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Evaluation of Passenger Thermal Comfort for Two Different Underground Metro Station Typologies in Istanbul

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Abstract

This study examines two different underground metro station typologies in Istanbul to evaluate passenger thermal comfort conditions. Long-term field measurements are conducted, and the relative warmth index (RWI) values are calculated to compare the stations' thermal comfort conditions. The RWI method is employed due to transient environments in metro stations. Dry-bulb temperature and relative humidity data are simultaneously measured at 19 points in Şişli/Mecidiyeköy and 17 points in Gayrettepe station at one-minute intervals. The measurements are conducted every day throughout spring, summer, and autumn. The results show that the expected thermal comfort conditions at the stations are not met for all three seasons. Passenger thermal comfort is at its lowest level in summer, followed by autumn and spring. The RWI values for the platform and concourse levels at the cut-and-cover type are higher than at the bored-tunnel type station due to the lower train-induced air velocity in cut-and-cover type stations.

Keywords: thermal comfort, field measurements, relative warmth index, underground metro station typology

1. Introduction

Reducing carbon emissions is fundamental in mitigating global warming and ensuring a more sustainable and livable world for future generations. The advancement and widespread implementation of public transportation, particularly rail systems, and reduced emissions from private vehicles in urban areas are essential for achieving this objective. Rail system lines must be designed with the following characteristics to encourage their use: accessibility, speed, comfort, reliability, safety, and integration. In recent years, Türkiye has witnessed a notable investment surge in expanding its rail infrastructure. Municipal budgets in major cities such as Istanbul, Ankara, Izmir, and Bursa have allocated a sizable portion of their resources to rail systems.

Istanbul, a vast metropolis situated at the confluence of the European and Asian continents, has a population exceeding 15 million. It is characterized by considerable traffic congestion, particularly on the European side. New rail system lines are being constructed citywide to reduce travel times and ease vehicle traffic in Istanbul. Istanbul's climate is influenced by both Mediterranean and Black Sea conditions, with cold, wet winters and hot, humid summers [1]. Istanbul's annual heating and cooling design dry-bulb air temperatures are −1.4 °C and 32.1 °C, respectively [2]. However, in recent years, the dry-bulb air temperature has reached 40 °C during the summer months due to global warming.

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In the design process of new rail system lines, it is paramount to consider the impact of these designs on the health and satisfaction of passengers. Despite the temporary exposure to the environment of a metro station, unfavorable conditions can nevertheless result in adverse effects on passengers' health or thermal comfort, potentially causing discomfort or other negative impacts [3]. Factors such as thermal environment, air quality, air velocity, noise levels, travel time, and vibration are paramount to passenger health and satisfaction. Most researchers have studied air quality issues for underground rail systems [4-11]. Despite the increasing recognition of indoor thermal comfort, most studies have concentrated on building environments, including offices, residential buildings, and non-residential buildings [12].

The operation of metro systems can generate considerable heat, which may lead to notable increases in the temperatures of the tunnels and stations. Without sufficient cooling, this can result in passenger discomfort, particularly in warm weather [13]. The combined heat from train engines, electric lighting, and passengers' bodies can cause excessively elevated temperatures beyond what is necessary to ensure adequate thermal comfort levels. Furthermore, installing air-conditioning units within the train cars introduces a significant heat source into the tunnels [14].

The thermal comfort of underground metro stations can be evaluated by applying various techniques. The thermal environment of underground metro stations is transient. Therefore, selecting the appropriate thermal comfort index to make a correct evaluation is significant. A review of the existing literature reveals two distinct methods for evaluating thermal comfort in underground metro stations that have gained prominence. One of these methods includes the relative warmth index (RWI) and heat deficit rate (HDR) thermal indices, which were designed explicitly for transient environments or metro systems. These indices are derived from the relative strain index (RSI) [15-16]. The other method includes the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices, which were derived for application in steady-state environments [17-19].

Several researchers have conducted theoretical and practical studies on the thermal environment and comfort in underground metro stations in various cities. Ordódy [20] recommended describing the primary characteristics of the existing ventilation system utilized in the Budapest metro. Subsequently, the climatic conditions and thermal comfort were presented, employing the PMV and PPD indices in both passenger and operative areas, based on previous empirical studies. Abbaspour et al. [21] researched thermal comfort in metro stations and trains on lines 1 and 2 in Tehran. Temperature, relative humidity, and air velocity values are measured in this study at distinct locations and times. Thermal comfort was evaluated using the RWI method. Marzouk and Abdelaty [22] employed a wireless sensor network (WSN) in conjunction with building information modeling (BIM) to determine thermal conditions in the Cairo metro. The WSN collected air temperature and humidity data, and the findings were then visualized using a BIM-based model.

Han et al. [23] examined the indoor environments and the comfort of passengers inside metro stations across three seasons. The study involved the selection of six metro stations in Seoul for physical environment measurements and administering a survey to 5,282 passengers, with both elements being carried out concurrently. Assimakopoulos and Katavoutas [24] conducted on-site measurements during the summer at the platforms of two metro stations in Athens, each with unique depth and design characteristics. The findings were subsequently evaluated against international standards utilizing the PMV and PPD indices. Sinha and Rajasekar [25] employed an agent-based modeling approach to gain insight into the dynamics of exposure time, metabolic rates, and clothing insulation to analyze thermal comfort conditions inside a metro station in New Delhi.

Pan et al. [26] applied a dynamic thermal comfort assessment method to investigate thermal sensations within the metro environment. Field studies were conducted at two subway stations in Beijing, where thermal sensation and comfort changes were evaluated. Passi et al. [27] investigated to ascertain the levels of indoor thermal comfort experienced by passengers on the metro platforms and trains in Chennai. This study was undertaken to understand passengers' comfort perceptions better. Field data was gathered from seven underground metro stations across the summer and winter seasons. This evaluation of passenger thermal comfort was conducted in two stages. Environmental conditions were initially assessed, and a subjective survey was subsequently conducted. Sui et al. [28] carried out an investigation involving field measurements and a questionnaire survey to evaluate the thermal environment and human thermal comfort at two metro stations in Xi'an during the summer months. The research utilized the RWI and a modified version, relying on a comparative analysis of the predicted results obtained from both the RWI and the survey methods.

A literature review reveals that field measurements are typically conducted at only one or a few points over short periods, commonly on an hourly, daily, or weekly basis for metro stations. These studies depend on limited data, which is insufficient for fully capturing the variability of environmental conditions within the station. Consequently, using such limited data to draw inferences for an entire season can result in inaccurate or incomplete interpretations, potentially failing to account for significant fluctuations in thermal comfort that occur over lengthy periods. This situation indicates the need for more exhaustive, long-term data gathering to ensure reliable thermal comfort evaluations in metro stations. Moreover, no study in the literature directly compared different station typologies regarding thermal comfort.

This study conducted long-term field measurements across three seasons: spring, summer, and autumn. The measurements were taken at two consecutive stations on the Istanbul M2 metro line, which is the busiest metro line in Istanbul. The dry-bulb temperature and relative humidity data were obtained at various locations on the stations' platforms and concourse levels. The data were then subjected to comparative analysis and evaluation with the RWI scale. The RWI method was selected to evaluate passenger thermal comfort due to its development for transient environments such as metro stations.

2. Materials and Methods

The Istanbul M2 Yenikapı-Hacıosman metro line is characterized by a length of 23.49 km and comprises 16 stations, 15 underground and one elevated. Moreover, it is integrated with other rail system lines at various stations. The platform length of the line is 180 meters, and eight-car trains are utilized on the line. The M2 metro line has an average daily ridership of 500,000, with a peak hour headway of 3 minutes and 55 seconds. The underground stations at Şişli/Mecidiyeköy and Gayrettepe, which are part of the M2 metro line, were constructed using different methods. The platform of the Şişli/Mecidiyeköy station was constructed using the tunneling method, whereas its concourse was constructed using the cut-and-cover method. The station is designed with an island platform and two concourses. The total area of the station is 6,100 m^2, with a platform depth of 28 m. The Gayrettepe station was constructed using the cut-and-cover method for the entire station. The station is designed with an island platform and a concourse. The total area of the station is 9,600 m^2, with a platform depth of 25 m.

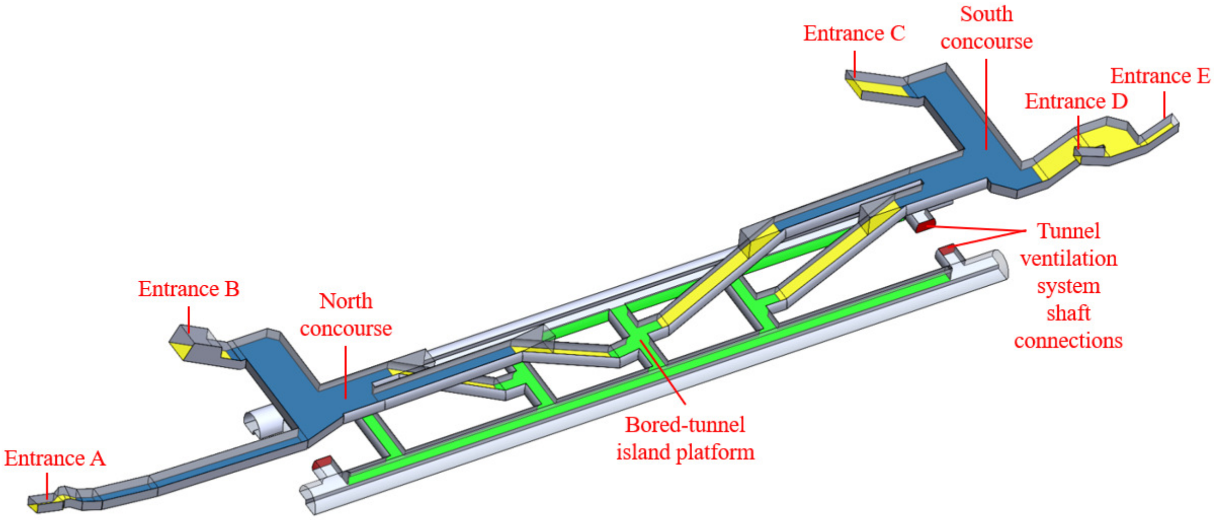


Fig. 1 3D schematic model of the Şişli/Mecidiyeköy station

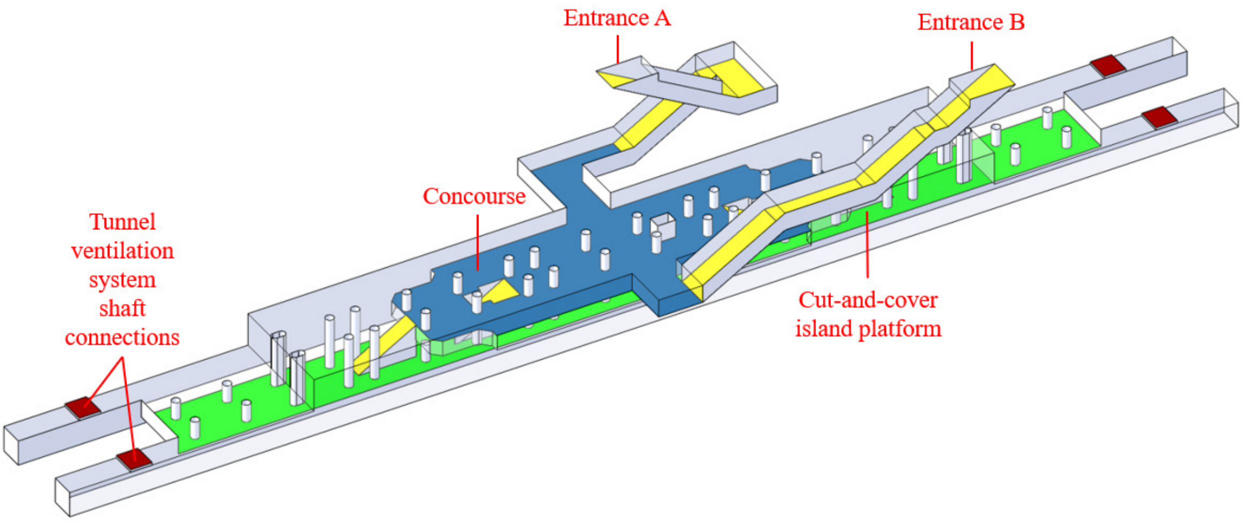


Fig. 2 3D schematic model of the Gayrettepe station

The two stations are situated near each other. It should be noted that the passenger areas at the stations are not equipped with an air-conditioning system. In extreme temperatures, the activation of exhaust fans extracts warm air from the station, while make-up air is introduced through stairwells and tunnels. Despite the presence of an air circulation system with a piston effect and exhaust fans, the quality and thermal conditions of the air entering the station remain uncertain. Three-dimensional schematic models of Şişli/Mecidiyeköy and Gayrettepe stations are presented in Fig. 1 and Fig. 2, respectively. In these schematic models, the concourse is represented in blue, the platform in green, and the stair zones in yellow. The red-colored areas indicate the regions where the tunnel ventilation system shafts are connected.

2.1. Field measurements

Dry-bulb temperature, relative humidity, and air velocity measurements were conducted at the Şişli/Mecidiyeköy and Gayrettepe stations to evaluate thermal comfort. Dry-bulb temperature and relative humidity measurements were conducted throughout three seasons: spring, summer, and autumn. Testo Saveris H2E ethernet probes were utilized to measure dry-bulb temperature and relative humidity. Furthermore, air velocity was gauged on the platform and concourse levels using a Testo 410 anemometer to determine the mean ambient air velocity (V_a). The technical parameters of the Testo Saveris H2E and Testo 410 devices are presented in Table 1.

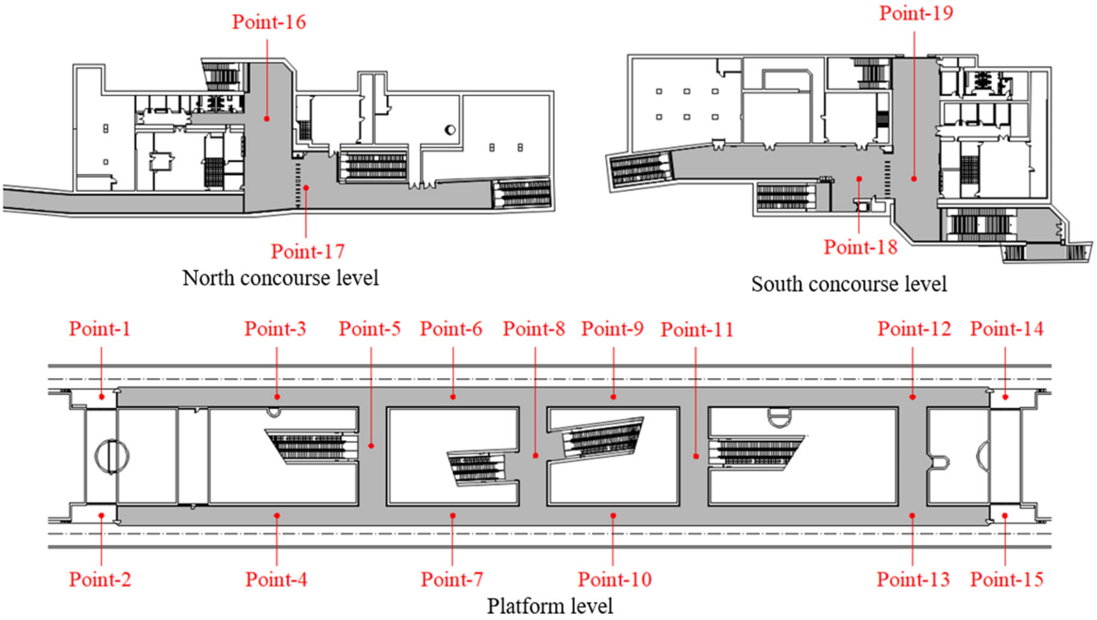
Table 1 Technical parameters of the measurement devices

Parameters	Dry-bulb temperature	Relative humidity	Ambient air velocity
Measuring range	−20 to +70 °C	0 to 100% RH	0.4 to 20 m/s
Accuracy	±0.5 °C	<90% RH: ±2% RH at +25 °C >90% RH: ±3% RH at +25 °C ±0.03% RH/K ±1 digit	±(0.2 m/s + 2% of mv)
Resolution	0.1 °C	0.1% RH	0.1 m/s

A total of 19 measurement devices were installed at Şişli/Mecidiyeköy station, with 15 on the platform and 2 at each of the two different concourses. A total of 17 measurement devices were installed at Gayrettepe station, with 13 on the platform and 4 on the concourse. The measurement devices were installed at a height of 2.5 m and mounted on structural columns, walls, and ceilings using custom-designed supports. This height was chosen to prevent passengers from intentionally or accidentally touching the devices.

The locations of the measurement points at Şişli/Mecidiyeköy and Gayrettepe stations are illustrated in Fig. 3 and Fig. 4, respectively. The gray-colored areas in the figures indicate the passenger areas. As illustrated in both figures, measurement Points 1, 2, 14, and 15 on the platform level of Şişli/Mecidiyeköy station, as well as measurement Points 1, 2, 12, and 13 on the platform level of Gayrettepe station, are not situated within the designated passenger areas. Instead, they are located within the tunnel ventilation system shaft regions at the beginning and end of the platforms. The dry-bulb temperature and relative humidity data of the air entering and leaving the station from the tunnel and shaft regions were obtained through direct measurement at these points.

Dry-bulb temperature and relative humidity data were collected from the stations at one-minute intervals, 24 hours a day, every day during the spring, summer, and autumn seasons. Measurements were conducted simultaneously at 19 points in Şişli/Mecidiyeköy and 17 points in Gayrettepe station from March 1 to November 30. The data from each measurement device was automatically transferred to the main computer and recorded minute by minute.

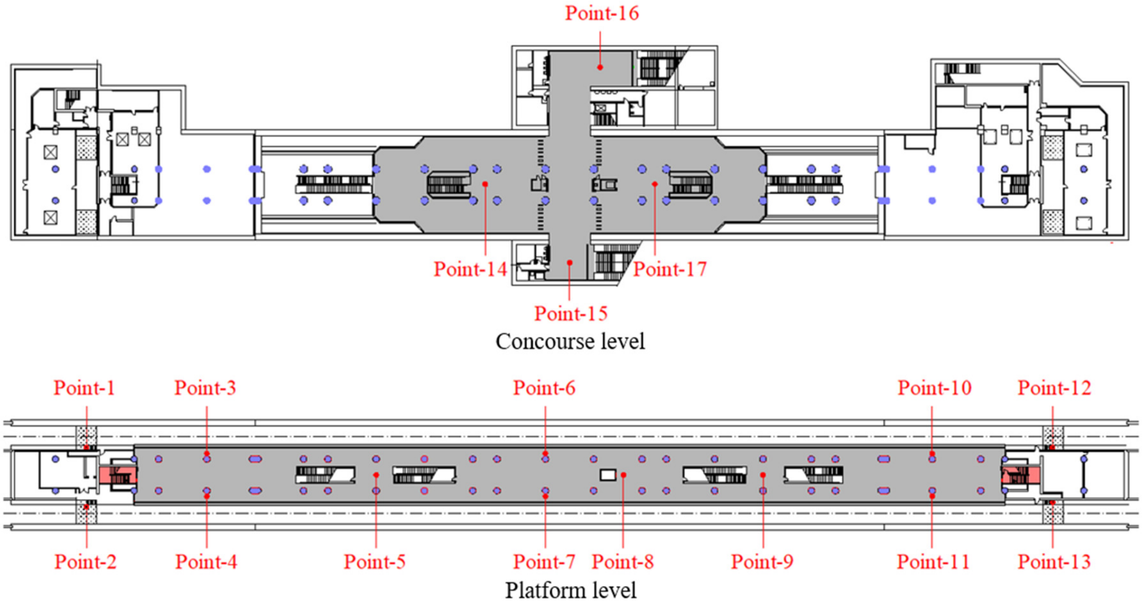


North concourse level

South concourse level

Platform level

Fig. 3 Measurement points at Şişli/Mecidiyeköy station



Concourse level

Platform level

Fig. 4 Measurement points at Gayrettepe station

2.2. *Evaluation of thermal comfort using the RWI*

The RWI is the preferred thermal index to evaluate thermal comfort in metro systems. The index was designed for transient environments and is based on the RSI. The RSI is a metric that quantifies the ratio between the actual quantity of sweating needed and the maximum sustainable quantity of sweating. It is, however, not an appropriate metric for metro applications, as it does not reflect thermal comfort. The RSI is adapted to warm environments by combining experimental data from comfort tests funded by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). This research led to the creation of a new index called RWI, which is based on the original theory but incorporates the findings of the comfort tests [15]. The RWI value is calculated for different humid conditions using the following:

$$\text{RWI} = \frac{M\left(I_{CW} + I_a\right) + 6.42\left(T - 35\right) + RI_a}{65.21\left(5858.45 - P\right)/1000} \quad \text{for } P > 2268.88 \text{ Pa} \tag{1}$$

$$\text{RWI} = \frac{M\left(I_{CW} + I_a\right) + 6.42\left(T - 35\right) + RI_a}{234.07} \quad \text{for } P \le 2268.88 \text{ Pa} \tag{2}$$

where M is the metabolic rate (W/m^2), I_{cw} is the insulation of clothing based on wet cloth assumption (clo), I_a is the insulation effect of air boundary layer (clo), T is the dry-bulb air temperature (°C), R is the mean incident radiant heat (W/m^2), and P is the vapor pressure of water in the air (Pa).

Metabolic rates depend on individual status, physical activity, and the surrounding environment. While metabolic rates remain constant during steady-state activities, fluctuations in metabolic rates are observed among passengers as their activities change frequently. The metabolic rate can be estimated using oxygen deficiency tests during the transition between activities. The average time for changes in oxygen consumption is approximately six minutes, and it is assumed that the change in metabolic rate occurs at a similar rate. The intermediate metabolic rates for passengers can be determined using linear interpolation from the formula below [15].

$$M_t = M_I - \frac{t}{6}\left(M_I - M_F\right) \tag{3}$$

where M_t is the metabolic rate at lapsed time t (W/m^2), M_I is the initial metabolic rate (W/m^2), t is the lapsed time (min), and M_F is the final metabolic rate (W/m^2).

The wet-cloth assumption is based on the premise that the insulation provided by clothing varies upon the wearer's activity level. In transient conditions, typical in metro stations, the I_{cw} values are presumed to undergo a six-minute transient period, aligning with the time typically associated with metabolic rate changes. To calculate the I_{cw} value during a transition between activity levels, it is first necessary to compute the I_{cw} values for each steady-state activity. These values can be used with the formula below to determine the I_{cw} during intermediate or transitional phases [15].

$$I_{cwt} = I_{cwI} - \frac{t}{6}\left(I_{cwI} - I_{cwF}\right) \tag{4}$$

where I_{cwt} is the insulation of clothing at lapsed time t (clo), I_{cwI} is the initial insulation of clothing (clo), and I_{cwF} is the final insulation of clothing (clo).

Table 2 presents data on metabolic rate, clothing insulation, and activity-induced velocity (V_b) values for a range of activity levels [15]. While selecting the parameters from Table 2, it was postulated that passengers walked at an average speed of 4.8 km/h at the concourse level and engaged in standing or occasional strolls when they reached the platform level, which is aligned with previous studies.

Table 2 Metabolic rate, insulation of clothing, and activity-induced velocity values for different activity levels

Activity	Metabolic rate, M (W/m^2)	Insulation of clothing (Wet Cloth Assumption), I_{cw} (clo)	Activity-induced velocity, V_b (m/s)
Basal	47.32	0.6	0
Seated at rest	63.09	0.6	0.1
Seated vending fares	78.86	0.4	0.25

Table 2 Metabolic rate, insulation of clothing, and activity-induced velocity values for different activity levels (continued)

Activity	Metabolic rate, M (W/m^2)	Insulation of clothing (Wet Cloth Assumption), I_{cw} (clo)	Activity-induced velocity, V_b (m/s)
Standing vending fares	88.33	0.5	0.15
Standing or occasional stroll	123.03	0.4	0.51
Walking, 3.2 km/h	123.03	0.4	1.02
Walking, 4.8 km/h	170.35	0.35	1.52
Walking, 6.4 km/h	223.98	0.3	2.03

The I_a varies according to the total air velocity (V_t), which is determined by adding the V_a to the V_b. Fig. 5 illustrates the correlation between V_t and the I_a [15]. As shown in Fig. 5, the I_a increases as the total air velocity decreases. The R typically originates from solar radiation. However, solar radiation is absent in the context of subway environments, rendering the mean incident radiant heat a non-applicable metric. In aboveground settings, the mean R-value is approximately 31.55 W/m^2, although it can rise to as much as 141.96 W/m^2 under extreme conditions [15]. Table 3 presents the ASHRAE comfort categorization and the corresponding RWI values. The warmth levels are divided into four different categories. This approach permits the quantitative expression of warmth levels across various activity and condition combinations [15].

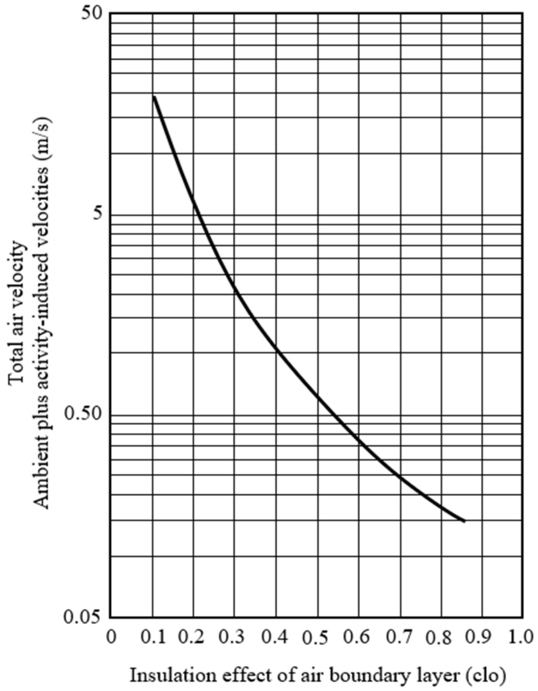


Fig. 5 Change of insulation effect of air boundary layer with total air velocity

Table 3 ASHRAE comfort categorization and corresponding RWI

ASHRAE comfort categorization	RWI
Warm	0.25
Slightly warm	0.15
Comfortable	0.08
Slightly cool	0

Fig. 6 illustrates the quantitative correlation between ASHRAE comfort designations, frequency distribution, and RWI. It emphasizes the proportion of individuals who perceive discomfort and prefer a cooler environment at different RWI values [15]. As indicated in Fig. 6, RWI values are positively correlated to the percentage of individuals seeking a cooler environment. Table 4 presents a selection of data and calculated values for RWI calculations, employing Eq. (1) and Eq. (2), at platform and concourse levels within the underground stations. Notably, there are differences in the V_a and the I_a between the Şişli/Mecidiyeköy and Gayrettepe stations. The initial values are presented for the Şişli/Mecidiyeköy station, followed by the subsequent values for the Gayrettepe station.

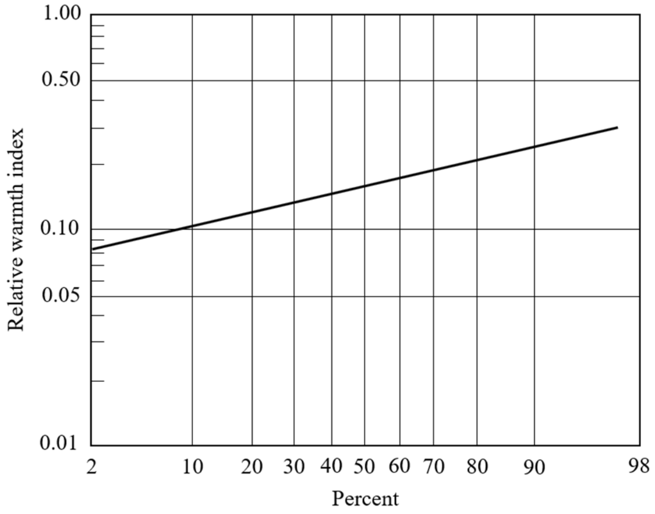


Fig. 6 Percentage of people who want a cooler environment in summer

Table 4 Used data for RWI calculations

Parameters	Concourse level	Platform level	
		Stopping immediately	235 s after stopping
Activity	Walking, 4.8 km/h	Standing or occasional stroll	
M (W/m^2)	170.35	170.35	139.46
V_a (m/s)	1.0/0.5	1.0/0.5	1.0/0.5
V_b (m/s)	1.52	0.51	0.51
I_a (clo)	0.27/0.31	0.34/0.41	0.34/0.41
I_{cw} (clo)	0.35	0.35	0.38
R (W/m^2)	0	0	0

3. Results

Outdoor air dry-bulb temperature data is obtained from the meteorological weather station near the examined metro stations. Fig. 7 illustrates the change in minimum and maximum outdoor air dry-bulb temperatures over the months. When the outdoor air data is analyzed, it is observed that the minimum dry-bulb temperature is 0.7 °C in March, while the maximum dry-bulb temperature is 33.8 °C in June. The hottest season is, undeniably, summer, followed by autumn and spring during the studied period.

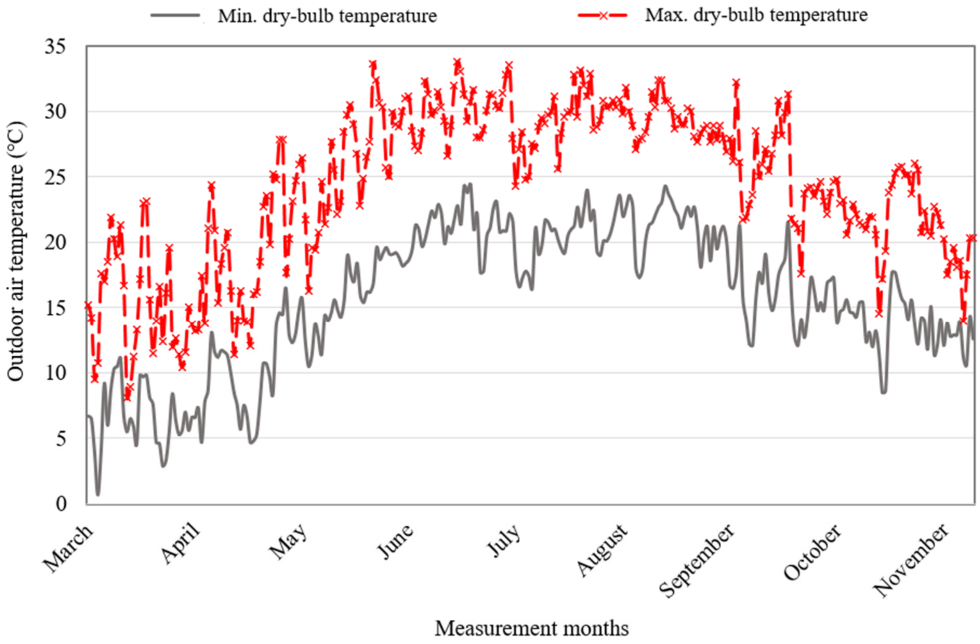
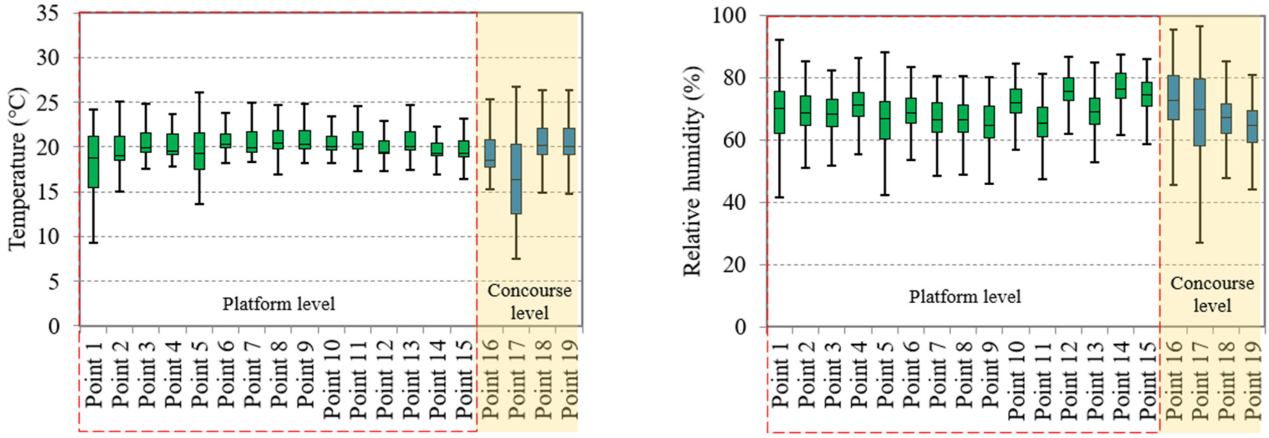


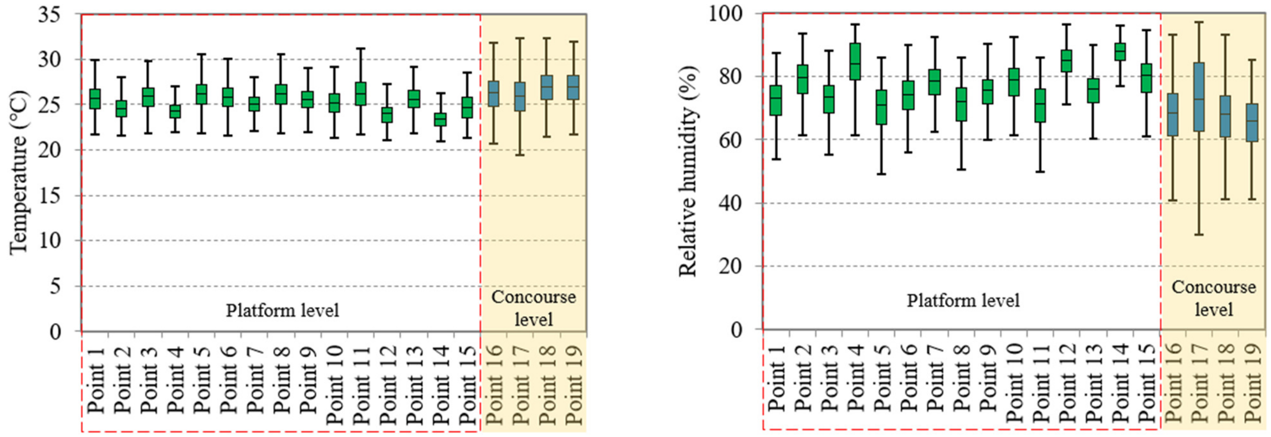
Fig. 7 Changes in outdoor air dry-bulb temperature over the months

Dry-bulb temperature and relative humidity values, recorded at one-minute intervals, 24 hours a day, every day during the spring, summer, and autumn seasons in the stations, were filtered for the operational hours of the M2 Yenikapı-Hacıosman metro line from 6:00 a.m. to 11:59 p.m. Then the data were visualized using box plots for all measurement points on a seasonal basis. This approach permits a broad examination of the fluctuations across distinct locations and periods.

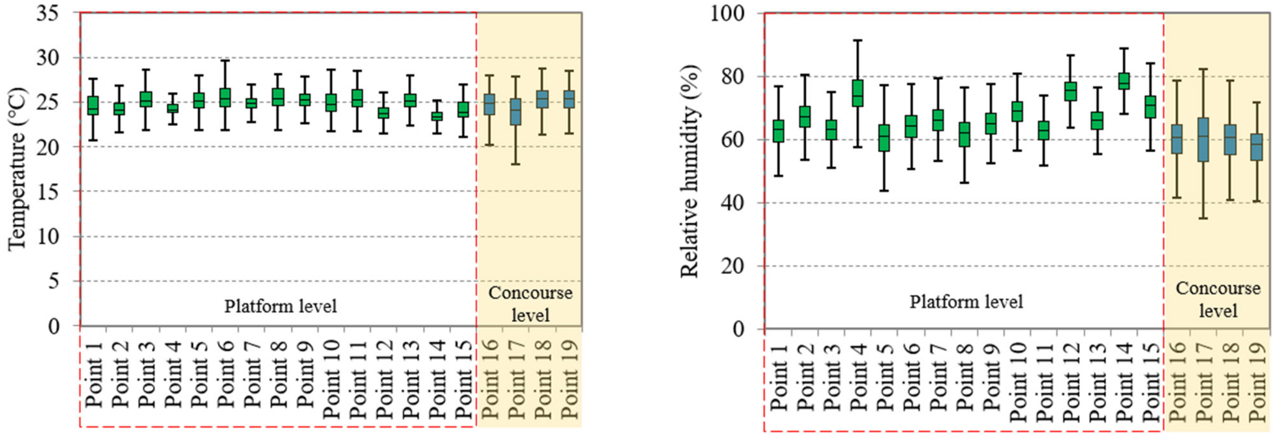
In the box plot of Fig. 8, Points 1 to 15 correspond to the measurement points on the platform level, while Points 16 to 19 correspond to those on the concourse level. Fig. 8 illustrates the dry-bulb temperature and relative humidity values measured at these points for the Şişli/Mecidiyeköy station in the spring, summer, and autumn seasons, respectively. The measurement Points 1, 2, 14, and 15 on the platform level are not situated within the designated passenger areas and have not been included in the evaluation.



(a) Spring



(b) Summer



(c) Autumn

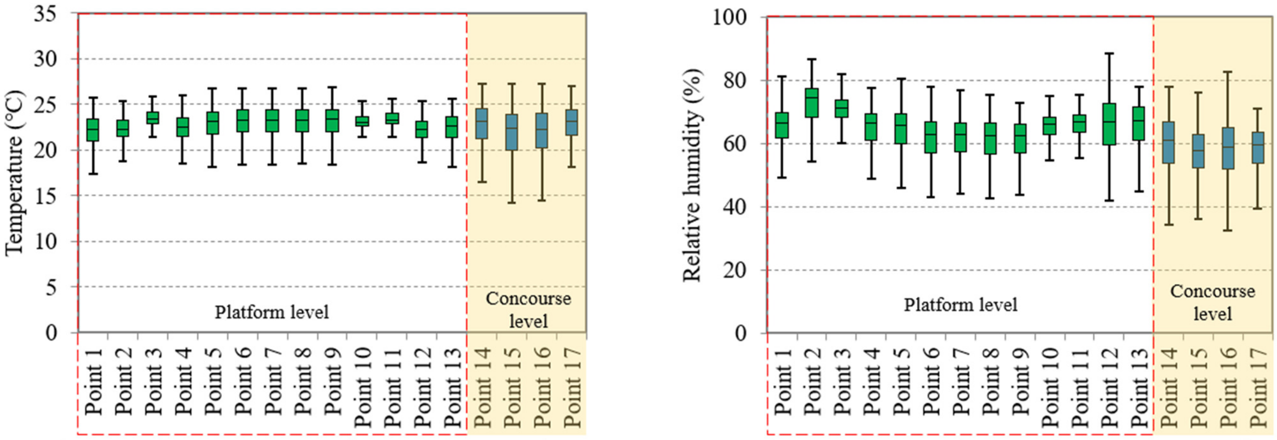
Fig. 8 Dry-bulb temperature and relative humidity at measurement points for the Şişli/Mecidiyeköy station

For the spring season, the maximum dry-bulb temperature and maximum relative humidity in the passenger areas of Şişli/Mecidiyeköy station were measured as 26.09 °C, 88.21% at Point 5 at the platform level, and 26.68 °C, 96.49% at Point 17 at the concourse level. In this season, the mean dry-bulb temperature and mean relative humidity in the passenger areas of Şişli/Mecidiyeköy station were calculated as 20.43 °C, 68.69% at the platform level, and 19.37 °C, 67.73% at the concourse level.

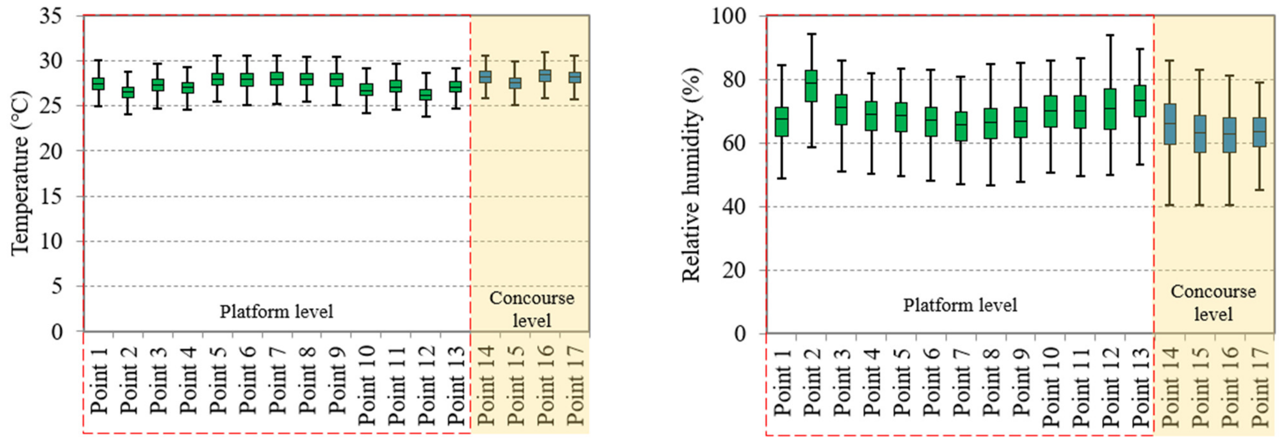
For the summer season, the maximum dry-bulb temperature and maximum relative humidity in the passenger areas of Şişli/Mecidiyeköy station were measured as 31.23 °C at Point 11, 96.32% at Point 12 at the platform level, and 32.36 °C, 97.26% at Point 17 at the concourse level. In this season, the mean dry-bulb temperature and mean relative humidity in the passenger areas of Şişli/Mecidiyeköy station were calculated as 25.42 °C, 75.47% at the platform level, and 26.48 °C, 67.97% at the concourse level.

For the autumn season, the maximum dry-bulb temperature and maximum relative humidity in the passenger areas of Şişli/Mecidiyeköy station were measured as 29.67 °C at Point 6, 91.56% at Point 4 at the platform level, and 28.72 °C at Point 18, 82.15% at Point 17 at the concourse level. In this season, the mean dry-bulb temperature and mean relative humidity in the passenger areas of Şişli/Mecidiyeköy station were calculated as 24.96 °C, 65.96% at the platform level, and 24.66 °C, 59.52% at the concourse level.

In the box plot of Fig. 9, Points 1 to 13 correspond to the measurement points on the platform level, while Points 14 to 17 correspond to those on the concourse level. Fig. 9 illustrates the dry-bulb temperature and relative humidity values measured at these points for the Gayrettepe station in the spring, summer, and autumn seasons, respectively. Measurement Points 1, 2, 12, and 13 on the platform level are not situated within the designated passenger areas and have not been included in the evaluation.

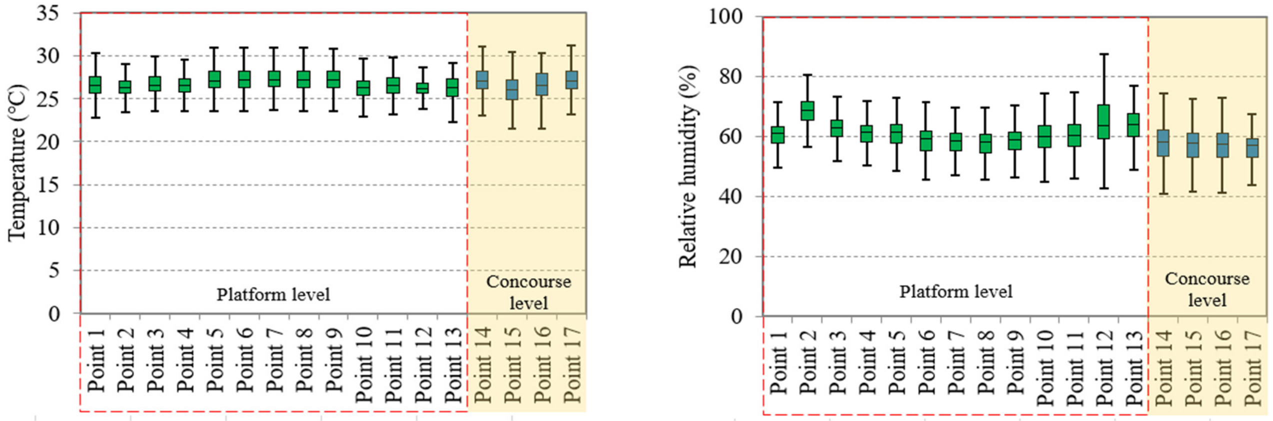


(a) Spring



(b) Summer

Fig. 9 Dry-bulb temperature and relative humidity at measurement points for the Gayrettepe station



(c) Autumn

Fig. 9 Dry-bulb temperature and relative humidity at measurement points for the Gayrettepe station (continued)

For the spring season, the maximum dry-bulb temperature and maximum relative humidity in the passenger areas of Gayrettepe station were measured as 26.90 °C at Point 9, 80.50% at Point 5 at the platform level, and 27.30 °C at Point 14, 82.80% at Point 16 at the concourse level. In this season, the mean dry-bulb temperature and mean relative humidity in the passenger areas of Gayrettepe station were calculated as 23.21 °C, 64.18% at the platform level, and 22.53 °C, 58.51% at the concourse level.

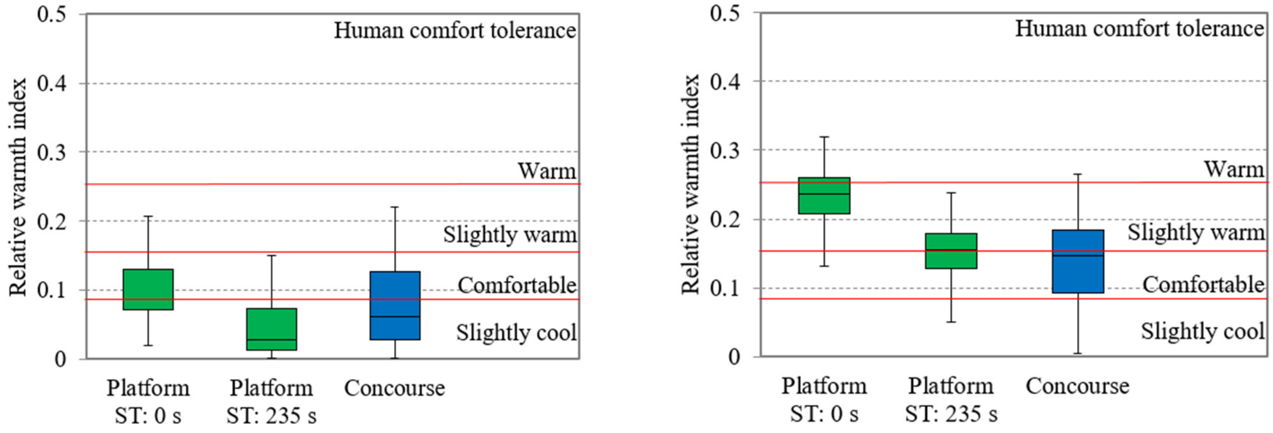
For the summer season, the maximum dry-bulb temperature and maximum relative humidity in the passenger areas of Gayrettepe station were measured as 30.60 °C at Point 6/Point 7, 86.80% at Point 11 at the platform level, and 30.90 °C at Point 16, 86.10% at Point 14 at the concourse level. In this season, the mean dry-bulb temperature and mean relative humidity in the passenger areas of Gayrettepe station were calculated as 27.44 °C, 67.89% at the platform level, and 27.98 °C, 63.35% at the concourse level.

For the autumn season, the maximum dry-bulb temperature and maximum relative humidity in the passenger areas of Gayrettepe station were measured as 31.00 °C at Point 6/Point 8, 74.70% at Point 11 at the platform level, and 31.20 °C at Point 17, 74.40% at Point 14 at the concourse level. In this season, the mean dry-bulb temperature and mean relative humidity in the passenger areas of Gayrettepe station were calculated as 26.87 °C, 59.30% at the platform level, and 26.69 °C, 56.36% at the concourse level.

Non-thermal comfort factors have been demonstrated to influence satisfaction considerably in environments characterized by markedly low humidity [19]. These factors include skin dryness, which can incur discomfort and irritation; irritation of mucous membranes, which may result in respiratory issues; dryness of the eyes, which may cause discomfort and reduce visibility; and the generation of static electricity, which can be irritating and disruptive. These factors can reduce comfort levels and affect an individual's well-being in dry conditions. The ASHRAE standard has no upper humidity limit, yet high humidity values can enhance the perception of warmth. Therefore, it is significant to manage humidity effectively to ensure a pleasant thermal environment, particularly when temperatures are already elevated. However, the relative humidity values exceeded the desired limits at all measurement points on the platform and concourse levels at both stations across all measured seasons.

Figs. 10-12 illustrate the calculated RWI values for the Şişli/Mecidiyeköy and Gayrettepe stations in the spring, summer, and autumn seasons, respectively. The graphs created for the same season are presented in a side-by-side format to facilitate a comparison of the RWI values for the stations. The RWI values were calculated for the platform and concourse levels of the stations, with the data being analyzed separately for each level. Two distinct scenarios were considered regarding the platform level. In the initial scenario, it was postulated that the passenger would board the train immediately upon descending to the platform level, thus allowing no time for transit (ST: 0 s). In the second scenario, it was assumed that the passenger arrives at the platform when the train doors are closing and then waits for the next train for the peak hour headway (ST: 235 s).

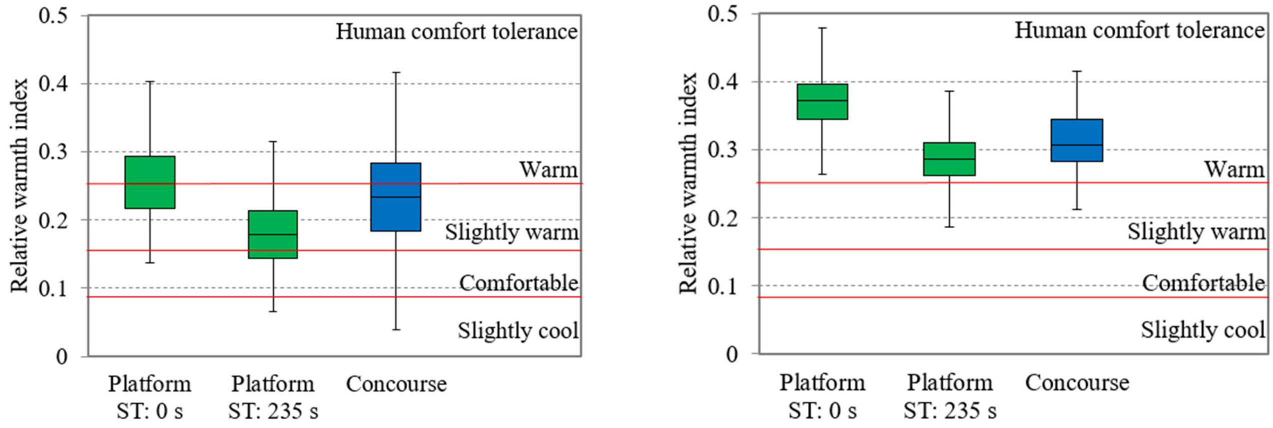
The mean RWI values were calculated as 0.10 for passengers boarding the train immediately (ST: 0 s) upon descending to the platform level, 0.04 for passengers who wait 235 seconds (ST: 235 s) for the next train at the platform level, and 0.08 for passengers at the concourse level in the spring season at Şişli/Mecidiyeköy station. The mean RWI values were calculated as 0.24 for passengers boarding the train immediately (ST: 0 s) upon descending to the platform level, 0.16 for passengers who wait 235 seconds (ST: 235 s) for the next train at the platform level, and 0.14 for passengers at the concourse level in the spring season at Gayrettepe station.



(a) Şişli/Mecidiyeköy station (b) Gayrettepe station

Fig. 10 RWI values at platform and concourse levels in the spring season

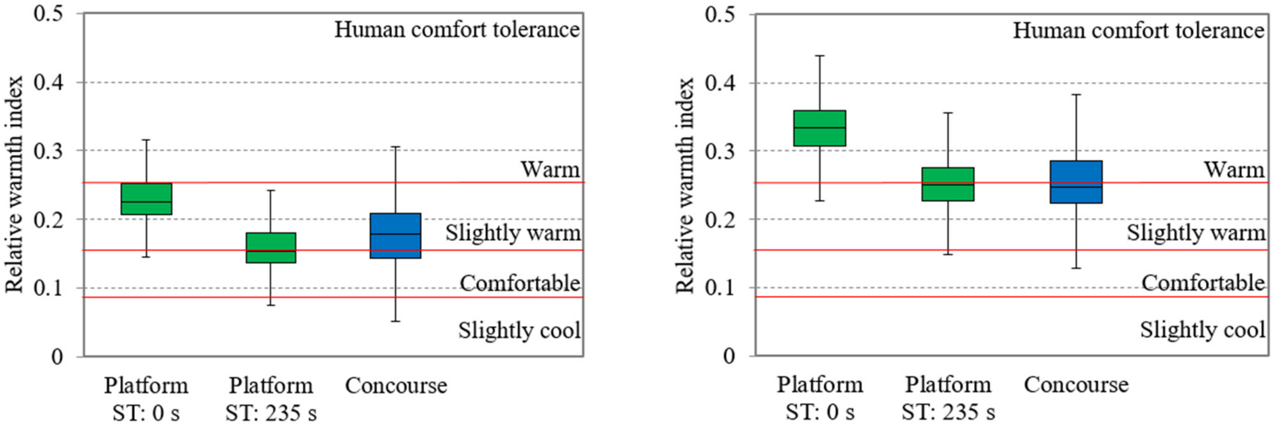
The mean RWI values were calculated as 0.26 for passengers boarding the train immediately (ST: 0 s) upon descending to the platform level, 0.18 for passengers who wait 235 seconds (ST: 235 s) for the next train at the platform level, and 0.23 for passengers at the concourse level in the summer season at Şişli/Mecidiyeköy station. The mean RWI values were calculated as 0.37 for passengers boarding the train immediately (ST: 0 s) upon descending to the platform level, 0.29 for passengers who wait 235 seconds (ST: 235 s) for the next train at the platform level, and 0.31 for passengers at the concourse level in the summer season at Gayrettepe station.



(a) Şişli/Mecidiyeköy station (b) Gayrettepe station

Fig. 11 RWI values at platform and concourse levels in the summer season

The mean RWI values were calculated as 0.23 for passengers boarding the train immediately (ST: 0 s) upon descending to the platform level, 0.16 for passengers who wait 235 seconds (ST: 235 s) for the next train at the platform level, and 0.18 for passengers at the concourse level in the autumn season at Şişli/Mecidiyeköy station. The mean RWI values were calculated as 0.34 for passengers boarding the train immediately (ST: 0 s) upon descending to the platform level, 0.25 for passengers who wait 235 seconds (ST: 235 s) for the next train at the platform level, and 0.26 for passengers at the concourse level in the autumn season at Gayrettepe station.



(a) Şişli/Mecidiyeköy station

(b) Gayrettepe station

Fig. 12 RWI values at platform and concourse levels in the autumn season

As shown in Figs. 8-12, the temperature measured at the underground metro stations and the calculated RWI values fluctuate seasonally with the outdoor air temperature trends obtained from the meteorological weather station. Passenger thermal comfort reaches its lowest level in the summer season, followed by the autumn and spring seasons.

4. Conclusions

This paper employs field measurements and RWI calculations to evaluate passenger thermal comfort in two different underground metro station typologies in Istanbul. Upon examining the measured data and calculated RWI values, the following conclusions are drawn:

(1) The mean RWI values at the platform and concourse levels of Gayrettepe station, where the cut-and-cover construction method is used, are higher in all measured seasons compared to the bored-tunnel type Şişli/Mecidiyeköy station.

(2) After 235 seconds of exposure at the platform level, a decrease in RWI values was observed due to a reduction in the metabolic rate. However, the calculated mean RWI values exceed the desired thermal comfort limits for both stations in all researched seasons, except the Şişli/Mecidiyeköy station in spring.

(3) Most passengers at Şişli/Mecidiyeköy station and nearly all passengers at Gayrettepe station preferred a cooler environment during the summer. These results demonstrate the detrimental effects of the prevailing thermal environment on passengers.

(4) Measurements indicate that the indoor air velocity values at Gayrettepe station are almost half those observed at Şişli/Mecidiyeköy station. This result can be attributed to the lower train-induced air velocity in cut-and-cover type stations with large cross-sectional areas. This leads to the RWI values being calculated as higher at the cut-and-cover type station.

(5) Water leaks from the tunnel walls, climatic conditions, and passengers contribute to the remarkably high humidity levels measured at the stations. This situation affects passengers' thermal comfort and creates a suitable environment for bacterial growth, negatively impacting passenger health.

The findings indicate that air-conditioning systems should be designed and installed in both existing and to-be-constructed stations to improve and ensure passenger thermal comfort and health by reducing dry-bulb temperature and relative humidity levels in Istanbul and cities with similar climatic conditions.

In future studies, the effects of different operating scenarios (headway, train length), station depths, climatic conditions, and types of platform screen doors (half-height, full-height) on thermal comfort can be analyzed through field measurements and computational fluid dynamics simulations. Passenger surveys can be conducted, and the calculated RWI values can be compared with passengers' perceived thermal comfort.

Nomenclature and Abbreviations

Abbreviations	
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building information modeling
HDR	Heat deficit rate
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
RSI	Relative strain index
RWI	Relative warmth index
ST	Stay time
WSN	Wireless sensor network
Symbols	
I_a	Insulation effect of air boundary layer, (clo)
I_{cw}	Insulation of clothing based on wet cloth assumption, (clo)
I_{cwF}	Final insulation of clothing, (clo)
I_{cwI}	Initial insulation of clothing, (clo)
I_{cwt}	Insulation of clothing at lapsed time t, (clo)
M	Metabolic rate, (W/m^2)
M_F	Final metabolic rate, (W/m^2)
M_I	Initial metabolic rate, (W/m^2)
M_t	Metabolic rate at lapsed time t, (W/m^2)
P	Vapor pressure of water in air, (Pa)
R	Mean incident radiant heat, (W/m^2)
T	Dry-bulb air temperature, (°C)
t	Lapsed time, (min)
V_a	Ambient air velocity, (m/s)
V_b	Activity-induced air velocity, (m/s)
V_t	Total air velocity, (m/s)

Conflicts of Interest

The authors declare no conflict of interest.

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