

>6°C of separation: Exploring the difference between perceived and measured temperature

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ABSTRACT

Questionnaires exploring tourists' perceptions of ideal climatic conditions are argued to be a more suitable data source for the development of tourism climate indices than the utilization and integration of expert opinion and pre-established thresholds. This assumes that those tourist respondents can accurately quantify meteorological conditions at a given point in time, and effectively discriminate between meteorological thresholds of suitable and unsuitable conditions. For variables such as rainfall and sunshine hours, this assumption is fairly reasonable. However, where tourists' perceptions, captured through questionnaire responses, are used to set thresholds for air temperature and thermal comfort, it is important to determine whether those perceptions are valid. Previous studies contest this, indicating considerable differences in perceptions of heat thresholds based on terminology, nationality, destination, and time of the year. In this study, a benchmarking exercise is performed comparing perceived temperatures and thermal comfort to measured values, through questionnaires administered to 984 adults in South Africa. Findings indicated that while 19.9% of responses are within 1 °C of measured temperatures, up to 12.8% of respondents perceive temperatures as being at least 6 °C higher or lower than the measured values. There are no clear geographic or demographic variables that effectively discriminate between accurate and inaccurate responses. When asked to classify their level of thermal comfort, as opposed to quantifying temperatures, results aligned more closely with measures and classifications of effective temperature. Based on these results, we argue that greater caution should be applied when using temperature thresholds derived from questionnaire data in developing and calibrating any biometeorological indices, and focus instead should be placed on categorized levels of self-reported thermal comfort in environments where raw meteorological conditions are measured.

1. Introduction

Human experience of air temperature, heat, and thermal comfort is influenced by a range of both exogenous and endogenous factors (Rana et al., 2013; Peng et al., 2021). The exogenous factors include the level of acclimatization to a local environment (Lam and Lau, 2018; 2021), clothing choice, location in sunshine or shade, and the speed and temperature of wind (Jendritzky et al., 2012), while the endogenous include age, sex and metabolism (Rohles, 1980; Li, 2005; Jendritzky et al., 2012; Wang et al., 2018a; Dzyuban et al., 2022). Perception of thermal comfort is further influenced by a range of psychological factors, including the colour of the walls of a room (Hanlon, 1979; Wastiels et al., 2012), furnishing type and arrangement (Rohles, 1980; Lenzholzer and van der Wulp, 2010; Vlaović et al., 2012), and the finishes of a building (Demattè et al., 2018), which affect a difference in perceived temperature within rooms of equivalent measured temperature. The furnishings

and finishes can also have a direct impact on the measured temperature through the degree of heat absorption, reflectance and insulation (Lenzholzer and van der Wulp, 2010; Wastiels et al., 2012). A range of thermal comfort indices have been developed to better replicate a 'real feel' measure of how hot or cold an environment is, and the threat of thermal stress, through incorporating measurements of temperature, relative humidity, wind speed and direct radiation (Jendritzky et al., 2012; de Freitas and Grigorieva, 2015). To date, there are over 150 thermal comfort indices, each developed and calibrated to specific applications, and which inform a range of adaptation strategies (De Freitas and Grigorieva, 2015, 2017; Li et al., 2023).

Human experiences of heat, and the suitability of thermal conditions, influence a range of daily activities (Chen and Ng, 2012). Thermal comfort has been found to directly influence productivity in the workplace (Kaushik et al., 2020; Kawakubo et al., 2023), tourists' enjoyment of a destination (Matzarakis, 2007; Salata et al., 2017), and the quality

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and duration of sleep at night (Minor et al., 2022). Humans, as mammals, perceive whether we are hot or cold, and make decisions accordingly to alter our sensation of thermal discomfort where possible (Nakamura et al., 2008; Nicol and Roaf, 2017). These decisions, however, relate to our individual feelings of (dis)comfort, and relative changes in heat exposure (Rana et al., 2013). This does not necessarily mean that we are able to quantify a specific temperature of a location, but rather that the temperature in question is suitable, or not, for our intended activities (Rana et al., 2013; Ličina et al., 2018).

Against this background, the use of survey questionnaires that collate human perceptions of thresholds of climatic suitability when developing biometeorological indices is questionable (Dubois et al., 2016a). Specifically, in the domain of tourism and climate change, an argument has been put forward that indices developed using tourists' stated preferences collected through questionnaires are more accurate than those compiled from expert knowledge and pre-existing index thresholds (De Freitas et al., 2008; Scott et al., 2016; Rutty et al., 2020). This requires that the questionnaires be compiled in a manner that would allow effective and accurate replicability and that can be generalized beyond the sampled population, particularly for those indices to be used globally. Dubois et al. (2016b: 347) demonstrate limitations in this assumption visually, plotting the differences in the distribution of the temperatures that are reported in questionnaires as too hot or too cold in two separate studies conducted by Dubois et al. (2009) and Rutty and Scott (2010). Moreover, such an approach assumes, without testing, that humans can accurately perceive air temperature (or thermal comfort as a metric thereof), and thus assign valid thresholds to the (un) suitability of temperature and thermal comfort. As Dubois et al. (2016b: 348) remark:

“No benchmarking exercise of stated temperatures with reality has to our knowledge ever been done. Whether tourists over or

underestimate the actual temperatures (even when accounting for humidity and wind) and to what extent, is unknown”.

This study follows this provocation, performing this suggested benchmarking through the process of asking a sample of 948 tourists across 10 cities in South Africa what the temperature is at a given place and moment in time and comparing this to measurements of temperature and real-feel temperature taken at the same location and moment in time using a high-accuracy hand-held weather meter. These results will contribute to determining whether questionnaire-based approaches to developing biometeorological indices are indeed preferable to an approach based on expert opinion.

2. Methods

2.1. Study region

Weather and climate form a key component of the competitive advantage of South Africa as a tourist destination (Cronjé and Martín-González et al., 2021). Marketed internationally as ‘sunny South Africa’, the country offers a respite to the long, cold winters in the Northern Hemisphere during the months of November through March, while the mild winter temperatures attract a range of domestic, regional and international tourists outside of the peak season (Saayman and Saayman, 2008; Fitchett and Hoogendoorn, 2018). Although the tourism sector suffered considerable losses during the COVID-19 lockdown-related travel bans (Ilo et al., 2024), tourist numbers are continuing to increase (Magubane, 2024).

While broadly classified as ‘ideal’ for tourism (Fitchett et al., 2017), the country is characterized by a heterogeneous climate influenced by a varied topography (Fig. 1) and the influence of the warm Agulhas current to the east, and cold Benguela to the west. This results in three

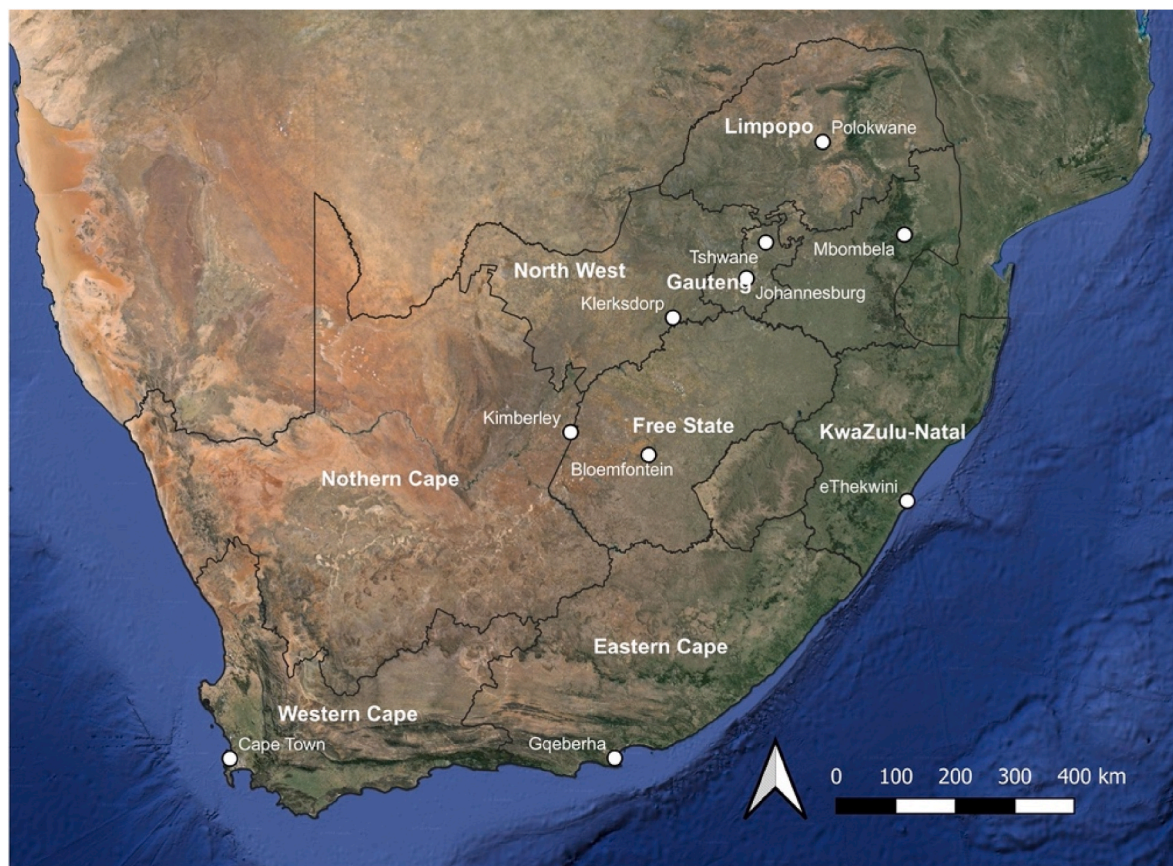


Fig. 1. Study site map.

distinct rainfall zones, and a wide range of temperature regimes (Roffe et al., 2021). Consequently, given the importance of location and acclimatization in experiences of temperature and heat (Lam and Lau, 2018), this study was conducted across 10 cities, located across the nine provinces of the country (Table 1, Fig. 1).

2.2. Data collection

Data collection involved asking tourists via a survey questionnaire, among other demographic questions, what the temperature was at that location and point in time (Dubois et al., 2016b), and how they perceived their level of thermal comfort on a Likert scale from very cold through to very hot (Ličina et al., 2018). While the tourist completed their questionnaire, the temperature and relative humidity were measured at the same location using a high-accuracy Kestrel 5000 hand-held weather meter at an average height of 1.5m above ground level (see Krøl and Krøl, 2023 including table of ranges and accuracy). The measured temperature and relative humidity data were captured on a separate form that was attached to the questionnaire once both were completed. The respondents were not made aware of the readings obtained from the Kestrel 5000 during their completion of the questionnaire. Data collection took place from June to November 2022, across all of the 10 cities of interest (Fig. 1, Table 1), using a combination of purposive (by city) and convenience (within city) sampling, approaching tourists in public spaces that are close to touristic attractions, and inviting them to take part in the study. The aim was not to obtain a sample that could be considered to be representative of all tourists to and within South Africa, but rather to explore the range in variability between measured and perceived temperature among a large group of respondents across 10 locations across the country with distinct climatic conditions and touristic attractions, and who have a range of demographic backgrounds to determine whether perceived temperature can be deemed a reliable form of data in biometeorological index development.

A total of 984 questionnaires were completed. Of these, 949 included responses to the relevant question on perceived temperature, and 861 answered the question relating to their perceived level of thermal comfort, forming the sample for this particular study. The latter was a close-ended question, with five classifications ranging from unacceptably hot through ideal to unacceptably cold (Wang et al., 2018b). In responding to the question asking what the temperature was at that moment in time, tourists could input any value (numerical or text, and to any decimal point), and were asked to state their unit of measurement.

Questionnaires and meteorological measurements were then captured into a single database, and temperatures were converted to degrees Celsius where necessary. As outlier values in authors' perceptions of the ambient temperature is a key point of interest in this study, no outlier values were removed from the database.

2.3. Data analysis

The data analysis for this study sought to explore the accuracy of tourists' perceptions of temperature when compared to measured meteorological conditions for the same location and time of the day. These comparisons could be made in all instances where respondents answered the question pertaining to what they thought the temperature was. Those questionnaires that did not include an answer to this question were excluded from the sample. Some of these responses included values which would be statistically considered outliers, but these are retained in the dataset as they demonstrate the range of (in)accuracy of the perception of temperature. These calculations are performed for both the measured air temperature and the calculated 'real feel' temperature. To assess the latter, Humidex was calculated for each of the measured meteorological data points. Humidex was developed by the Canadian Centre for Occupational Health and Safety as a measure of how hot the weather feels to the average person, by combining measurements of temperature and relative humidity (Diaconescu et al., 2023). The output scores are classified on the basis of the level of exertion and the degree of acclimatization if used in determining heat stress risk and response (Calkins et al., 2019). While there is a range of other real-feel measures of thermal comfort (see de Freitas and Grigorieva, 2015), Humidex is currently the most widely used as the input variable for the thermal comfort component of tourism and climate indices (cf. Demirogu et al., 2020; Rutty et al., 2020; Craig et al., 2023), and thus the most appropriate 'real feel' index to use when determining the suitability of questionnaire-based thermal thresholds in the development of these biometeorological indices.

Humidex is calculated by:

$$\text{Humidex} = T + \frac{5}{9} \times \left(6.112 \times 10^{7.5 \times \frac{T}{237.7+T}} \times \frac{H}{100} - 10 \right)$$

Where T = air temperature (°C)

H = relative humidity (%)

Humidex is designed with a primary focus on occupational health and safety, and consequently, the traditional output classifications align

Table 1
Geographic attributes of the 10 study locations.

City	Province	GPS Coordinates	Mean altitude (m. asl)	Koppen Geiger Climate Zone	Mean Temperature (°C)	Mean Relative Humidity (%)	Month of fieldwork
Bloemfontein	Free State	29.1129°S, 26.2149°E	1395	BSk	16.1	42.8	September 2022
Cape Town	Western Cape	33.9221°S, 18.4231°E	42	Csb	16.9	70.9	November 2022
eThekweni	KwaZulu-Natal	29.8587°S, 31.0218°E	880	Cfa	20.9	75.3	July 2022
Gqeberha	Eastern Cape	33.9137°S, 25.5827°E	15	Cfb	17.4	70.9	November 2022
Johannesburg	Gauteng	26.2056°S, 28.0337°E	1753	BSk	16	59.2	July 2022
Kimberley	Northern Cape	28.7435°S, 24.7626°E	1184	BWh	18	34.8	November 2022
Klerksdorp	North-West	26.8607°S, 26.6654°E	1297	BSh	18.1	45.0	September 2022
Mbombela	Mpumalanga	25.4753°S, 30.9694°E	680	Cwa	19.8	68.3	September 2022
Polokwane	Limpopo	23.9097°S, 29.4497°E	1310	CWb	17.3	64.1	August 2022
Tshwane	Gauteng	25.6051°S, 28.3929°E	1339	BSk	17.3	50.6	July 2022

with interventions to alleviate heat stress (Diaconescu et al., 2023). However, applying a similar rating to that of the UTCI (Jendritzky et al., 2012), we can broadly classify the outputs as in Table 2:

While Humidex is a good representation of how hot or cold it feels, and is the primary input variable for the ‘thermal’ component of biometeorological indices computing climatic suitability for tourism, people encounter information on air temperatures frequently in their daily lives, from indoor and outdoor temperatures displayed inside cars to the settings on an air conditioning system, and weather forecasts on television and cellphone applications. This information is conveyed to people while they are experiencing the temperatures stated on these devices. It is thus possible that when asked what the temperature is, the response may align more closely with air temperature than real feel temperature. This raw variable is therefore also explored.

In the first instance, the measured air temperatures and the Humidex values calculated from measured temperatures and relative humidities are each compared to the respondent’s reported perceived temperatures using a *t*-test to determine whether the differences between each of the two sets of values are statistically significant. The two sets of values are then compared using linear regression, exploring the mean offset, and the correlation between the pairs.

The degree of variance between the measured and perceived conditions is then explored through frequency distributions. This is followed by an analysis of possible factors that might influence the degree of difference between measured and perceived conditions, including the region of origin, age, the highest level of geographical education, altitude of the location, and the time of day at which the survey and meteorological record were collated. For these variables, within each category, the mean, standard deviation and maximum and minimum temperature differentials are compared, and the proportion of accurate responses, and responses within one degree. Finally, the perceived level of thermal comfort is compared first to the calculated effective temperature, and then to the broad Humidex classifications.

3. Results

A total of 984 survey questionnaires were completed across the 10 cities spanning South Africa, each coupled with a concurrent *in situ* measurement of the air temperature and relative humidity. Of these 984 completed questionnaires, 949 included completed, numerical answers for the question asking what the respondent perceived the temperature to be at that time and location. From this total sample, an average perceived temperature of 23.5 °C (*n* = 949) was calculated, spanning a maximum perceived temperature of 40 °C to a minimum of 8 °C (Table 3). This average is statistically significantly different from the measured temperatures (*t* = 2.75, *p* = 0.0059), which have an average of 24.1 °C (*n* = 984), spanning a maximum of 33.8 °C–15.6 °C (Table 3). An even greater difference in means (*t* = 8.88, *p* < 0.0001) is calculated when comparing the perceived temperature to the Humidex ‘real feel’ temperature score, which averaged at 25.4 °C (*n* = 984), with individual values ranging from 35.5 °C to 14.5 °C (Table 3).

Exploring these values visually through scatter plots, there is a broad coherence in the measured and perceived values (Fig. 2), yet relatively low levels of correlation (*r* = 0.58–0.59), consistent with the results of the *t*-tests (Table 3). The scatter plots reveal the extent of anomalously high and low perceived values relative to their measured counterparts

Table 3

Comparison of the aggregated measured temperatures, Humidex scores and perceived temperatures of the full sample.

Variable	Measured Temperature	Humidex Score	Perceived Temperature
Mean	24.1 °C	25.4 °C	23.5 °C
Maximum	33.8 °C	35.5 °C	40 °C
Minimum	15.6 °C	14.5 °C	8 °C
Standard Deviation	4.17	4.84	4.91
Sample Size	984	984	949
<i>T</i> (comparing with perceived temperature)	2.75	8.88	
<i>P</i> (comparing with perceived temperature)	0.0059	<0.0001	

for both air temperature and ‘real feel’ temperature (Fig. 2). The degree of variance does not appear to increase with temperature, with a similar spread of values at higher and lower measured temperatures (Fig. 2).

These aggregated results for responses and meteorological readings collected across South Africa potentially obscure location-specific results. While the local climate and time of the year of the survey are unlikely to influence how accurately respondents’ perceptions of temperature align with measured air and real feel temperatures, regional differences are observed in the data (Table 4). For Bloemfontein and Mbombela, the differences between perceived temperatures and both measured air temperature and Humidex are not statistically significant (Table 4). For Gqeberha, Cape Town and eThekweni, notably all coastal cities, there is no statistically significant difference between measured and perceived air temperature, but the difference for Humidex is statistically significant (Table 4). For Johannesburg, the difference between perceived temperature and the ‘real feel’ Humidex score is not statistically significant, but the difference with air temperature is (Table 4). There are no distinct patterns in the locations for which differences are more and less pronounced across each sample.

Overall, while there is co-variance, average perceived temperatures are different to both measured air temperature and Humidex values calculated from measured air temperature and relative humidity (Fig. 2). It is therefore of interest to explore the distribution of the level of difference between perceived and measured temperature. Overall, there is an average 0.6 °C difference (*n* = 949) between measured air temperature and perceived temperature. This relatively low mean difference, but masks maximum differences between measured and perceived temperatures ranging from +15 °C (ie. measured temperatures were 15 °C higher than the perceived temperature), to −17.7 °C (where measured temperatures were 17.7 °C lower than the perceived temperature). Across the sample, 58.1% of respondents underestimated the temperature, while 49.1% overestimated the temperature (Fig. 3). Only 1.1% of respondents cited a perceived temperature that was identical to the measured temperature (to the nearest degree Celsius). This is incorporated in the 19.9% of respondents indicated perceived temperatures which were within 1 °C of the measured temperature (Fig. 3). A total of 12.8% of respondents perceived temperatures that were at least 6 °C different from the measured conditions (Fig. 3).

Notably, and consistent with the results of the *t*-test comparison of means, perceived temperatures are considerably closer to measured temperature than they are to the ‘real feel’ Humidex value calculated from the measured temperature and relative humidity (Fig. 3). Comparing perceived temperature to Humidex, a mean difference of 2.8 °C is calculated, with extreme under-estimations of 34.6 °C, and over-estimations of 19 °C. None of the respondents cited perceived temperatures equal to Humidex, while 15.4% of respondents cited perceived temperatures within 1 °C of the Humidex value (Fig. 3). When comparing perceived temperature to the Humidex measure of ‘real feel’ conditions, a considerable 73.3% of respondents cited temperatures below the calculated index output, while 26.7% perceived temperatures higher than the Humidex score (Fig. 3). Almost double the proportion of

Table 2
Humidex score output classifications.

Humidex Score	Classification
<9 °C	Cold
10–14 °C	Cold to cool (slight cold discomfort)
15–29 °C	Ideal
30–39 °C	Warm to hot (slight heat discomfort)
>40 °C	Unacceptably hot (heat stress risk)

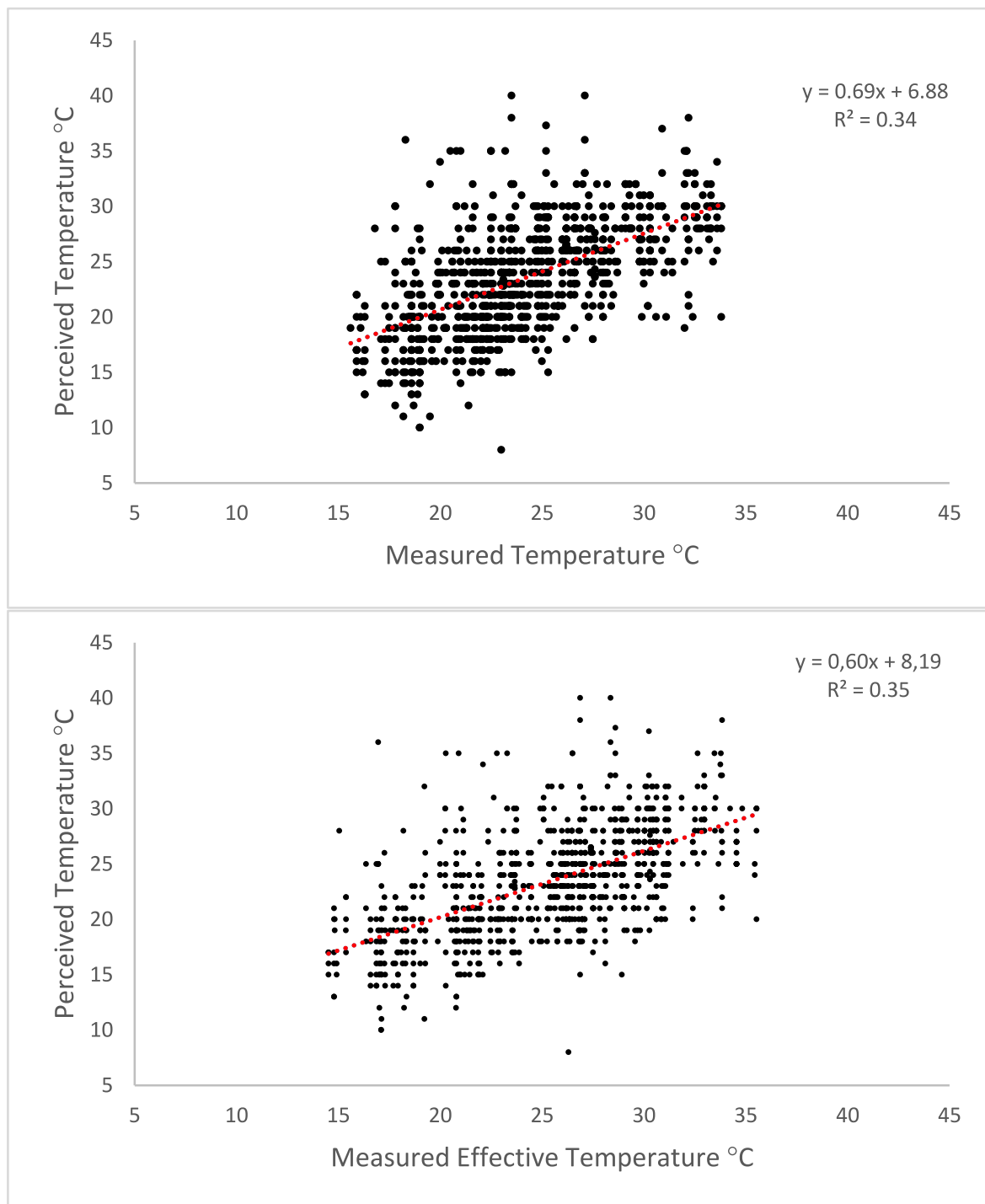


Fig. 2. Scatter plots for measured and perceived temperature, and effective temperature and perceived temperature.

respondents, at 24.4%, perceived temperatures that were 6 °C or more different from the Humidex value (Fig. 3). Importantly, this does not necessarily dispute the value of Humidex as a measure of real feel conditions but may indicate that people are more frequently exposed to measures of air temperature, as opposed to real feel conditions, in daily life. This is explored further in the discussion. Nonetheless, hereafter we explore the difference between only the air temperatures and perceived temperatures, except when making a comparison to perceptions of thermal comfort.

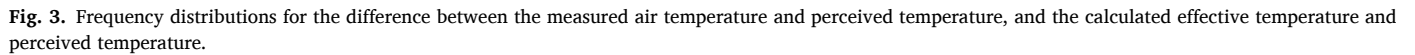
A key component in our experience of heat and perception of temperature is argued to be the level of acclimatization to a local climate.

Therefore, one could expect variation in the degree of difference between measured and perceived temperatures when comparing local residents with regional and international tourists. Of the total sample of 948 respondents, 71.8% were local tourists travelling within South Africa. This group contributes to the 74.5% ($n = 948$) who are local to the southern African region. The remaining 25.5% of the sample are international tourists, travelling into South Africa from countries on other continents, and north of 20°S on the African continent (Saayman and Saayman, 2008). Counter-intuitively, it is the local tourists who have the greatest spread in results, and the smallest percentage of respondents whose perceived temperatures are within 1 °C of the measured air

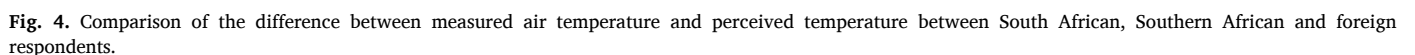
Table 4

Comparison of the aggregated measured temperatures, Humidex scores and perceived temperatures per location. Grey shading indicates statistically insignificant differences between the measured temperature or Humidex score and the perceived temperature.

Altitude range	City	Variable	Measured Temperature	Humidex Score	Perceived Temperature
<200 m.asl	Cape Town	Mean	22.6 °C	25.2 °C	22.7 °C
		Maximum	31.4 °C	35.4 °C	32 °C
		Minimum	18.6 °C	20.8 °C	13 °C
		Standard Deviation	3.15	3.56	3.50
		Sample Size	121	121	114
		T (comparing with perceived temperature)	−0.3	5.53	
		P (comparing with perceived temperature)	0.7647	<0.0001	
	Gqeberha	Mean	22.6 °C	27.1 °C	22 °C
		Maximum	26.2 °C	31.5 °C	29 °C
		Minimum	20 °C	23.3 °C	18 °C
		Standard Deviation	1.69	1.71	2.62
		Sample Size	80	80	80
		T (comparing with perceived temperature)	1.81	14.75	
		P (comparing with perceived temperature)	0.0726	<0.0001	
501–1000 m.asl	eThekwin	Mean	24.1 °C	27.7 °C	24.7 °C
		Maximum	26.7 °C	31.2 °C	35 °C
		Minimum	22.2 °C	21.1 °C	8 °C
		Standard Deviation	1.50	2.09	3.66
		Sample Size	100	100	100
		T (comparing with perceived temperature)	−1.49	7.17	
		P (comparing with perceived temperature)	0.1374	<0.0001	
	Mbombela	Mean	29 °C	30.1 °C	29.3 °C
		Maximum	33.6 °C	34.8 °C	40 °C
		Minimum	20 °C	22.1 °C	20 °C
		Standard Deviation	3.52	3.27	3.81
		Sample Size	103	103	102
		T (comparing with perceived temperature)	−0.51	1.55	
		P (comparing with perceived temperature)	0.6123	0.1219	
1001–1500 m.asl	Klerksdorp	Mean	31.2 °C	29.8 °C	26.9 °C
		Maximum	33.8 °C	35.5 °C	32 °C
		Minimum	23 °C	21.0 °C	15 °C
		Standard Deviation	3.03	3.57	4.45
		Sample Size	42	42	42
		T (comparing with perceived temperature)	5.22	3.33	
		P (comparing with perceived temperature)	<0.0001	0.0013	
	Bloemfontein	Mean	25.3 °C	24.2 °C	23.6 °C
		Maximum	31.1 °C	32.4 °C	35 °C
		Minimum	16.8 °C	15.1 °C	18 °C
		Standard Deviation	4.22	4.56	4.16
		Sample Size	36	36	36
		T (comparing with perceived temperature)	1.75	0.56	
		P (comparing with perceived temperature)	0.0838	0.5743	
	Tshwane	Mean	24.0 °C	24.8 °C	22.7 °C
		Maximum	29.1 °C	33 °C	32 °C
		Minimum	19 °C	17.1 °C	10 °C
		Standard Deviation	3.24	4.69	4.65
		Sample Size	100	100	100
		T (comparing with perceived temperature)	2.24	3.13	
		P (comparing with perceived temperature)	0.0262	0.0020	
	Kimberley	Mean	24.1 °C	27.2 °C	25.5 °C
		Maximum	28 °C	31 °C	40 °C
		Minimum	17.8 °C	20.3 °C	12 °C
		Standard Deviation	2.53	2.86	5.14
		Sample Size	87	87	77
		T (comparing with perceived temperature)	−2.17	2.72	
		P (comparing with perceived temperature)	0.0314	0.0073	
	Polokwane	Mean	27.1 °C	28.3 °C	25.8 °C
		Maximum	31.2 °C	34.5 °C	31 °C
		Minimum	18.4 °C	19.1 °C	18 °C
		Standard Deviation	2.64	3.32	2.43
		Sample Size	101	101	95
		T (comparing with perceived temperature)	3.69	6.03	
		P (comparing with perceived temperature)	0.0003	<0.0001	
>1500 m.asl	Johannesburg	Mean	20 °C	19.3 °C	18.9 °C
		Maximum	25.2 °C	25.3 °C	36 °C
		Minimum	15.6 °C	14.5 °C	11 °C
		Standard Deviation	2.44	2.69	3.5
		Sample Size	214	214	203
		T (comparing with perceived temperature)	3.91	1.148	
		P (comparing with perceived temperature)	0.0001	0.1406	



changes as we age (Frank et al., 2000). It could therefore be possible that the difference between very accurate and inaccurate perceptions of air temperature could be age-related. There is little variation in the distribution of variance across the different age-groups, although notably the oldest cohort (60–69 years of age) had one of the smallest mean



differences between measured and perceived temperature (Fig. 5). In this age-group, one would expect respondents to be more sensitive to extreme temperatures (Frank et al., 2000). Age does not, however, serve as a good discriminator between more- and less-accurate responses (Fig. 5).

A third factor that could influence the level of difference between measured and perceived temperatures is the level of education of the respondent, and in turn, the level of education that they had received on topics relating to weather, climate and measures of temperature. Across the six levels of aggregated education exit level, there is a relatively consistent inter-quartile range in the difference between measured and perceived temperature (Fig. 6). There is a slight tendency to under-estimating temperatures amongst the small (1.4%, $n = 948$) proportion of the sample who left education at primary school level (Fig. 6). Notably, however, this group had the second largest proportion of respondents whose perceived temperatures were within 1 °C of measured air temperature (Fig. 6). The sample cohort with the largest proportion of perceived temperatures within 1 °C of measured temperatures were those who exited education at PhD level, albeit a small total sample group, while the largest proportion citing the exact temperatures were those who exited education at an Honours level – a postgraduate one-year qualification that follows a three-year undergraduate degree in South Africa (Fig. 6). The bimodal peak observed particularly for the cohort who exited at high school and Honours level is interesting (Fig. 6), but the reasons for this are unclear.

The time of day during which the questionnaire and meteorological measurements were completed could influence the degree of variation in values through the level of micro-scale acclimatization to the meteorological conditions of that day, the cumulative exposure to hot or cold conditions, and the probability of having seen thermometers or weather forecasts on that day. The results, however, similarly show little distinct variation in means or inter-quartile ranges (Fig. 7).

The altitude of the destination could also potentially influence the level of accuracy of the perceived temperature, particularly as South

Africa has such a large altitudinal range. This altitudinal range, coupled with the distance from the ocean, results in greater diurnal temperature ranges in the interior plateau than in the lowveld or coastal regions. The inter-quartile ranges at 1001–1500m.asl and >1500m.asl are more similar than those at lower altitudes, but the overall range in values is relatively similar (Fig. 8). Altitude of the location can therefore not be used as an effective discriminator between accurate and inaccurate results, or as a corrective factor for temperature threshold reporting (Fig. 8).

While no distinct patterns in the degree of variation between measured and perceived temperatures can be detected from the results, one would expect a degree of consistency between the stated level of thermal comfort and the measured conditions at that time. This is done by comparing the effective temperature, calculated with Humidex, for the air temperature and relative humidity at the time of the questionnaire, to the respondent-selected classification of thermal comfort. From the category of ‘cool to cold’ through to ‘warm to hot’, the respondent-selected classification for thermal comfort escalates with increasing temperatures, with averages of 23.1 °C (cold to cool), 25.9 °C (ideal) and 27.9 °C (warm to hot; Fig. 9). For the extreme classifications, there is greater variation. For the category ‘unacceptably cold’, the mean measured temperature was 26.3 °C (Fig. 9), albeit with only four respondents who selected this classification, and the temperatures at the time of their completion of the questionnaire varied from 20.8 to 30.3 °C. For ‘unacceptably hot’, the interquartile range was similar to that of ‘warm to hot’, but with a lower mean measured temperature of 27.6 °C calculated from the measurements concurrent with those 31 responses (Fig. 9). There is also notably no distinct discrimination in the measured air temperature between the five classifications assigned by the respondents (Fig. 9).

As the distribution of the classifications selected in responses does not yield clear discrimination in Humidex values for each category, we compare the selected category to the three levels of calculated heat stress that occur from the measured data (Table 5). The majority of the

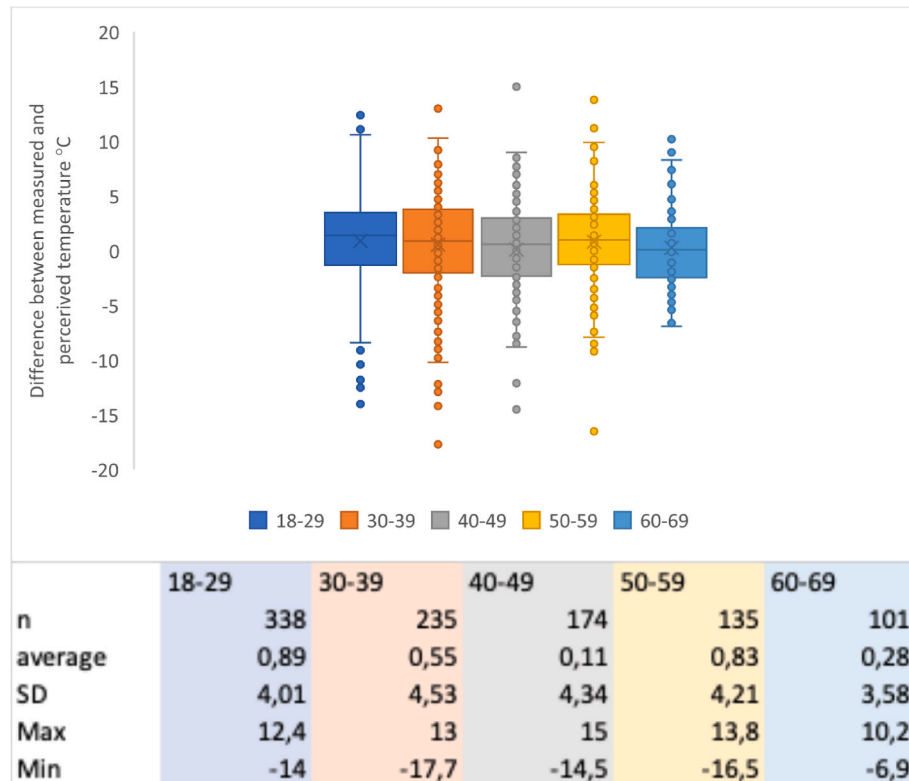


Fig. 5. Distribution of the difference between measured and perceived temperature by age-bracket.

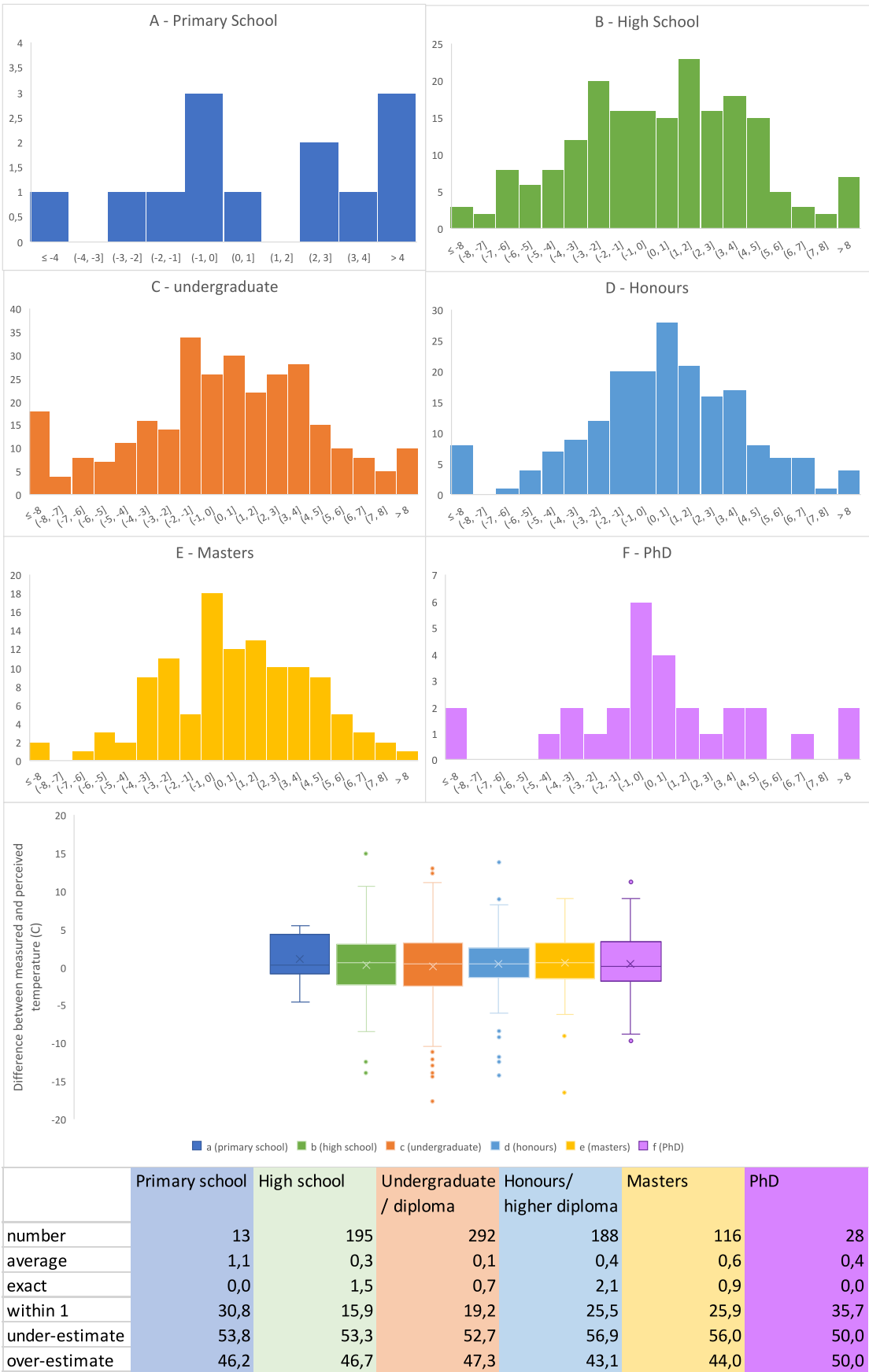


Fig. 6. Comparison of the difference between measured air temperature and perceived temperature between respondents by their reported highest levels of education.

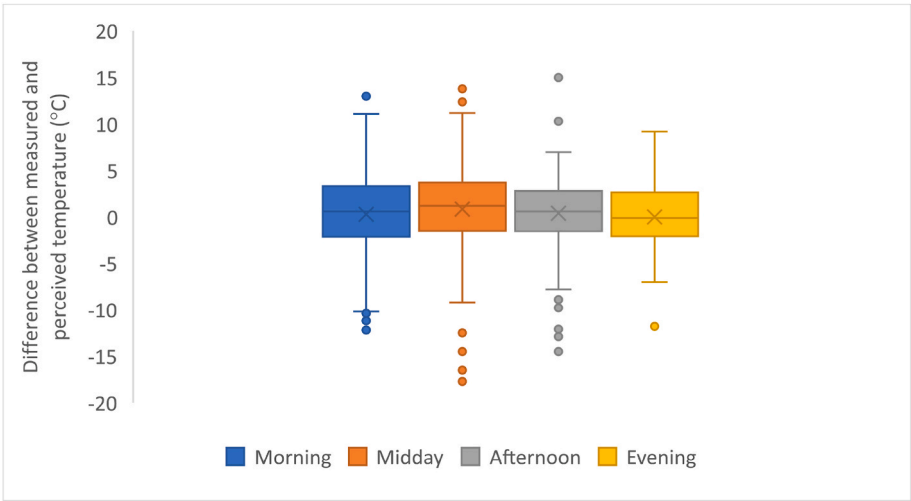


Fig. 7. Comparison of the difference between measured air temperature and perceived temperature as categorized by the time of the day, where morning is classified as 06:00–10:59, midday as 11:00–13:59, afternoon as 14:00–16:59, evening as 17:00–19:59, and night (no responses in this category) as 20:00–05:59.

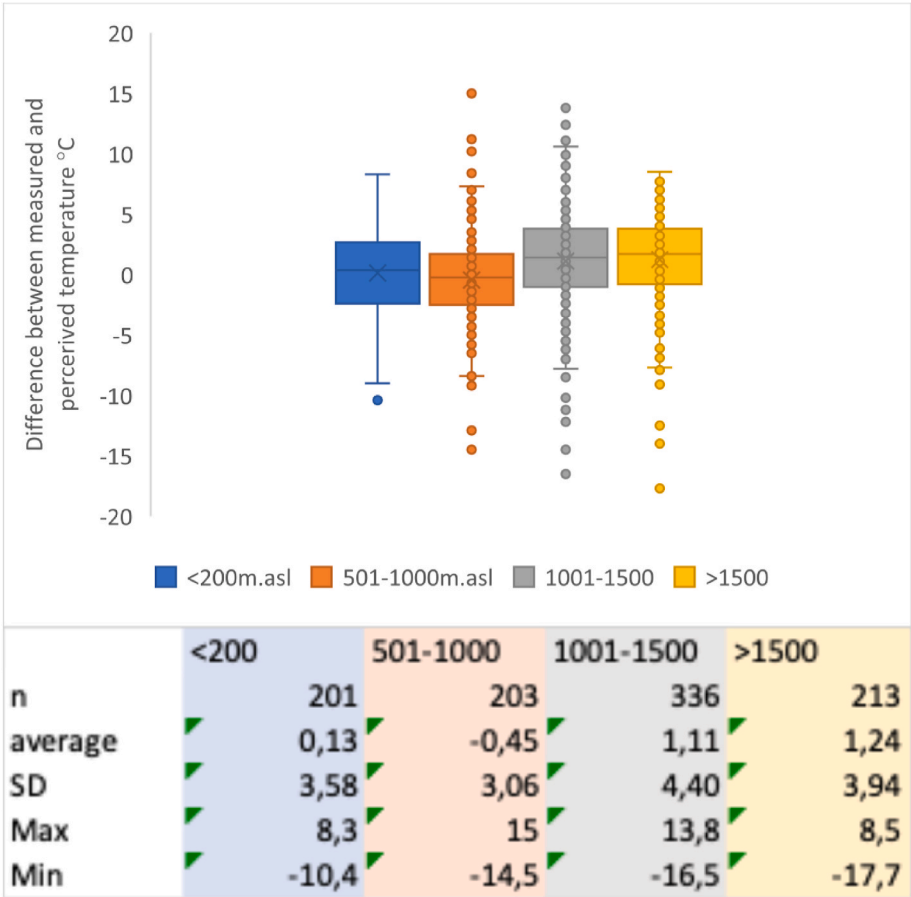


Fig. 8. Comparison of the difference between measured air temperature and perceived temperature as categorized by the altitudinal range of the study location.

respondents (43.1%, $n = 948$) were exposed to what can broadly be considered ‘ideal’ conditions of thermal comfort and selected that classification when describing their thermal experience (Table 5). This is followed by 17.4% of respondents who were exposed to what can be considered thermally ideal conditions, but which they perceived to be ‘warm to hot’ (Table 5). By contrast, 13.1% of respondents who were likewise exposed to conditions that were thermally ‘ideal’, found these to be ‘cool to cold’ (Table 5). Of the respondents who were exposed to

what could be considered ‘hot’ conditions, 10.1% concurred, indicating a classification of ‘warm to hot’, while 9.3% of these respondents classified the conditions as ideal (Table 5). Importantly, with consideration of the risk of thermal stress to tourists, perceptions of ‘hot’ conditions during periods which are classified by Humidex as ‘ideal’, or ‘unacceptably hot’ during either ‘hot’ or ‘ideal’ conditions is likely to increase shade-seeking activities to minimize the experience of heat, and therefore reduce health risks. Of greater

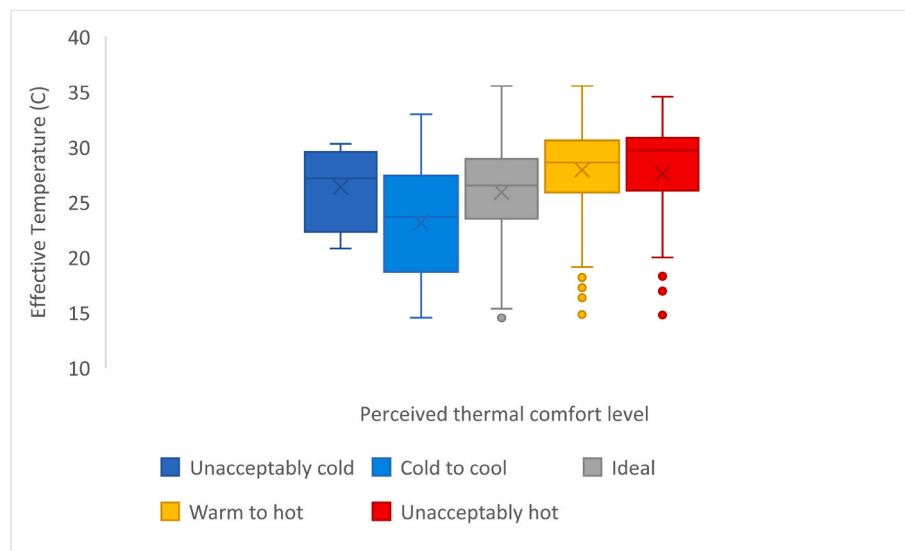


Fig. 9. Comparison of the measured effective temperature, and the self-classified levels of thermal comfort of the full respondent sample.

Table 5
comparison of the perceived classification of thermal comfort, and the Humidex output classifications.

		Humidex-classified thermal comfort		
		Cold	Ideal	Hot
Perceived thermal comfort	Unacceptably cold	0%	0.3%	0.1%
	Cold	1%	13.1%	1.3%
	Ideal	0.6%	43.1%	9.3%
	Hot	0.1%	17.4%	10.1%
	Unacceptably hot	0.1%	1.7%	1.7%

concern are perceptions of cold weather when Humidex scores are indicative of ideal or hot conditions, as this would reduce the likelihood of making adaptations in behaviour, clothing and location to minimize heat risk.

4. Discussion

This paper primarily set out to determine the extent to which tourists are able to state perceived temperatures that are consistent with measured meteorological conditions. Where the perceived temperatures are not consistent with measured conditions, the level of over- and under-estimation of actual temperatures and any patterns that differentiate the level of accuracy, are important to explore to determine whether it is possible to obtain accurate results through screening respondents for those characteristics. This heeds the call of Dubois et al. (2016b: 348) for a “benchmarking exercise”. As demonstrated by Dubois et al. (2016a,b), this is critical in determining whether tourists’ stated perceptions of the thresholds that discriminate between ideal and unsuitable temperatures are a valid source of input data in climate and tourism research generally, and in the development of tourism climate indices specifically. This has broader implications for the development and calibration of a wider range of human biometeorological indices (Krüger et al., 2021). Through asking 948 tourists across 10 South African cities what the temperature is, concurrent with recording the temperature at the same location and time on a high-accuracy hand-held weather meter, this benchmarking could be performed. The findings of this study reveal that while there is a broad positive linear relationship between measured and perceived temperatures, the difference between the means of the two is statistically significant. While the average difference between measured and perceived temperatures across the full

sample is 0.6 °C, and ~20% of respondents perceived temperatures within 1 °C of the measured temperature, the majority of respondents over- or under-estimated temperatures, with 12.8% citing temperatures at least 6 °C different from measured conditions.

For some of the locations, the differences between measured and perceived temperatures were not statistically significantly different, yet there appears to be no distinct pattern to discriminate between the regions where accuracy was higher or lower, and no clear climatological explanation for this. This would not allow for future studies using questionnaire-based data to identify regions, globally, where data are likely to be more or less meaningful. Exploring a range of demographic factors, there likewise appears to be no clear factors which can effectively discriminate between accurate and inaccurate responses. Further demographic and physiological features including the sex of the respondent, their metabolic rate, time since their last meal, and time awake (Rohles, 1980; Li, 2005; Jendritzky et al., 2012; Wang et al., 2018a; Dzyuban et al., 2022), among others, could be tested in future research to continue to attempt to identify factors that improve the accuracy of responses. However, such factors become increasingly difficult to screen in the types of large-scale questionnaires distributed across many cities when developing biometeorological indices (de Freitas et al., 2008; Scott et al., 2016). Similarly, while there could well be cultural and broader environmental factors that could influence the accuracy of responses, these are both difficult to test for, and challenging to screen a population of responses for. This, critically, means that there is no way of pre-determining which members of a sample group are likely to be less accurate, and whose data therefore should be down-weighted or excluded when using survey data to delineate thermal thresholds. In short, index development that involves the classification of thermal suitability from responses to questionnaires is inherently limited in its accuracy.

If tourists as a collective sample are unable to consistently accurately reflect current temperatures, and if we cannot identify demographics or geographic factors that characterize the less accurate respondents, tourists cannot be seen as a reliable source of data on the thresholds for (un)suitable temperatures. This is because the data suggest tourists, and likely humans as a collective, would be unlikely to quantify the temperature at the point at which such threshold is exceeded. Humans can reliably identify the point in time at which they feel thermally uncomfortable (Wang et al., 2018b), but the findings of this study indicate that they would not be able to accurately identify the temperature at which this sensation is experienced. This supports the hypothesis of Dubois et al. (2016b) and confirms that while differences in the wording of

questionnaires likely exacerbate this issue, a more fundamental problem of our ability to accurately perceive temperature, as opposed to contentment with the level of heat, prevails. This is unsurprising given the impact of age, gender, hormones, fitness level, fat stores, type and fabric of clothing and exertion on our experience of temperature (Li, 2005). While lab-based tests are able to identify the temperatures at which people become uncomfortable (Lan et al., 2011), and start to experience physiological effects of uncompensable heat stress (Vecellio et al., 2022), these cannot effectively replicate the wide range of activities that characterize tourism, with activities as disparate as business tourism through to adventure tourism (Sibson et al., 2010; Gonda and Csapó, 2019). Approaches that integrate the more extensive evaluations of thermal (dis)comfort and stress, such as ASHRAE (Rohles, 1980; Ličina et al., 2018), which was used in the original tourism climate index (Mieczkowski, 1985), or Humidex and the classifications thereof (Diaconescu et al., 2023) are more scientifically robust. These thresholds coupled with expert-based assignment of weightings, or weightings derived from regression analysis from visitor arrivals (Ma et al., 2020), can be complemented by tourists' perceptions of the relative importance of various climatic components, but should ideally not be replaced by them. Indeed, where for thermal comfort indices there is a very wide range, often used in combination through a multi-index approach, tourism climate studies should similarly engage with multiple indices developed through a range of approaches, to most effectively explore the climatic suitability of a destination (Prinsloo and Fitchett, 2024).

While the results of this study have been unable to identify specific geographic or demographic factors that can discriminate between respondents likely to provide accurate and inaccurate perceptions of temperature respectively, it is interesting to reflect on factors that could increase the likelihood of accuracy. These could vary not only by the intrinsic and extrinsic factors particular to the person but also by their activities during the day. Exposure, both generally and on the day of responding, to visual quantification of the temperature could well increase the level of accuracy. If a person has just left a vehicle which displays a reading of the outdoor temperature, they would likely be more accurate when asked the temperature, as they have a point of reference. Similarly, if they have seen a weather forecast for that day, a respondent would have a reference range for the likely temperatures on that day in which their answer would be constrained. Another place where measures of temperature are often displayed is on air conditioners. Over time, continued exposure to these sources of quantified information on temperature might intrinsically align a person's feeling of thermal comfort to a quantified measure of temperature. This could explain why the perceived temperatures stated by respondents were more closely aligned to the air temperature than to measures of effective temperature. However, these sources of information on ambient temperature are not universally accurate, and in many instances indicate the likely rather than the actual temperature. In the case of a vehicle thermometer, there is both the effect of the error margin of the device and the location in which it is parked (Donegan, 2017). For air conditioning systems, the temperature on the display indicates, again with a margin of error, the temperature of the air as it exits the device, but due to the dynamics of air temperature and heat transfer, there is often considerable variation in the resultant temperature across that indoor space (He et al., 2021).

Weather forecasts are perhaps the case in which the public is the most aware of the level of uncertainty, although they remain widely used in planning for daily activities (Joslyn and Savelli, 2010). Moreover, across all of these sources of information regarding measured temperatures, it is important to note the exact temperature depends heavily on microclimatic conditions, and even small differences in location between the place of temperature information and that of being questioned on temperature can influence accuracy (Peng et al., 2021).

Finally, it is worth reflecting on the bearing that the results of this study have on the validity and suitability of Humidex as a measure of real feel conditions, and the meaning of real feel in the context of

thermal comfort. The results of this study indicate that perceived temperatures align more closely to the measured air temperature, than the Humidex score calculated from measured temperature and relative humidity. However, when exploring the respondents' self-reported classification of thermal comfort, the importance and validity of Humidex emerges. Although there are no discrete threshold values, the Humidex values increase as the classifications of thermal (dis)comfort scale from very cold through to ideal, and on to very hot. Moreover, the majority of respondents classify their thermal comfort in categories consistent with those of Humidex scores. Humidex becomes important when it comes to our perception of the level of thermal comfort and the risk of heat stress (Rana et al., 2013). With the exception of 'unacceptably cold', a category cited by only four respondents, there is a broad increase in the perception of cool through to hot conditions with increasing Humidex values, consistent with the findings of Rana et al. (2013) and Li et al. (2023). Particularly important in the setting of tourism, are the recommended adaptations to escalating heat stress that are indicated by the Humidex score classifications, which range from the provision of water, through to the length of breaks that should be taken (Diaconescu et al., 2023). Given the alignment between perceived thermal comfort, and both the Humidex output scores and their classifications, more proactive enactment of these classification-based adaptations is advisable in the tourism sector, particularly where tourists are unacclimatised to the local climate, and taking part in heavy-exertion activities. Critical engagement with Humidex should also be extended to broader settings within the domain of human biometeorology (Rana et al., 2013; Diaconescu et al., 2023).

This study involves the analysis of 984 questionnaires distributed across 10 cities in South Africa. As the findings very clearly demonstrate differences between perceived and measured temperature, a larger sample or the inclusion of a greater number of sites is highly unlikely to change the primary finding – that such data are unreliable. It should not, however, be interpreted as a demographic measure of the level of accuracy of all tourists in their perceptions of temperature, or generalized beyond the point of cautioning the use of a questionnaire approach. If questionnaire-based data do remain used in biometeorological index development, the results of this study underscore the importance of concurrently measuring the meteorological conditions *in situ* to identify respondents who can accurately perceive the current weather conditions. Exploring a larger range of demographic, cultural, physiological and environmental conditions through this process could allow for more effective screening of accurate responses. It would also be of interest to sample a much larger population, across a number of continents, climate zones and tourist attractions to determine reasons behind the large variability in perceptions of thermal conditions.

5. Conclusion

A range of biometeorological indices have been developed using questionnaire responses of tourists, students and the public, including perceived thresholds for (un)suitable thermal conditions. This approach assumes that humans, collectively, are accurate in their perception of the temperature of their environment. If they are not collectively able to accurately perceive temperature, it might still be possible to use such questionnaire data on thermal thresholds if distinct demographic factors could effectively discriminate between the accurate and inaccurate results. This, however, was not found to be the case. The findings of this study, provoked by the work of Dubois et al. (2016a), confirm that tourists specifically, and likely humans generally, are not consistently able to accurately state the temperature of their local environment at a specific moment in time. The ability to accurately perceive the threshold at which an environment would become thermally uncomfortable is therefore compromised, as is the ability to identify inaccurate responses from the demographics of a respondent.

Therefore, thresholds for thermal (dis)comfort and stress in a range of biometeorological settings should not be determined from survey

questionnaires, as this compromises their accuracy. Rather, the thresholds for thermal comfort should be adopted directly from more comprehensive measures of human response and categorized experiences of thermal (dis)comfort relative to independently measured meteorological conditions, whether in laboratory settings or in work and living spaces. A careful re-evaluation of indices, and a process of verifying the physiological validity of the thermal comfort thresholds contained therein, is therefore an important avenue for future research, to ensure that the outputs of these indices can be accurately used in improving the tourism experience at destinations, and improving the climate resilience of those locations.

Although not the primary focus of this research, this study has highlighted the wide range in human perception of their thermal environment. This emphasizes the importance of future research exploring both climate-literacy and familiarity among the general public and tourists, and in factors that influence experiences of environments that are perceived to have much warmer or cooler conditions than the measured values. This sample of 949 responses highlights the wide variation between measured and perceived temperatures, but represents a small proportion of all tourists to and in South Africa, and indeed of the global population. Further research at a much larger scale would be very useful in achieving this aim.

Ethics

This study received ethics clearance from the University of the Witwatersrand Human Non-Medical Ethics Committee, protocol reference number H22/05/09. All participants were provided with a participant information sheet prior to agreeing to participate, and provided explicit written consent to take part in the questionnaire, and could choose not to answer any of the questions, or to exit prematurely.

Data accessibility statement

In line with the ethics clearance granted, these data are not accessible and remains confidential.

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Declaration of competing interest

The authors declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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