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Perception of Wind in Open Spaces

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Abstract: Dense urbanization influences the livability of cities. Changes in local meteorological conditions can be adverse for human health and well-being. In urban open spaces, it is widely known that changes in building density and configuration in cities influence wind speed (V_a). This influence modifies latent heat flux between the human body and surrounding environment and thereby affecting the thermal comfort conditions in open spaces between buildings. Several studies have demonstrated the significant effect of wind speed on outdoor thermal comfort. Melbourne's Central Business District (CBD) has recently experienced dense urbanization and this pattern of development has instigated noticeable changes in meteorological conditions. Some evidence has suggested that the patterns of wind flow induce thermal discomfort during cool seasons. Conversely, the wind is most welcomed during warm seasons. This study was conducted to assess outdoor users' responses to V_a in three open spaces of an educational precinct in Melbourne's CBD. The open spaces studied are different in terms of design and function. Users' responses and meteorological conditions were examined through a series of field measurements and questionnaire surveys from November 2014 to May 2015. This study used three perceptual scales to analyze participants' experience of V_a during field surveys: "Bedford preference", "thermal sensation" and "personal acceptability". Analytical results yielded the wind perceptual comfort thresholds for different seasons as well as the entire study period. The results suggested that in addition to the geometry of the urban open space, the function of place could influence people's perceptions of V_a. The research findings contribute to developing thermally comfortable outdoor environments.

Keywords: wind speed values; urban precinct; outdoor thermal perception; wind speed threshold sensitivity

1. Introduction

Dense urbanization influences the livability of cities. Among other consequences, changes in local meteorological conditions are more severe for human health and well-being. As such, people's attendance and behavior patterns can be significantly affected. Gaitani, et al. [1] maintained that micrometeorological conditions through people's thermal perceptions determine attendance and human activities in outdoor spaces. They also argued that the level of activities hinges on the extent of satisfaction under the given thermal conditions. Thermal satisfaction in open space is typically assessed by thermal comfort. Thermal comfort by definition is "... *that condition of mind that expresses satisfaction with the thermal environment*" [2]. Technically, assessment of thermal comfort is based on the calculation of the collective effect of four meteorological variables including air temperature (T_a), relative humidity (RH), wind speed (V_a) and mean radiant temperature (T_{mrt}) on thermal perceptions of a large group of people [2]. These parameters are known to have the most impact on human thermoregulation system [3]. The research on thermal comfort has substantially grown over the last decade [4]. Among the factors that significantly influence people's thermal comfort, wind speed (V_a) was found to play a key role in cities and particularly in densely built-up areas and between buildings [5,6].

Research on wind comfort perception is underpinned by four major methods: software simulations, field tests, wind tunnel tests and questionnaire survey [6]. Questionnaire survey on people's feeling about wind speed is believed to provide accurate, comprehensive and cost-effective method. Since this method evaluates the impact of four parameters (T_a, RH, V_a, and T_{mrt}) it is possible to gain an insight into the impact of V_a in comparison with the other three parameters. Several studies have demonstrated the significant effect of V_a on outdoor thermal comfort [7–9]. For instance, the study by Walton, Dravitzki and Donn [7] revealed that gustiness and V_a were the most significant factors in shaping outdoor thermal satisfaction. The results of a questionnaire survey in Hong Kong [9] showed that participants were highly sensitive to V_a fluctuations. In urban open spaces, it is widely known that recent drastic changes in the design of building density and configuration in cities influence V_a profile [5,10–12]. This modifies latent heat flux between human body and the surrounding environment and thereby affecting the thermal comfort conditions in open spaces between buildings. However, seasonality can make this influence pleasant or unwelcome as follows.

In hot weather conditions, the correct design of open spaces will direct wind into an air corridor which can reduce the duration of thermal discomfort [13]. The positive role of wind corridors in creating an acceptable outdoor thermal environment has been well researched [14–19] and is recommended as a thermal adaptive strategy for many climate conditions [6,20]. Conversely, in cool seasons, strong wind blows induce thermal discomfort which can be mitigated by windbreakers or shields [21]. Consequently, the proper design of open spaces has a critical role in the formation of local wind environment and thermal comfort [19,22,23]. Blocken and Carmeliet [5] and later Abd Razak, et al. [24] have conducted reviews on literature studying the link between design and pedestrians' wind environment.

Capital cities in Australia have undergone significant changes in the last three decades [25]. Particularly, the Melbourne Central Business District (CBD) has experienced dense urbanization characterized by the construction of multiple high-rise buildings over a small area [26]. This pattern of development has instigated noticeable changes in meteorological conditions causing urban heat island effects and human thermal discomfort [27]. Some evidence has suggested that wind chill sometimes is the source of thermal discomfort in cool seasons [28]. This wind chill factor makes the "real feel" temperature much cooler than the actual meteorological readings. Conversely, this wind is most welcomed during warm seasons when it can lessen the number of hours of thermal discomfort.

The research on wind comfort perceptions in Australian capital cities is limited [29–31]. Melbourne [31] was a pioneer in the investigation of wind speed on people in Australia which resulted in the development of Melbourne's wind acceptability criteria. GWTS [30] conducted a study to understand people's sensitivity against changes in wind speed. Sadeghi, de Dear, Wood and Samali [29] simulated the comfort cooling effect of wind in Sydney and developed a wind rose biometeorological data visualization tool. The tool integrates the thermal comfort dimension into the conventional climatology wind rose visualization.

Thermal comfort research in Australia is typically not well- focused on wind comfort [32–35]. However, the significant role of proper wind flow to human thermal comfort is underlined in these studies. Sharifi, Sivam and Boland [33] for instance indicated that wind flow is a critical element in public outdoor living, in the case of Adelaide, especially during summer. Furthermore, currently, there are only two urban planning-related policies that consider the issues of urban design and wind in Australia [36,37].

This study has provided the opportunity to better understand the relationship between wind speed and people's perception in Melbourne CBD in different seasons. Determination of wind comfort perceptions can inform urban planning guidelines and help to create better and sustainable outdoor spaces. For this reason, comprehensive meteorological data was collected as part of a research project evaluating the thermal perception of an educational precinct. On this basis, the following are the main objectives of this research study:

(1) Determine people's wind perception in different seasons;
(2) Examining the impact of spatial configuration on people's wind perceptions;
(3) Determining the wind sensitivity thresholds for two seasons (cool and warm);
(4) Comparing the impact of meteorological parameters on people's perceptions in different seasons.

2. Methodology

2.1. Study Sites

This study was conducted in Melbourne, which has an oceanic temperate climate (*Cfb*) according to Köppen-Geiger classification [38]. Melbourne is known for its unpredictable weather conditions where one may experience totally different micrometeorological conditions from one day to the next [39]. In summer, the minimum and maximum average air temperature reach 16.8 °C and 31.9 °C and RH ranges from 47% (3:00 PM) up to 64.3% (9:00 AM). In autumn, these values are 12 °C and 20.5 °C for minimum and maximum average air temperature, respectively and RH averages 67.2% [40]. The thermal variability is greatest in spring and summer months due to the formation of cold fronts from the northwest, west, and south. The cold fronts are the cause of all the types of harsh weather conditions ranging from gales to severe thunderstorms and hail, torrential rain and sharp drops in temperature. When a cold front passes through Melbourne, the temperature rapidly falls within the space of a few minutes and causes a shift in the direction of the wind to south-westerly. This shift is attributed to cumulus clouds and showers and the cycle starts again; often cycles such as these recur on an almost weekly basis with one day or two of clear skies occurring on same days each week. To better understand wind conditions in Melbourne, historical wind speed values (between 1970–2015) and directions in Melbourne were extracted from the Australia Bureau of Meteorology (BOM) database [41], Melbourne Airport Station (ID: 086282, elevation: 113 m above sea level). The following wind rose diagrams (Figure 1) display the seasonal wind characteristics in Melbourne at 3:00 PM in three months: November, February, and May representing three seasons of spring, summer, and autumn. As can be seen, the dominant wind pattern in May (autumn) is noticeably different from the two other months in terms of magnitude and direction.

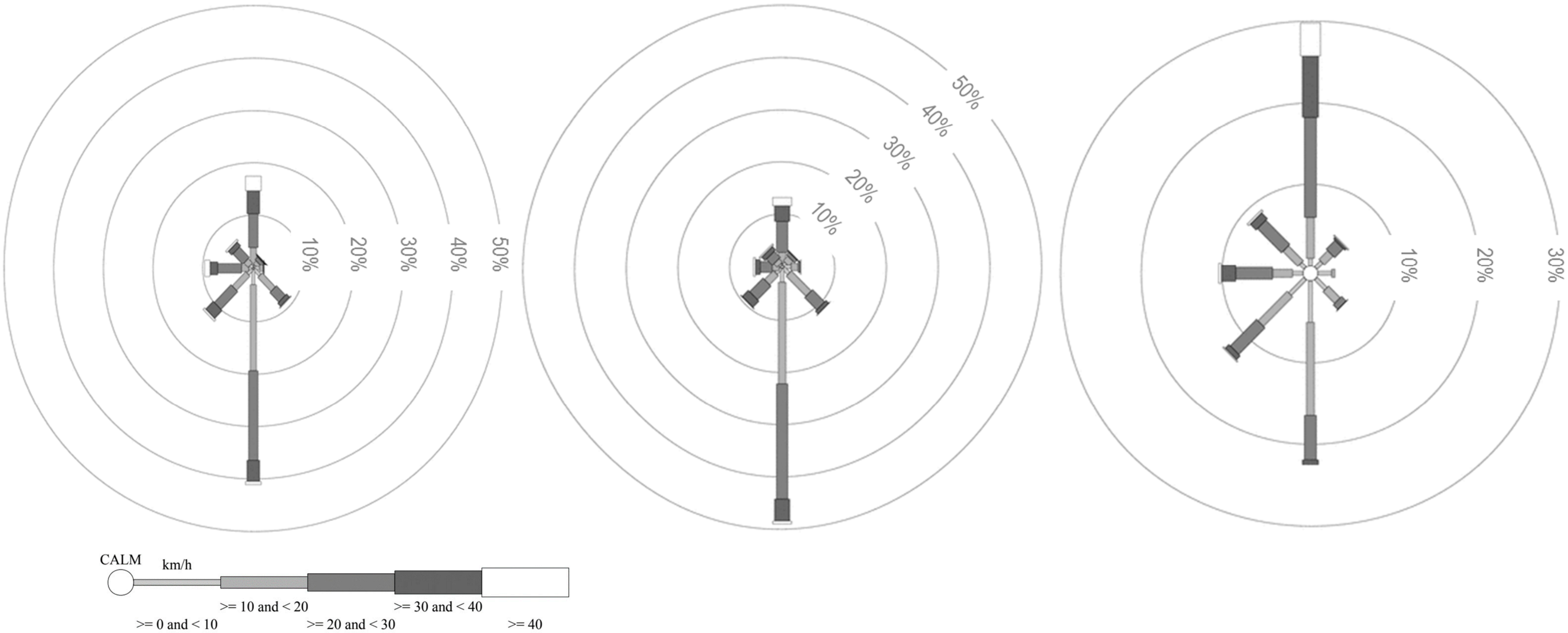

Figure 1. Wind rose diagrams for (from left to right) November, February and May. 3:00 pm. Adapted from Australia Bureau of Meteorology [41].

Three sites that are located in Melbourne's CBD were selected as the case study sites (Figure 2). These three sites are the premises of RMIT University City Campus and represent the typical urban spaces in the Australian capital city centers. The potential users were mostly among the university students and staff who often spend most of their time indoors and semi indoors. Below is the description of study sites.

Figure 2. Three open spaces in Melbourne CBD under study.

Site 1: RMIT's University Lawn which was used as recreational space by university students and staff. Due to its compact design, a relatively prevalent form in Melbourne's built-up areas, this space was an appropriate symbol of inner-city Melbourne's recreational outdoor spaces. This site has a 1473 m^2 area and contained several urban elements including shading device in a café, timber deck and benches, water features, natural green space, and an artificially turfed area which generated varying micrometeorological conditions. The café served visitors both inside and outside and it was fitted with shading devices.

Site 2: RMIT's Ellis court was used for different purposes: as the main passageway to other parts of the campus, and a venue for outdoor activities and social events. This site has a 1302 m^2 area and accommodated a range of urban settings (e.g., large patches of artificial grass, trees, and small garden beds), which potentially created an outdoor space with varying local micrometeorological conditions. The full description of different covering materials and the extent of their usage in the three sites was presented before [42]. Like Site 1, this site had buildings that were heritage listed by the Heritage Council of Victoria. Due to its particular location, this site was largely frequented by students and staff during teaching hours; it was also partly occupied by them in break times. Many on-campus events are conducted at Bowen Street. Some visitors from neighboring offices routinely used the space to relax, eat or drink, or walk through to reach other streets.

Site 3: RMIT A'Beckket Urban Square was a 2800 m^2 recreational project, which provided multi-functional courts for outdoor activities, spare modern green spaces, a large artificially turfed area, and shading features. This site represented many outdoor settings in Melbourne's inner city and was designed to serve a wide range of visitors, mainly university students, staff and other visitors. A few restaurants and cafés were near this site on Stewart Street. Building 80 was the closest educational building and students and staff from schools located in this building were typically the main visitors of facilities in this site.

Figure 3 shows the variations in the design of these three sites using sky view factors (SVF) as a design descriptor [43,44]. The SVF was quantified by calculations of the ratio between obstacles and total vertical horizon using 180° fish-eye images. The images were taken using a Canon EOS 6D SLR camera which was fitted with a Canon EF 8e15 mm f/4 L Fisheye USM lens. The SVF percentages were calculated through Rayman Software [45]. As shown in Figure 3, among the study sites, Site 3 has the largest value of horizon limitation followed by that in Site 2 and Site 1. The limited horizon signifies the occurrence of longer duration of shade in an outdoor space, which may also influence wind sensitivity of outdoor users.

Figure 3. The percentage of level of sky clearness among the study sites.

2.2. Field Survey

This study used a questionnaire survey concurrent to on-site measurement to understand people's wind comfort perception. The field surveys were conducted in three seasons: Spring (November 2014), summer (February 2015) and autumn (May 2015). A portable measurement equipment (Testo 480 IAQ Pro Measurement Kit) was used to monitor the values of four major micrometeorological parameters: T_a, V_a, RH, and globe temperature (T_g) (Figure 4).

Figure 4. Measurement equipment.

The anemometer (TESTO COMFORT probe 0628 0143) registered V_a values ranging from 0.01 m/s to 5 m/s. A data logger was set to record the data at five-minute intervals. The *Tg, RH and Va* sensors in the portable device were mounted at around 1 m height. Additionally, the solar radiation intensity (S_r), was measured using a Silicon Smart HOBO S-LIB-M003 sensor, mounted at 95 cm height on a separate tripod, in the proximity of the portable device. The above-mentioned devices were placed close to participants, within a radius of 2 m, to measure immediate thermal conditions to the human body's core. The full specification of instruments devised in this study including their measuring accuracy is presented in Table 1.

Table 1. Technical specifications of instruments used in this study.

Measured Parameter	Logger	Specifications	Measuring Range	Accuracy and Resolution	Unit
Air temperature (T_a)	TESTO IAQ probe 0632 1543	IAQ probe for analysing indoor air quality, CO_2, humidity, temperature and absolute pressure measurement	0 to 50	±0.5 (at 22); 0.1	°C
Relative humidity (RH)	TESTO IAQ probe 0632 1543	IAQ probe	0 to +100 (non-condensing)	±(1.8 +0.7 of meas. val.) and ±0.03 RH/K (based on 25 °C); 0.1	%
Globe temperature (T_g)	TESTO Globe thermometer 0602 0743	Black painted Globe probe Ø 150mm, TC Type K, made of copper	0 to +120	Class 1 (−40 to +1000); 0.1	°C
Air velocity (V_a)	TESTO COMFORT probe 0628 0143	Omni-directional Comfort probe for the degree of turbulence measurement according to EN 13779	0 to 5	0.5 ±(0.03 + 4% of meas. val.); 0.01	m/s

Structured according to universal thermal comfort standards [46,47], a questionnaire survey during 9 days elicited information about people's thermal perceptions including wind comfort perceptions. Three scales used include "Bedford preference" (i.e., weaker, no change and stronger), "thermal sensation" (i.e., hot, warm, moderately warm, neutral, slightly cool, moderately cool, cold), and "personal acceptability" (i.e., acceptable and unacceptable). As stated before, the study population consisted of university students, staff and others using these spaces at the time of the survey. The questionnaire surveys were conducted close to the portable device (TESTO IAQ probe), while this device was recording surrounding micrometeorological conditions with five-minute intervals. On average, the questionnaire surveys took less than five minutes to complete, and participants had been briefed prior to taking surveys about the objectives of the study.

In total, 1059 questionnaires were collected over the three seasons: spring (368), summer (413) and autumn (278) across the three sites. The survey population consisted of male (N = 704, 66.5%) and female participants (N = 355, 33.5%) who were mostly from the age group of 18–30 (60.5%). The majority of participants were students (62.7%) who were mostly born somewhere other than Melbourne (65%). The respondents were present in the outdoor environments predominantly for a short time period (5–10 min) and in most cases less than 5 min (39%).

2.3. Data Processing and Analysis

This study employed both descriptive and inferential methods to analyze wind and comfort data. Following data screening, the frequency distribution of comfort data was determined for different seasons and sites. Regression model and probit analysis [48] were also applied to comfort data to shed light on the characteristics of people's perceptions of V_a values. The probit analysis was conducted based on the ratio between the number of those who preferred weaker V_a values to the entire number of participants. For the purposes of analysis, comfort votes were averaged and compared against measured V_a. Furthermore, Spearman's rank correlation was used to compare the impact of four environmental parameters on participants' thermal sensations. Microsoft Excel Spreadsheets V. 2010 and SPSS V.25 were used to screen and analyze the collected data. The following sections present the outcome of data analysis in this study.

3. Results

3.1. Micrometeorological Measurements

The results of on-site measurements showed differences in outdoor meteorological conditions in different seasons (Table 2). On average, except for Site 1 in which spring was slightly warmer, the participants experienced higher mean T_a values in summer (25.2°C) than spring (22°C) and autumn (16.4°C) in the study open spaces. Similarly, in the case of mean T_g, summer ranked the highest (29.7°C) followed by spring (26.2°C) and autumn (18.1°C). However, except in Site 2, the greatest values of S_r occurred in spring, followed by summer and autumn. In terms of V_a, on average, the study seasons had experienced similar values. The greatest and lowest V_a values were recorded in autumn in Site 3 (2.3 m/s) and Site 1 (1.1 m/s) respectively which is representative of highly variable microclimate in Melbourne. Analysis of meteorological conditions among the study sites and SVF indicated that people in Site 3 were less exposed to solar radiation (T_g and S_r) and therefore, had experienced relatively cooler conditions during field surveys.

Table 2. Seasonal meteorological conditions in different sites.

	Site 1				Site 2				Site 3			
Parameter Unit of Measurement	T_a (°C)	T_g (°C)	S_r (W/m^2)	V_a (m/s)	T_a (°C)	T_g (°C)	S_r (W/m^2)	V_a (m/s)	T_a (°C)	T_g (°C)	S_r (W/m^2)	V_a (m/s)
Spring	22.8	26.4	644	1.4	23.8	28.7	443	1.7	19.3	23.6	486	1.6
Summer	22.2	27.3	502	1.9	29.1	34.6	517	1.5	24.3	27.2	352	1.5
Autumn	17.4	20.5	204.3	1.1	16.7	18.2	129.6	1.2	15.1	15.8	64.8	2.3
Aggregated	22.0	24.5	516	1.6	25.2	29.8	461	1.5	16.6	17.5	320	1.6

Furthermore, to better understand wind conditions during the survey time (10:00 AM–16:00 PM), the average hourly wind speed values for each season and all study sites are presented in Figure 5. As it can be seen in Figure 5, V_a values in autumn showed a greater fluctuation over the period of survey and had several spikes.

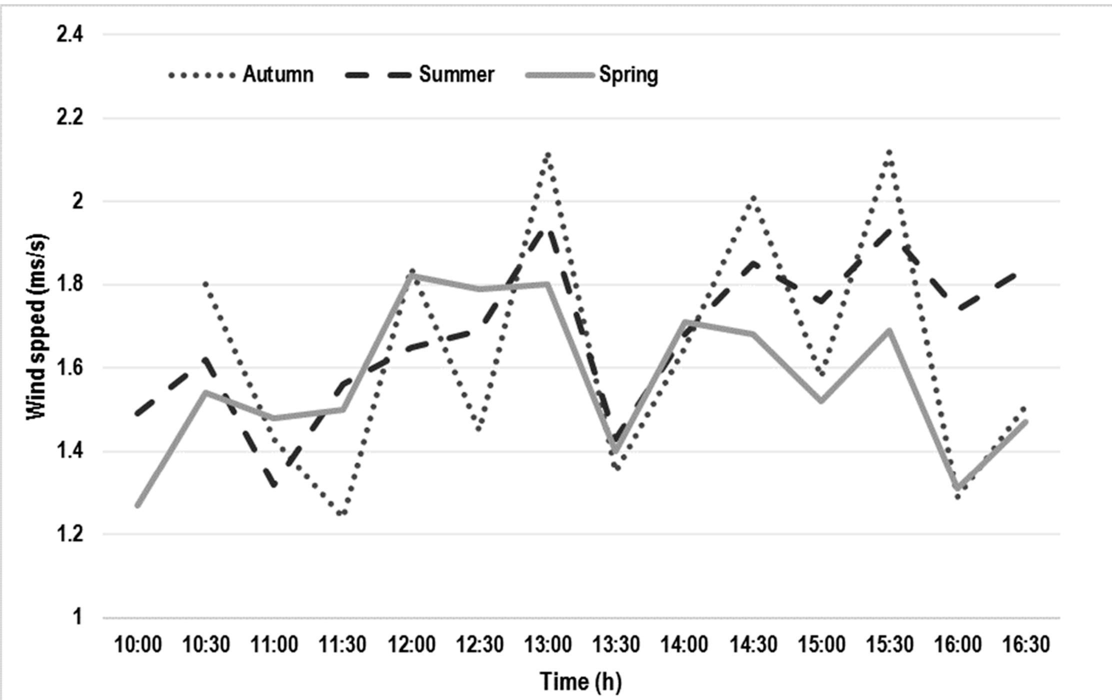

Figure 5. Seasonal wind conditions in the study sites during the survey time.

Descriptive analysis was also conducted to confirm the occurrence of greater fluctuations in the autumn dataset (Table 3). As can be seen in Table 3 the autumn season had the largest standard deviation which represents a large variability in wind speed values during the survey time.

Table 3. Statistics related to seasonal wind conditions during the survey time.

	N	Minimum	Maximum	Mean	Std. Deviation
Spring	368	0	4	1.59	0.657
Summer	413	0	5	1.67	0.735
Autumn	242	0	6	1.64	1.090

3.2. Wind Perceptions in Different Seasons

Participants' by season and by site wind preference and acceptability votes were collected (Figure 6). The overall results showed that in the warm months (spring and summer), on average 59% of people required "no change" in V_a values, whereas, in autumn this percentage declined to 37.4%. Furthermore, among the seasons the request for lower V_a in autumn (60.9%) was much higher than it was in spring (37.6%) and summer (32.3%). Hence, the demand for stronger winds accounted for very small fractions of total votes (i.e., spring: 3%, summer: 9% and autumn: 1.7%). V_a values were perceived equally acceptable in spring and summer with about 84% of people expressed their acceptance with current conditions. Wind acceptability in autumn, however, was found to be lower by around 29%. Figure 6 illustrates the frequency distribution of wind comfort perception votes.

3.3. Wind Perceptions in Different Sites

A closer analysis in each site showed varying and interesting patterns of wind comfort perceptions. It seems that among the study sites, Site 3 had the lowest percentages of "no change" votes in all seasons (Figure 7). Correspondingly, in Site 3 more people required weaker V_a than they did in Sites 1 and 2. For instance, the requests for weaker V_a between Sites 3 and 2 differed between 11.3% and 29.3% in spring and autumn, respectively. In terms of V_a acceptability, Site 3 had comparatively the greatest frequency of votes for wind acceptability in general (29.1%; Figure 7), in spring (22.7%; Figure 6) and in autumn (55.4%: Figure 6).

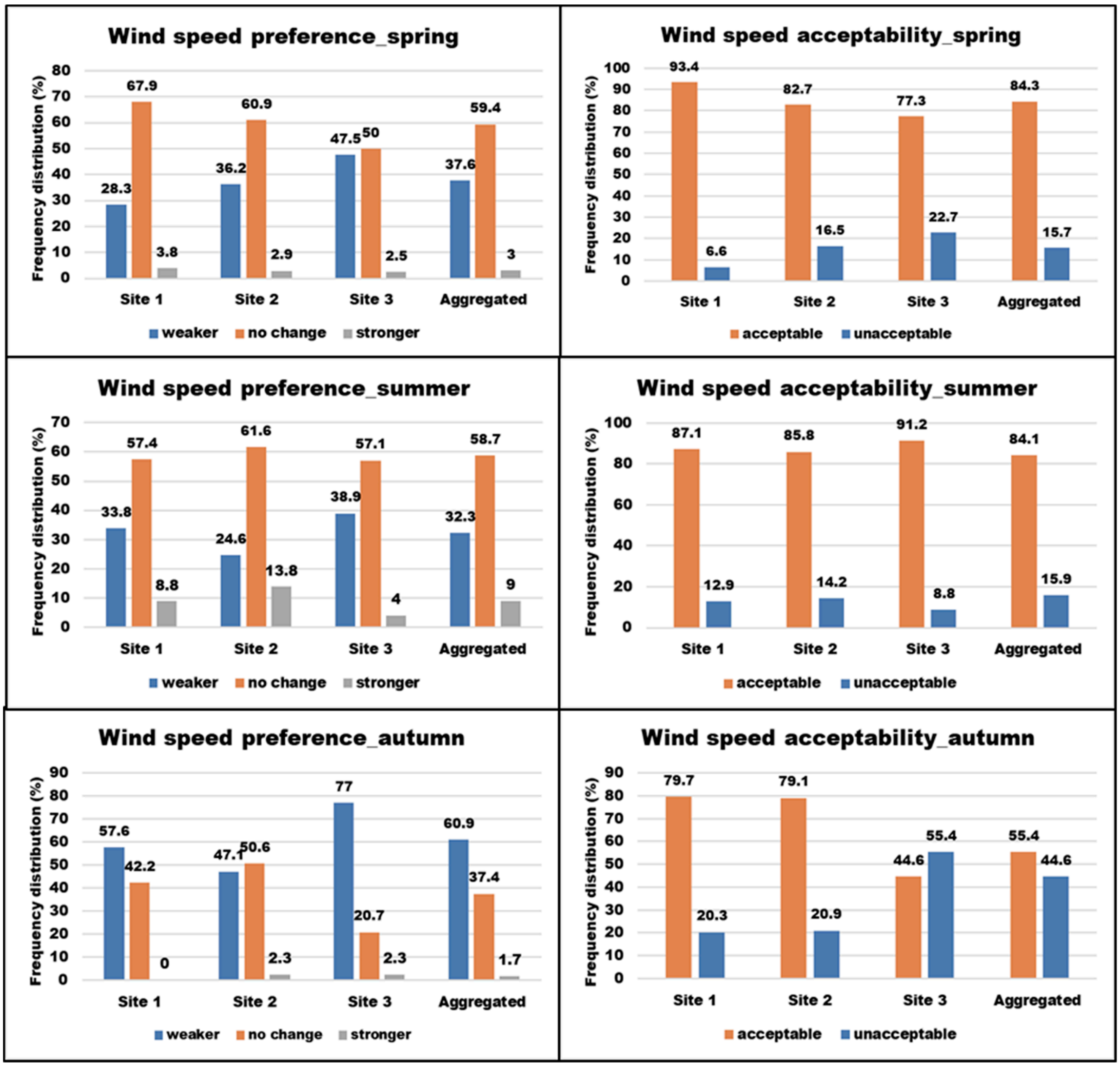

Figure 6. Distribution of seasonal wind comfort perceptions in different sites.

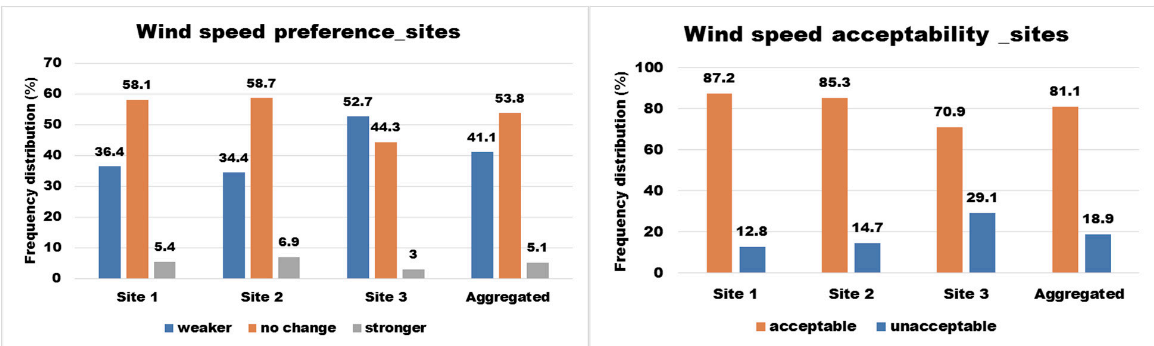

Figure 7. Distribution of annual wind comfort perceptions in different sites.

3.4. Association between Wind Perceptions and V_a

To understand the association between people's responses (wind preference) and V_a values, a quadratic regression model was applied to individual and aggregated wind comfort data. For analysis purposes, the V_a values were binned to 0.26 m/s intervals that generates a better distribution of comfort data; the average of votes within each interval was calculated. As presented in Table 4, the results showed notable variations in this association in different seasons and sites. Among the seasons, V_a values in spring ($R^2 = 0.82$, $p < 0.01$) and autumn ($R^2 = 0.85$, $p < 0.01$) had the largest degree of association with people's preference votes. Site analysis showed that on average people in Site 3 were most sensitive to V_a values ($R^2 = 0.83$), followed by people in Site 2 ($R^2 = 0.66$) and then Site 1 ($R^2 = 0.20$).

Table 4. Quadratic regression between people's wind preference and different V_a values.

Season	Site 1 R^2	Site 2 R^2	Site 3 R^2	Total R^2
Spring	0.44	0.70	0.37	0.82
Summer	0.09	0.28	0.82	0.45
Autumn	0.46	0.33	0.39	0.85
Total	0.20	0.66	0.83	

To determine wind sensitivity thresholds, probit analysis was applied to seasonal preference data using SPSS. SPSS produces a range that contains three values: an optimum (preferred) point, lower and upper bounds. The preferred point (V_a) indicates a V_a value where respondents neither want a stronger nor weaker wind speeds. As shown in Table 5, the preferred V_a values range from 1.2 m/s in autumn to 2.04 m/s in spring, and to 4.51 m/s in summer. Furthermore, wind preference data were used to determine sensitivity ranges. These include 1.76–2.49 m/s (spring), 3.11 m/s and above (summer), and 0.94–1.4 m/s (autumn).

Table 5. Probit analysis for preferred Va and the associating lower and upper bounds.

Measure Unit of Measurement Season	Preferred V_a (m/s)	Lower Bound (m/s)	Upper Bound (m/s)
Spring	2.04	1.76	2.49
Summer	4.51	>3.11	
Autumn	1.2	0.94	1.4
Collective	2.35	2.05	2.86

3.5. *Comparative Analysis of Thermal Perception and Environmental Parameters in Different Seasons*

It is critical to understand the individual impact of environmental parameters on people's thermal perceptions to explain the patterns of thermal comfort requirements. Spearman's rank correlation analysis served to explore the association between the study environmental parameters and people's thermal judgment in different seasons. The Spearman's rank correlation test is appropriate for examining the relationship between an independent variable and a categorical (ordinal) dependent variable [49]. For comparison purposes, only peoples' thermal sensation votes (TSV) were used as an indicator of thermal perceptions. Table 6 compares the correlation between meteorological parameters and TSV.

Table 6. Regression between thermal sensation vote and various meteorological parameters.

Variable	TSV (Spring)	TSV (Summer)	TSV (Autumn)	TSV (Pooled)
T_a	58 **	58 **	43 **	71 **
T_g	47 **	62 **	42 **	70 **
V_a	−8	−11 **	−27 **	−10 **
RH	−47 **	−45 **	−26 **	−36 **
Sr	29 **	37 **	23 **	48 **

** Correlation is significant at the 0.01 level.

Generally, the results revealed that among the environmental parameters, T_a and T_g had the highest correlation with people's TSV throughout the study period (r = 71, $p < 0.01$). The general trend of the V_a association, in particular, showed a negative relationship with people's thermal judgments. The seasonal comparison, however, demonstrated a varied impact of wind speed on people's TSV. The strongest association was found in autumn (r = 27, $p < 0.01$) when it had an almost similar impact as RH and Sr did. On this basis, it can be speculated that this association would have been greater if data collection had been performed in winter. In warm seasons, the V_a impact was not as great as other parameters. Moreover, the absolute values for RH and Sr are similar, but they have opposite sign, indicating that those variables have opposite effect on TSV.

4. Discussion

4.1. Meteorological Conditions and Wind Comfort Perception

Although the results of people's wind comfort perceptions of both scales (preference and acceptability) indicated generally similar trends (Figure 6), further examinations revealed the conceptual differences in the behavior of these two scales. When thermal acceptability is considered, out of nine occasions (three study sites and three seasons), only one occasion (Site 3 in autumn) was found to be rated unacceptable. Indeed, the frequency of acceptable votes substantially outweighed the unacceptable ones in the other eight occasions. However, when their preferences for wind conditions were compared, more people in autumn were found to prefer weaker V_a values. As such, the difference between the frequency of preference votes for "no change" and "weaker/stronger" was comparatively much lesser in all study sites in different seasons than it was in the case of thermal acceptability. As reflected in its definition, the main aim of thermal comfort assessment is to determine the degree of satisfaction of a group of people with their thermal conditions. Thermal satisfaction is traditionally assumed to be synonymous to "no change" and "acceptability" in preference and personal acceptability scales, respectively. However, some studies have provided evidence that violates this assumption [50–52]. Brager et al. (1993) pointed out that the three concepts of thermal perceptions are qualitatively very different and, cannot equate to thermal acceptability. Therefore, care must be taken when interpreting comfort data obtained from different scales.

Geometry and Wind Perceptions

The findings from the site analysis implied the importance of urban geometry on people's wind comfort perceptions. A factor that seemed to have an impact on people was the degree of exposure to solar radiation (Table 2). For instance, in Site 3, participants were found to experience relatively lower T_g values than in the other two sites. As such, more people on this site required weaker V_a values. Furthermore, in the case of personal acceptability except for the summer, more people in Site 3 perceived wind conditions unacceptable (Figure 6). This may attribute to the urban geometry, as the open spaces are surrounded by high-rise buildings (Figure 3). These surrounding tall buildings block solar radiation from reaching the open space and also induce stronger V_a through wind funneling effect. On the same line of reasoning, lower T_a occurred in this site in all seasons (Table 2) which further impacted people's wind acceptability.

The other factor that might have impacted people's wind perceptions in different sites is the wind direction in different seasons. As evident in the wind rose diagrams for Melbourne (Figure 1), the seasonal direction and strength of prevalent wind significantly differ between autumn and two warmer seasons (summer and spring). This seasonal difference together with the changes in urban geometry could contribute to varied microclimate conditions and thus people's perceptions of wind.

GWTS [30] has proposed several design options to engineer wind flow for better thermal comfort in Melbourne CBD. Additionally, the adoption of lift-up design for the densely built-up area with high rise buildings is advocated recently by several researchers around the world [11,22,53,54] and this applies to Melbourne's CBD conditions. They have demonstrated that this design can favorably influence thermal comfort at the pedestrian level.

It was also found that among the study seasons, wind preference votes in summer were rather less subject to V_a values. Furthermore, among the study sites, there was a better match between V_a values and their preference for no change/change in Site 3 than other sites. This could be probably related to the occurrence of lower solar radiation values that amplified the impact of V_a on outdoor visitors.

4.2. Wind Comfort Sensitivity Thresholds

The threshold for wind speed is a relative and arbitrary criterion [55] that differs significantly. In this study, probit analysis was used to develop wind comfort sensitivity thresholds for the three seasons as well as the entire study period. Since there are some disparities in the information provided through the two scales used, this study calculated thresholds for people's sensitivity against V_a values (Table 6) using people's wind preference votes. It seems that wind conditions in the warm seasons were rather acceptable to more people partook in the field surveys (Figure 4) and accordingly stronger preferred V_a values are recorded in spring (2.04 m/s) and summer (4.51 m/s). In the cool season, however, while people generally rated the wind conditions acceptable, they preferred weaker V_a values and therefore their preferred V_a is calculated as 1.25 m/s. It is worthwhile to compare the wind sensitivity thresholds found in this study with those in previous studies. Table 7 presents these comparisons within different contexts.

In many of these studies and reports, the wind speed thresholds are provided according to the type of activity and for all year round. However, reporting a single sensitivity threshold that is specific to all-year-round can be problematic due to the impact of seasonality on the specified thresholds. As the findings of this research showed, each season has a quite different sensitivity threshold. The result of the comparison showed that the thresholds calculated in this study conform to what previous studies reported. Particularly, these thresholds calculated in this study do not seem to contradict with wind comfort criteria guideline developed for Melbourne CBD before [30]. The guideline that is based on Melbourne Wind Criteria [31] advised that for different postures, V_a values should not be greater than 3 m/s for sitting, 4 standing and 5 m/s for walking individuals. Overall, it is valuable that future wind comfort assessments provide sensitivity thresholds that are based on season and type of activity.

Table 7. Comparison of wind sensitivity thresholds (at the pedestrian level) between different cities.

	City/Country/Province	Spring m/s	Summer m/s	Autumn m/s	Winter m/s	All Year Round m/s
This study	**Melbourne**	2.04 (1.76–2.49)	4.51 (>3.11)	1.25 (0.94–1.4)	NA	2.53 (entire study period) (2.05–2.86)
City of Montreal [56]	**Montreal, Canada**	NA	6.11<	NA	4.15<	NA
Willemsen and Wisse [55]	**Netherland**	NA	NA	NA	NA	Traversing: <10 (good), 10–20 (moderate), >20 (poor) Strolling: <5 (good), 5–10 (moderate), >10 (poor) Sitting: <2.5 (good), 2.5–5 (sitting), >5 (poor)
Szűcs [57]	**Dublin**	NA	NA	NA	NA	Walking: <5.4 Standing: <3.9 Sitting: <2.6
Shi, et al. [58]	**Jiangsu, China**	NA	NA	NA	NA	Walking: < 5 Standing: <3.9 Sitting: 2.5
GWTS [30]	**Melbourne**	NA	Sitting: ≤3 Standing: ≤4 Walking: ≤5	NA	NA	NA

5. Conclusions

This study conducted a series of outdoor thermal comfort field surveys in three seasons (spring, summer, and autumn) in three open spaces of an educational precinct in Melbourne, Australia. The research aim was to explore outdoor users' wind comfort perceptions and determine seasonal wind comfort sensitivity thresholds. People's wind comfort perceptions were evaluated using "Bedford preference" and "personal acceptability" scales. The results showed that while a large proportion of people perceived wind conditions acceptable in most of the times, their preferences for V_a varied in different seasons and sites (preference). This difference is attributed to the conceptual differences between these two scales resulting in discrepancies in people's wind comfort perceptions. Furthermore, this study determined seasonal wind sensitivity thresholds for open spaces in Melbourne CBD.

Designers and urban planners can use these findings to make an informed decision about outdoor spaces in urbanized areas. In addition, wind engineers who aim to manipulate wind flows in cities in the quest of providing better thermal conditions will benefit from the research findings. However, the results should be used with this caveat in mind that the majority of respondents were students. Therefore, it will be useful if further research is undertaken to quantify wind perception for other populations. Lastly, it is recommended that further studies consider wind conditions in wintertime during which people's thermal comfort is expected to be profoundly influenced by V_a values.

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