-point scale (“Not Annoying,” “Slightly Annoying,” and “Annoying”) was analyzed to determine the acoustic impact of each fan technology across different speed settings for the P1 and P2 groups (Figure 4.7 and Figure 4.8). Annoyance metrics were recorded only during fan operation (T_1, T_6, T_{10}), as there was no induced sound prior to fan operation.

4.4.1 Bladed Fan

The bladed fan session evaluated the annoyance level associated with the turbulent airflow noise generated by conventional rotating blades.

P1 Response. The acoustic response for the P1 user group is summarized as follows:

- **High-Speed Exposure (T_1):** High-speed operation introduced immediate acoustic dissatisfaction. 50% categorized it as "Slightly Annoying" and 10% as "Very Annoying" while 40% found the noise "Not Annoying."
- **Low-Speed Exposure (T_6 – T_{10}):** Reducing the speed effectively mitigated the acoustic disturbance. "Not Annoying" ratings rose significantly to 90% at T_6 ($Z = -2.77$, $p = 0.006$, $r = 0.44$) and remained at 85% by T_{10} ($Z = -2.61$, $p = 0.009$, $r = 0.41$).

P2 Response. P2 nearby occupant perception resulting from the fan operation of the P1 primary user is summarized as follows:

- **High-Speed Exposure (T_1):** High-speed operation resulted in a noticeable acoustic spillover, with 40% of the P2 group reporting the noise as "Slightly" to "Very" Annoying.
- **Low-Speed Exposure (T_6 – T_{10}):** The reduction in fan speed successfully resolved the acoustic nuisance for the nearby occupant. Annoyance decreased to 15% at T_6, and by T_{10}, 100% of P2 participants rated the fan as "Not Annoying," confirming that low-speed operation of the bladed fan did not compromise the acoustic comfort of the nearby occupant in the shared environment. ($Z = -2.64$, $p = 0.008$, $r = 0.42$ for T_1 vs. T_{10}).

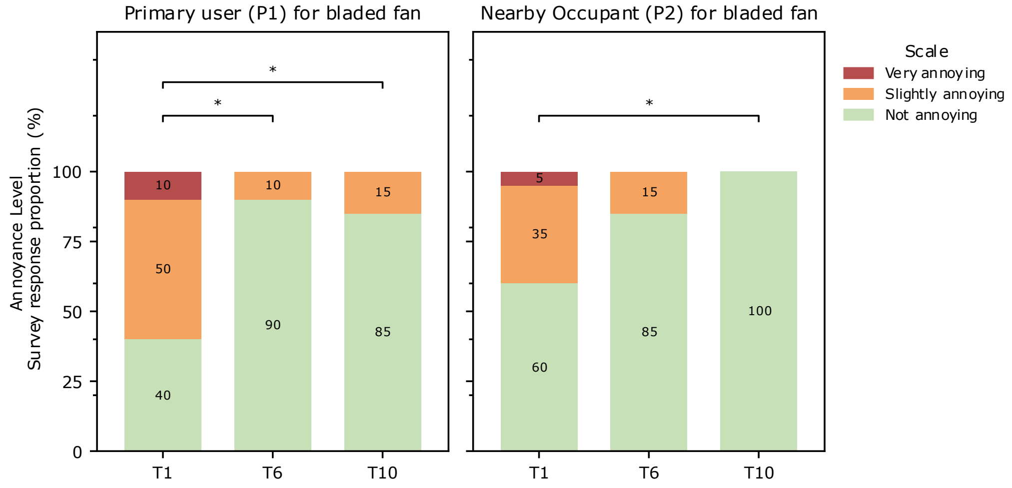


Figure 4.7: Distributions of subjective noise annoyance responses for bladed fan (N=20) for Primary User (P1) and Nearby Occupant (P2) across the experimental timeline. Note: Asterisks (*) indicate significant differences within a group relative to baseline (T_0) (Wilcoxon test, *p < .05, **p < .01, ***p < .001). Daggers () denote significant differences between P1 and P2 at a specific timestamp (Mann-Whitney U, p < .05).

4.4.2 Bladeless Fan

The bladeless fan session investigated the acoustic impact of air-multiplier technology in the shared environment.

P1 Response. Acoustic perception for the P1 user group to the bladeless fan is summarized as follows:

- **High-Speed Exposure (T_1):** Similar to the trends observed with the bladed fan, 65% of P1 users categorized the noise from the high-speed setting as “Slightly” to “Very” Annoying, while 35% rated the device as “Not Annoying.”
- **Low-Speed Exposure (T_6 – T_{10}):** Transitioning to low speed resulted in a significant increase in acoustic acceptability. “Not Annoying” ratings increased from 35% at high speed to 85% at both T_6 ($Z = -2.93$, $p = 0.003$, $r = 0.46$) and T_{10} ($Z = -3.08$, $p = 0.002$, $r = 0.49$).

P2 Response. The P2 nearby occupant group reported the following noise annoyance to the bladeless fan session:

- **High-Speed Exposure (T_1):** The acoustic spillover was notably higher at this setting, with 85% of the P2 group rating the noise as “Slightly” to “Very” Annoying. This rating is significantly higher than that of the P1 group for the same technology (65%) and nearly double the annoyance reported by the P2 group in the bladed session (40%), potentially due to the high-frequency acoustic profile of air-multiplier induction at high velocity.
- **Low-Speed Exposure (T_6 – T_{10}):** Similar to the P1 user group, the shift to low speed effectively removed the acoustic annoyance, with 95% of P2 participants reporting the device as “Not Annoying” by T_{10} ($Z = -4.10$, $p < 0.001$, $r = 0.65$ for T_1 vs. T_{10}). This recovery was already highly significant by the first low-speed interval ($Z = -3.97$, $p < 0.001$, $r = 0.63$).

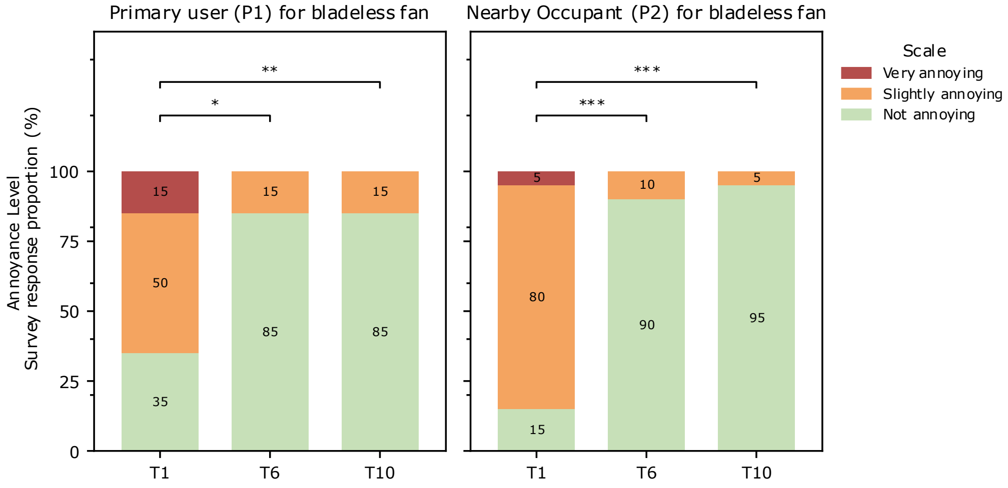


Figure 4.8: Distributions of subjective noise annoyance responses for the bladeless fan (N=20) for Primary User (P1) and Nearby Occupant (P2) across the experimental timeline. Note: Asterisks (*) indicate significant differences within a group relative to baseline (T_0) (Wilcoxon test, *$p < .05$, **$p < .01$, ***$p < .001$). Daggers (†) denote significant differences between P1 and P2 at a specific timestamp (Mann-Whitney U, $p < .05$).

4.5 Multi-Domain Interaction

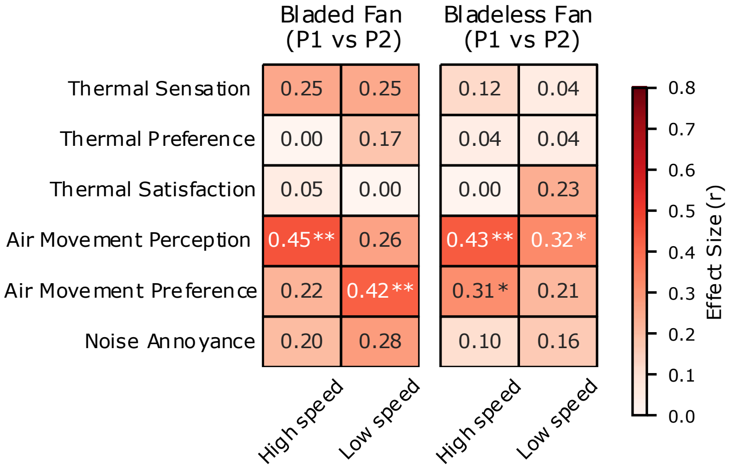


Figure 4.9: Heatmap of Mann-Whitney U effect sizes (r) comparing Primary User (P1) and Nearby Occupant (P2) across all perceptual domains (thermal, air movement, and acoustic). 'High' corresponds to the fan speed at the initial exposure (T_1), and 'Low' corresponds to the fan speed at the 10-minute interval (T_{10}). Asterisks (*) indicate significant differences ($p < 0.05$).

The Mann-Whitney U test was used to compare the subjective responses of P1 and P2 at high and low speeds for both fan technologies. The resulting heatmap (Figure 4.9) shows the effect sizes (r) from the Mann-Whitney U test across three domains: air movement, thermal, and acoustic. Significant differences ($p < 0.05$) are indicated by an asterisk, identifying where the experiences of the user and the nearby occupant diverged most sharply.

Across both fan technologies, air movement perception emerged as the domain with the most pronounced and statistically significant divergence between P1 and P2. For the bladed fan, the largest effect size occurred in air movement perception at the high speed ($r = 0.45$, $p < 0.01$), followed by a moderate effect at the low speed ($r = 0.26$), although the difference at the low speed was not statistically significant. Air movement preference also showed a moderate effect size at low speed ($r = 0.42$, $p < 0.01$). Similarly, with the bladeless fan, air movement perception showed the strongest divergence at high speed ($r = 0.43$, $p < 0.01$) and remained statistically significant at low speed ($r = 0.32$, $p < 0.01$). Air movement preference showed a small to moderate effect size ($r = 0.31$, $p < 0.05$ at high speed; $r = 0.21$ at low speed). This trend across both fan technologies confirms that air movement is the primary source of inter-occupant perceptual variance.

In contrast, the thermal domain exhibited high convergence across all three thermal metrics (sensation, preference, and satisfaction). For both fan technologies, effect sizes for thermal preference and thermal satisfaction remained negligible to small, ranging from 0 to 0.17, with a minor exception for bladeless thermal satisfaction at low speed ($r = 0.23$). Thermal sensation also followed a trend of convergence; however, the effect sizes varied by fan design. The bladed fan had a small effect size (r = 0.25) at both speeds, while the bladeless fan achieved a relatively high convergence in thermal sensation (r = 0.12 at high speed; r = 0.04 at low speed). These results demonstrate that while the physical air movement is perceived differently due to proximity, the resulting thermal perception is largely shared between the user and the nearby occupant.

The acoustic domain showed consistently small effect sizes, indicating a shared noise experience regardless of proximity. For the bladed fan, noise annoyance effect sizes were r = 0.20 (high speed) and r = 0.28 (low speed). The bladeless fan demonstrated even greater convergence, with values of r = 0.10 (high speed) and r = 0.16 (low speed). These findings suggest that while specific acoustic signatures may be annoying (as noted in Section 4.4), the degree of annoyance does not differ substantially between the user and the nearby occupant. Finally, the influence of inherent physiological characteristics was examined. Between-group analyses for biological sex and BMI revealed no significant differences across the evaluated metrics, confirming that the observed perceptual shifts were driven by local environmental changes rather than demographic factors. See Appendix (Tables A.4 and A.5) for the Mann-Whitney U test results for BMI and sex.

5 Discussion

This section discusses the study's findings in relation to the research questions and explores the implications of using desk fans in shared office environments.

5.1 The Impact of Fan Speed on P1 and P2 Perception (Addressing RQ1)

The results show that a fan's operational speed is a primary factor in determining the perceived comfort for users and its subsequent impact on nearby occupants. The transition from High to Low speed affects thermal and airflow perceptions for P1 and P2, highlighting consistent trends across both fan technologies. Interestingly, the findings indicate that using a fan can affect nearby occupants, but this effect is generally perceived positively rather than negatively.

At high speed, the thermal responses of P1 and P2 were notably similar. For P1, High speed provided immediate cooling necessary to offset the initial warm sensation from increased metabolic activity. This response suggests a state of thermal alliesthesia (He et al. 2022) in which a cooling stimulus is perceived as a pleasurable relief because it facilitates a return toward thermal neutrality. This became a shared benefit, as at least 40% of P2 participants also reported cool sensations and satisfaction levels exceeding 80% across both fan technologies (Figures 4.2 and 4.3). This suggests that the high-speed spillover provides a desirable effect for the nearby occupant in stagnant conditions. However, P1 reached a point of diminishing returns more rapidly; the bladed fan led to overcooling, while the bladeless fan resulted in a shift towards neutral sensations. Despite these changes, over 60% of both occupant groups preferred "No change" and reported high satisfaction, confirming that the initial high-intensity cooling was perceived as pleasurable relief rather than a disruption. As the fan transitioned into the low speed, the shared experience continued, with both groups shifting toward thermal neutrality. 50%-80% of participants across both fan technologies reported neutral sensations, and thermal satisfaction remained high (exceeding 85%) (Figures 4.2 and 4.3), indicating that once the initial metabolic heat is dissipated, reduced airspeed is sufficient to maintain occupant comfort.

In contrast, air movement preferences diverged based on proximity to the fan's location. For P1, High-speed airflow was mostly perceived as breezy across both fan types, leading to a mixed preference for "Less air movement" and "No change." Conversely, P2 found this airflow "Just right," particularly with the bladeless fan (65%) (Figures 4.5). This suggests that the high-speed airflow is "filtered" by distance and the intensity that P1 perceives as excessive is attenuated into a comfortable breeze by the time it reached P2. This positive reception is likely attributed to the baseline conditions of the space, since both participants characterized the room air as still before fan activation. At Low speed, the "Just right" condition dominated for P1, but 25-40% of P2 participants began to experience stillness, desiring more air movement (Figures 4.4 and 4.5). Ultimately, the airspeed that satisfies the primary user often wasn't enough for the nearby occupant. Noise annoyance was also speed dependent. At low speed, annoyance was negligible for both P1 and P2 but at high speed P1 was mostly annoyed while P2’s responses were more varied based on the specific fan technology.

5.2 The Impact of Fan Technologies on P1 and P2 Perception (Addressing RQ2)

Across all domains, the bladeless fan exhibited a more localized and stable performance, whereas the bladed fan led to divided outcomes and spillover effects. The distinction between fan technologies is most pronounced in the air movement and thermal comfort metrics. At High speed, the bladed fan’s pulsatile turbulence was perceived by P2 as a disruptive draft, while the bladeless fan’s uniform induction flow acted as beneficial ventilation. Specifically, 45% of P2 participants preferred less air movement during bladed fan use, compared to only 25% for the bladeless fan (Figures 4.4 and 4.5). Bladed fan spillover also resulted in a 25% increase in cool sensations for P2 (Figure 4.2), suggesting a wider, high-velocity air jet that extends beyond the user's primary workstation. For P1, the bladeless fan provided a more steady neutral sensation, whereas the bladed fan’s turbulent pulses frequently led to overcooling and a "too breezy" perception. Consequently, 75% of P2 participants preferred "no change" in air speed during bladeless fan operation (Figure 4.5), demonstrating that its laminar flow effectively cools P1 without compromising P2's thermal and air movement preferences.

Acoustic performance, however, introduces a different set of trade-offs. At Low speed, noise impact was negligible for both groups across both fan technologies. At High speed, a significant "perception-control gap" emerged; while P1 tolerated the noise for the sake of thermal relief, P2 exhibited a heightened sensitivity to the bladeless fan, with 85% reporting annoyance nearly doubling the rate of the bladed session (40%) (Figures 4.7 and 4.8). This suggests that for a passive recipient with no control over the device, the high-frequency induction profile of air-multiplier technology is more intrusive than the lower-frequency "white noise" of traditional axial fans. Ultimately, the efficacy of each fan technology in a shared setting depends on providing sufficient cooling without triggering airflow or acoustic spillover. At High speed, the bladed fan often resulted in overcooling and excessive air movement for both occupants. In contrast, the bladeless fan maintained P1 in a state of thermal neutrality and provided comfortable ventilation for P2, though its acoustic signature remained a barrier to operational balance. The bladeless fan at Low speed emerged as the ideal configuration for shared environments. By eliminating disruptive aerodynamic and acoustic spillover, it functions as a better localized PCS solution, targeting the user without affecting the microenvironment of the co-occupant.

5.3 Multi-domain Comparisons (Addressing RQ3)

The collective interplay among thermal, airflow, and acoustic domains determines the level of indoor environmental quality (IEQ) conflict in high-density offices. The air movement domain represents the primary point of divergence between P1 and P2, showing significantly higher effect sizes than the thermal and acoustic domains (Figure 4.9). These moderate effect sizes in the air movement domain reflect the fan's convective cooling mechanism, where airflow intensity, rather than the ambient temperature in an air-conditioned space, dictates occupants' experience. For the bladed fan, the significant divergence at high speed is attributed to the 40% gap in perceived "breezy" conditions between P1 and P2 (90% vs 50%) (Figure 4.4). This difference confirms that the bladed fan airflow at this speed is notably more intense for the primary user due to the proximity and pulsating nature of the bladed fan. Similarly, the bladeless fan showed a smaller but still significant gap at high speed, where 60% of P1 reported breezy sensations compared to 25% of P2 (Figure 4.5). This relatively lower percentage of air movement perception for the nearby occupant supports the conclusion that bladeless technology is more aerodynamically localized than the bladed fan. While both fans showed a difference in air movement perception at high speed between P1 and P2, the lower spillover profile of the bladeless fan suggests it provides a more controlled microclimate that is less likely to infringe upon the neighbor's space. The IEQ conflict arises when the primary user's thermal relief causes local discomfort for nearby occupants. Even in air-conditioned spaces (~24ºC), a user's thermal state and perception of stagnant airflow can prompt the use of a personal fan. While a nearby occupant in a state of thermal neutrality may welcome subtle air movement, any high-velocity spillover in a densely occupied office may be perceived as a disruptive draft. In contrast to these findings, there was minimal difference between P1 and P2 in the thermal domain. The minimal, non-significant effect sizes in thermal sensation suggest that both occupants perceived the cooling effect similarly at both speeds, effectively sharing a coupled thermal microclimate.

However, the acoustic results reveal a critical "perception-control" gap: at high speeds, the bladeless fan showed a 30% difference in reported noise annoyance, with 80% of P2 identifying the noise as "slightly annoying" compared to only 50% of P1 (Figure 4.8). Although the overall effect size for noise annoyance was statistically small (Figure 4.9), this subjective gap suggests that the high-frequency spectral profile of induction fans can exacerbate the sense of physical intrusion. Because nearby occupants did not experience the same elevated metabolic conditions as the primary user, their cooling needs were different, and therefore their noise tolerance dropped.

These findings have significant implications for the standard provisions for PCS (e.g., ASHRAE Standard 55), which typically define these devices as solutions that should not affect the environment of surrounding occupants. The results suggest that operational balance in multi-occupant spaces is not achieved solely by individual control or by limiting fan speeds. Rather, the aerodynamic and acoustic signatures of the fan technology itself play a significant role in shaping the overall perception and experience of both the users and nearby occupants. Hence, it is important to consider the ideal operational mode for decentralized cooling as a function of technology, speed, and proximity. This provides a balanced approach to ensure sufficient corrective power for the user while maintaining an acoustic and aerodynamic profile that does not compromise the nearby occupants who do not have control over the device.

6 Conclusions

For a desk fan to be adopted as a cooling PCS in office environments, the speed and air delivery technology should be evaluated for their effectiveness in providing the required cooling and also adhering to the ASHRAE Standard 55 definition of PCS. This study assessed the multi-domain impacts of desk fan operation on the user and nearby occupants within a shared workspace. The results highlight the importance of selecting fan technology and operational speeds that provide localized thermal relief to users with minimal or no impact on the microclimate of nearby occupants.

Thermal, airflow, and acoustic metrics were used to assess the impact on users and nearby occupants. Across both technologies, the bladeless fan performed better in terms of thermal comfort and airflow perception for the primary user (P1). The bladeless fan achieved 95% thermal satisfaction at high speed, compared to only 60% for the bladed fan for P1. The result also revealed that 50% of P1 were at neutral sensation at high speed, a comfort level achieved with the bladed fan at low speed. In the air movement domain, P1 perceived the airflow as “Just right” rather than the “Breezy” conditions reported with the use of a bladed fan.

For nearby occupants (P2), the pulsating, wide-jet airflow from the bladed fan was disruptive to 45% of them, causing unintended cooling. In contrast, the bladeless fan’s spillover was perceived as beneficial ventilation, with 75% of P2 preferring “No change,” and overall satisfaction increased compared to the baseline initial condition. At low speed, the bladeless fan airflow became localized, with 50% of P2 occupants reporting air stillness conditions identical to the initial state of the office. This confirms that the room air movement returned to ambient levels, showing the bladeless fan’s efficacy as a localized PCS.

In the acoustic domain, the fans' performance was reversed, with the bladed fan demonstrating greater acceptance. At high speed, 85% of P2 found the bladeless fan annoying, more than double the annoyance caused by the bladed fan (40%). The high-frequency noise of the bladeless fan proved more intrusive to the nearby occupant (85%) than to the primary user (65%), suggesting the sound profile is particularly disruptive in a shared workspace.

For shared workspaces with mechanical cooling, the low-speed setting is recommended. This configuration eliminates acoustic annoyance for both fan technologies (0-5% annoyance) while maintaining high thermal satisfaction for P1 and minimal intrusion into the nearby occupant’s environment.

6.1 Limitations

While this study provides a multi-domain characterization of inter-occupant environmental interaction, several limitations remain that offer opportunities for further investigation:

1. **Baseline Environmental Conditions:** The environmental conditions in the experimental room were representative of a mechanically cooled office (~24ºC). Although this enhances the realistic scenario for typical multi-occupant applications, it introduced minor fluctuations in environmental conditions on some days. The room condition was subject to the central HVAC system's operation. Most participants perceived the baseline ambient conditions as still, which may have heightened the subjective sensitivity of both P1 and P2 to the introduced air movement. Future studies should evaluate these interactions across a wider range of ambient temperatures to determine the extent to which the" shared benefit" of spillover ventilation persists.
2. **Speed Settings and Technology Range:** The bladed and bladeless fans used in this study featured three and nine speed levels, respectively. To maintain a manageable experimental duration for participants, only two speeds were tested. It is possible that the intermediate speed levels, particularly for the bladeless fan, could offer an even more optimal setting that provides sufficient cooling for P1 without negatively affecting P2. Future studies could employ user-defined control settings to identify the specific airspeeds and acoustic profiles that maximize operational harmony.
3. **Exposure Duration and Ordering Effects:** The duration and sequence of fan exposure may also have influenced subjective perceptions. Responses to the high-speed setting were collected after 1 minute of exposure. Collecting responses at the 5th-minute mark at high speed may have provided insights into the progression of overcooling and the cumulative effect of acoustic disturbance for both participants. Furthermore, the experiment always started with high speed followed by low speed, which could have introduced an ordering effect, in which the relief felt at low speed was amplified by the preceding intensity of the high-speed setting. Randomizing the exposure sequence in future experiments would mitigate this bias.
4. **Physical Layout and Metabolic Variability:** This study used a fixed workstation distance (1.5 m). Changes in office density or device orientation could significantly alter the airflow spillover and acoustic propagation. Additionally, the metabolic activity was fixed to treadmill walking to achieve a level of 1.8 MET for P1. Including diverse metabolic states as well as varying the device location/configuration would improve the generalizability of these findings to a broader range of high-density office layouts.
5. **Acoustic Spectral Analysis:** While subjective noise annoyance was recorded, objective sound level and frequency measurements were not performed. The high annoyance reported by P2 during high-speed bladeless operation suggests that the spectral profile (e.g., high-frequency induction noise) is as important as the decibel level (dB). Future work should incorporate acoustic monitoring to correlate specific sound and frequency ranges with subjective annoyance across different PCS technologies.

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Appendix A. Comprehensive Statistical Test Results

Statistical Notation:

The following symbols are used throughout the statistical tables:

χ^2 – Chi-square statistic from the Friedman test

Z – Z-score (standardized test statistic)

W – Kendall's coefficient of concordance (effect size for Friedman test)

r – Effect size (Cohen's r) for Mann-Whitney U and Wilcoxon tests

U – Mann-Whitney U test statistic

p – Probability value (statistical significance level)

W (in Wilcoxon tables) – Wilcoxon signed-rank test statistic

SD – Standard deviation

$p < .05$ – Statistically significant at the 5% level

$p < .01$ – Statistically significant at the 1% level

$p < .001$ – Statistically significant at the 0.1% level

Table A.1: Friedman results showing the differences in subjective response across the speeds

Fan Technology	Metric	Occupant Group	χ^2	Z	p	Effect Size (W)
Desk Fan	Thermal Sensation	Primary User (P1)	46.7	5.77	< .001	0.78
	Thermal Satisfaction	Primary User (P1)	20.84	3.61	< .001	0.35
	Thermal Preference	Primary User (P1)	49.07	5.92	< .001	0.82
	Air Movement Perception	Primary User (P1)	48.35	5.88	< .001	0.81
	Air Movement Preference	Primary User (P1)	46.28	5.74	< .001	0.77
	Annoyance Level	Primary User (P1)	15.17	3.23	< .001	0.38
	Thermal Sensation	Nearby Occupant (P2)	17.3	3.19	< .001	0.29
	Thermal Satisfaction	Nearby Occupant (P2)	0.25	-1.79	0.969	0
	Thermal Preference	Nearby Occupant (P2)	20.94	3.62	< .001	0.35
	Air Movement Perception	Nearby Occupant (P2)	29.94	4.51	< .001	0.5
	Air Movement Preference	Nearby Occupant (P2)	33.18	4.78	< .001	0.55
	Annoyance Level	Nearby Occupant (P2)	10.52	2.55	0.005	0.26
Bladeless Fan	Thermal Sensation	Primary User (P1)	22.48	3.79	< .001	0.37
	Thermal Satisfaction	Primary User (P1)	25.98	4.14	< .001	0.43
	Thermal Preference	Primary User (P1)	22.77	3.82	< .001	0.38
	Air Movement Perception	Primary User (P1)	51.86	6.1	< .001	0.86
	Air Movement Preference	Primary User (P1)	40.36	5.34	< .001	0.67
	Annoyance Level	Primary User (P1)	18.62	3.64	< .001	0.47
	Thermal Sensation	Nearby Occupant (P2)	13.99	2.74	0.003	0.23
	Thermal Satisfaction	Nearby Occupant (P2)	7.67	1.62	0.053	0.13
	Thermal Preference	Nearby Occupant (P2)	15.26	2.92	0.002	0.25
	Air Movement Perception	Nearby Occupant (P2)	24.49	4	< .001	0.41
	Air Movement Preference	Nearby Occupant (P2)	24.73	4.02	< .001	0.41
	Annoyance Level	Nearby Occupant (P2)	32.12	4.9	< .001	0.8
	Thermal Sensation	Primary User (P1)	22.48	3.79	< .001	0.37
	Thermal Satisfaction	Primary User (P1)	25.98	4.14	< .001	0.43

	Thermal Preference	Primary User (P1)	22.77	3.82	< .001	0.38
	Air Movement Perception	Primary User (P1)	51.86	6.1	< .001	0.86
	Air Movement Preference	Primary User (P1)	40.36	5.34	< .001	0.67
	Annoyance Level	Primary User (P1)	18.62	3.64	< .001	0.47

Table A.2: Wilcoxon signed rank test results comparing the pairwise differences between the different speeds.

Fan Technology	Occupant Group	Metric	Comparison	W	Z	p	Effect Size (r)
Bladed	Primary User (P1)	Thermal Sensation	T0 vs T1	0	-3.95	< .001	0.62
			T0 vs T6	0	-3.95	< .001	0.62
			T0 vs T10	0	-3.84	< .001	0.61
			T1 vs T6	18	2.44	0.014	0.39
			T1 vs T10	13.5	2.25	0.025	0.36
			T6 vs T10	10.5	0	1.000	0
		Thermal Satisfaction	T0 vs T1	44.5	2.28	0.023	0.36
			T0 vs T6	3.5	3.58	< .001	0.57
			T0 vs T10	12	3.22	0.001	0.51
			T1 vs T6	22	2.21	0.027	0.35
			T1 vs T10	29.5	1.47	0.140	0.23
			T6 vs T10	9	-1.22	0.222	0.19
		Thermal Preference	T0 vs T1	0	4.04	< .001	0.64
			T0 vs T6	0	3.92	< .001	0.62
			T0 vs T10	0	4.12	< .001	0.65
			T1 vs T6	2	-0.29	0.773	0.05
			T1 vs T10	0	-1.8	0.072	0.28
			T6 vs T10	0	-1.44	0.149	0.23
		Air Movement Perception	T0 vs T1	0	3.94	< .001	0.62
			T0 vs T6	4	3.69	< .001	0.58
			T0 vs T10	3.5	3.71	< .001	0.59
			T1 vs T6	0	-3.66	< .001	0.58
			T1 vs T10	5.5	-3.55	< .001	0.56

		T6 vs T10	6	0.89	0.374	0.14
	Air Movement Preference	T0 vs T1	0	-3.97	< .001	0.63
		T0 vs T6	0	-3.92	< .001	0.62
		T0 vs T10	0	-4.04	< .001	0.64
		T1 vs T6	5.5	2.62	0.009	0.41
		T1 vs T10	6	2.66	0.008	0.42
		T6 vs T10	2	-0.29	0.773	0.05
	Annoyance Level	T1 vs T6	5.5	-2.77	0.006	0.44
		T1 vs T10	5	-2.61	0.009	0.41
		T6 vs T10	0	0	1.000	0
Nearby Occupant (P2)	Thermal Sensation	T0 vs T1	0	-3.24	0.001	0.51
		T0 vs T6	17	-2.28	0.023	0.36
		T0 vs T10	18.5	-1.3	0.193	0.21
		T1 vs T6	19	1.26	0.209	0.2
		T1 vs T10	12	2.48	0.013	0.39
		T6 vs T10	30	1.13	0.260	0.18
	Thermal Preference	T0 vs T1	0	3.38	< .001	0.53
		T0 vs T6	4	2.25	0.025	0.36
		T0 vs T10	4.5	2.25	0.025	0.36
		T1 vs T6	4.5	-2.04	0.041	0.32
		T1 vs T10	0	-2.55	0.011	0.4
		T6 vs T10	6	-0.3	0.766	0.05
	Air Movement Perception	T0 vs T1	8	3.26	0.001	0.52
		T0 vs T6	11	3.02	0.003	0.48
		T0 vs T10	4.5	2.92	0.004	0.46
		T1 vs T6	24	-2.6	0.009	0.41
		T1 vs T10	6.5	-3.2	0.001	0.51
		T6 vs T10	10.5	-0.54	0.588	0.09
	Air Movement Preference	T0 vs T1	0	-3.85	< .001	0.61
		T0 vs T6	5	-2.27	0.023	0.36
		T0 vs T10	11	-1.84	0.066	0.29
		T1 vs T6	0	3.57	< .001	0.56

			T1 vs T10	0	3.71	< .001	0.59
			T6 vs T10	6	0.3	0.766	0.05
		Annoyance Level	T1 vs T6	11	-1.84	0.066	0.29
			T1 vs T10	0	-2.64	0.008	0.42
			T6 vs T10	0	-1.44	0.149	0.23
Bladeless Fan	Primary User (P1)	Thermal Sensation	T0 vs T1	0	-3.21	0.001	0.51
			T0 vs T6	3	-3.14	0.002	0.5
			T0 vs T10	0	-3.09	0.002	0.49
			T1 vs T6	27.5	0.92	0.356	0.15
			T1 vs T10	18	0.97	0.331	0.15
			T6 vs T10	10.5	0	1.000	0
		Thermal Satisfaction	T0 vs T1	3	3.49	< .001	0.55
			T0 vs T6	7.5	3.27	0.001	0.52
			T0 vs T10	0	3.4	< .001	0.54
			T1 vs T6	44	0.07	0.942	0.01
			T1 vs T10	49	0.19	0.846	0.03
			T6 vs T10	21	0.12	0.903	0.02
		Thermal Preference	T0 vs T1	7	3.23	0.001	0.51
			T0 vs T6	6	2.66	0.008	0.42
			T0 vs T10	7	3.01	0.003	0.48
			T1 vs T6	4.5	-2.04	0.041	0.32
			T1 vs T10	3.5	-1.52	0.129	0.24
			T6 vs T10	2.5	0.8	0.424	0.13
		Air Movement Perception	T0 vs T1	0	3.94	< .001	0.62
			T0 vs T6	0	3.82	< .001	0.6
			T0 vs T10	0	3.8	< .001	0.6
			T1 vs T6	0	-3.51	< .001	0.55
			T1 vs T10	0	-3.41	< .001	0.54
			T6 vs T10	2	0.29	0.773	0.05
		Air Movement Preference	T0 vs T1	0	-4	< .001	0.63
			T0 vs T6	0	-3.42	< .001	0.54
			T0 vs T10	0	-3.57	< .001	0.56
			T1 vs T6	0	3.16	0.002	0.5

			T1 vs T10	0	3	0.003	0.47
			T6 vs T10	2	-0.29	0.773	0.05
		Annoyance Level	T1 vs T6	6	-2.93	0.003	0.46
			T1 vs T10	0	-3.08	0.002	0.49
			T6 vs T10	1.5	0	1.000	0
Bladeless Fan	Nearby Occupant (P2)	Thermal Sensation	T0 vs T1	0	-3.08	0.002	0.49
			T0 vs T6	3	-1.56	0.120	0.25
			T0 vs T10	5	-1.08	0.279	0.17
			T1 vs T6	2.5	1.91	0.056	0.3
			T1 vs T10	7	1.84	0.066	0.29
			T6 vs T10	2	0.29	0.773	0.05
		Thermal Preference	T0 vs T1	0	3.27	0.001	0.52
			T0 vs T6	0	2.44	0.015	0.39
			T0 vs T10	0	2.22	0.026	0.35
			T1 vs T6	8	-1.04	0.299	0.16
			T1 vs T10	16.5	-1.21	0.227	0.19
			T6 vs T10	6	-0.3	0.766	0.05
		Air Movement Perception	T0 vs T1	6	3.32	< .001	0.52
			T0 vs T6	8.5	1.69	0.092	0.27
			T0 vs T10	13.5	1.09	0.275	0.17
			T1 vs T6	6.5	-2.96	0.003	0.47
			T1 vs T10	12	-2.62	0.009	0.41
			T6 vs T10	9.5	-0.7	0.482	0.11
		Air Movement Preference	T0 vs T1	0	-3.46	< .001	0.55
			T0 vs T6	0	-1.67	0.095	0.26
			T0 vs T10	0	-2.09	0.037	0.33
			T1 vs T6	5.5	2.47	0.013	0.39
			T1 vs T10	0	2.93	0.003	0.46
			T6 vs T10	2	0.29	0.773	0.05
		Annoyance Level	T1 vs T6	0	-3.97	< .001	0.63
			T1 vs T10	0	-4.1	< .001	0.65
			T6 vs T10	0	0	1.000	0

Table A.3: Mann-Whitney U test results comparing the subjective responses between Primary Users (P1) and Nearby Occupants (P2) at the different timestamps.

Fan Technology	Metric	Timestamp	P1 Mean	P2 Mean	Effect Size (r)	Z-score	U	p-value
Bladed Fan	Thermal Sensation	T0	1.8	0.2	0.74	4.67	367	< .001
	Thermal Sensation	T1	-1.2	-0.75	0.25	1.58	146	0.114
	Thermal Sensation	T6	-0.45	-0.45	0.03	0.16	194	0.869
	Thermal Sensation	T10	-0.45	-0.15	0.25	1.55	150.5	0.121
	Thermal Preference	T0	-0.9	-0.5	0.39	2.45	129	0.014
	Thermal Preference	T1	0.25	0.25	0	0	200	1.000
	Thermal Preference	T6	0.2	-0.05	0.19	1.23	239.5	0.221
	Thermal Preference	T10	0.05	-0.1	0.17	1.1	227.5	0.269
	Thermal Satisfaction	T0	-0.7	0.85	0.61	3.86	61	< .001
	Thermal Satisfaction	T1	0.5	0.65	0.05	0.29	189	0.769
	Thermal Satisfaction	T6	1.25	1	0.1	0.62	222.5	0.538
	Thermal Satisfaction	T10	0.95	0.95	0	0	200	1.000
	Air Movement Perception	T0	-1.6	-1	0.32	2.05	127.5	0.040
	Air Movement Perception	T1	1.55	0.65	0.45	2.84	301	0.004
	Air Movement Perception	T6	0.1	-0.05	0.1	0.65	223	0.517
	Air Movement Perception	T10	0.25	-0.15	0.26	1.65	255	0.099
	Air Movement Preference	T0	0.95	0.55	0.37	2.35	261	0.019
	Air Movement Preference	T1	-0.65	-0.45	0.22	1.38	155.5	0.168
	Air Movement Preference	T6	-0.15	0.2	0.26	1.67	144.5	0.094
	Air Movement Preference	T10	-0.2	0.25	0.42	2.66	122.5	0.008
	Annoyance Level	T1	0.7	0.45	0.2	1.26	242	0.209
	Annoyance Level	T6	0.1	0.15	0.07	0.45	190	0.654
	Annoyance Level	T10	0.15	0	0.28	1.75	230	0.080
Bladeless Fan	Thermal Sensation	T0	1.25	0.2	0.53	3.38	315	< .001
	Thermal Sensation	T1	-0.2	-0.45	0.12	0.74	225	0.462
	Thermal Sensation	T6	0	-0.05	0.07	0.45	214.5	0.655
	Thermal Sensation	T10	0	0	0.04	0.28	208	0.781
	Thermal Preference	T0	-0.8	-0.55	0.29	1.86	144.5	0.062
	Thermal Preference	T1	-0.05	0	0.04	0.25	192	0.806
	Thermal Preference	T6	-0.35	-0.15	0.14	0.91	170.5	0.365
	Thermal Preference	T10	-0.25	-0.2	0.04	0.24	192.5	0.807
	Thermal Satisfaction	T0	-0.75	0.65	0.56	3.52	74	< .001

	Thermal Satisfaction	T1	1.1	1.05	0	0.03	201.5	0.977
	Thermal Satisfaction	T6	1.1	0.45	0.25	1.6	257	0.111
	Thermal Satisfaction	T10	1.2	0.6	0.23	1.47	251.5	0.142
	Air Movement Perception	T0	-1.45	-0.8	0.39	2.45	116.5	0.014
	Air Movement Perception	T1	0.9	0.15	0.43	2.74	293	0.006
	Air Movement Perception	T6	-0.15	-0.45	0.22	1.4	246	0.162
	Air Movement Perception	T10	-0.1	-0.6	0.32	2.02	268	0.043
	Air Movement Preference	T0	0.8	0.65	0.16	1.03	230	0.302
	Air Movement Preference	T1	-0.4	-0.05	0.31	1.96	137.5	0.049
	Air Movement Preference	T6	0.2	0.35	0.15	0.93	169.5	0.354
	Air Movement Preference	T10	0.15	0.4	0.21	1.32	158	0.186
	Annoyance Level	T1	0.8	0.9	0.1	0.66	179	0.510
	Annoyance Level	T6	0.15	0.1	0.07	0.45	210	0.654
	Annoyance Level	T10	0.15	0.05	0.16	1.01	220	0.310

Table A.4: Mann-Whitney U test results comparing the subjective responses between males and females.

Fan Technology	Metric	Male Mean	Female Mean	Z-score	Effect Size (r)	U	p-value
Bladed Fan	Thermal Sensation	-0.28	-0.33	0.42	0.03	7437.5	0.676
	Thermal Preference	-0.05	0.12	1.97	0.12	6235.5	0.049
	Thermal Satisfaction	0.6	0.62	0.17	0.01	7120.5	0.861
	Air Movement Perception	0.14	0.44	1.65	0.1	6321	0.100
	Air Movement Preference	-0.01	-0.15	1.39	0.09	7940	0.166
	Annoyance Level	0.3	0.31	0.14	0.01	4311	0.891
Bladeless Fan	Thermal Sensation	0.08	0.04	0.38	0.02	6435	0.706
	Thermal Preference	-0.28	-0.18	1.25	0.08	5724	0.212
	Thermal Satisfaction	0.65	0.68	0.27	0.02	6139	0.788
	Air Movement Perception	-0.27	-0.14	0.85	0.05	5867	0.396
	Air Movement Preference	0.24	0.07	1.87	0.12	7119	0.062
	Annoyance Level	0.37	0.4	0.34	0.03	3530.5	0.734

Table A.5: Mann-Whitney U test results comparing the subjective responses between Normal and High BMI categories

Technology	Metric	High BMI Mean	Normal BMI Mean	Z-score	Effect Size (r)	U	p-value
Bladed Fan	Thermal Sensation	-0.22	-0.32	0.88	0.07	4121.5	0.381
	Thermal Preference	-0.18	0.05	2.31	0.17	3149.5	0.021
	Thermal Satisfaction	0.4	0.77	1.95	0.15	3200	0.051
	Air Movement Perception	0.02	0.23	1.17	0.09	3456	0.241
	Air Movement Preference	0.11	-0.1	1.88	0.14	4433	0.060
	Annoyance Level	0.27	0.32	0.67	0.06	2174	0.500
Bladeless Fan	Thermal Sensation	0.16	0.01	1.14	0.09	3688.5	0.254
	Thermal Preference	-0.33	-0.24	1.16	0.09	3069	0.246
	Thermal Satisfaction	0.38	0.89	2.54	0.2	2629.5	0.011
	Air Movement Perception	-0.34	-0.21	0.72	0.06	3175	0.474
	Air Movement Preference	0.32	0.17	1.45	0.11	3784	0.147
	Annoyance Level	0.31	0.42	1.01	0.09	1774.5	0.313

Note: Participants were categorized into two groups: **Normal** (comprising 'Underweight' and 'Normal' BMI) and **High** (comprising 'Overweight' and 'Obese' BMI) for the purpose of this analysis. Mean values in Table A.4 and A.5 represent the average subjective vote for each BMI group across all measurement timepoints.