Adaptive approach of thermal comfort and correlation between experimental data and mathematical model in some schools and traditional buildings of Madagascar under natural ventilation

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A R T I C L E   I N F O

A B S T R A C T

A good ventilation is important to improve indoor air in buildings. In Sub-Saharan Africa regions and other countries, both health and productivity are indeed elements depending on indoor comfort. The purpose of this research is to suggest a new thermal comfort approach based on subjective responses of occupants and mathematical models. There is a lack of data about indoor comfort in residential buildings in the tropical islands of Indian Ocean and the aim of the research is to propose guidelines for more comfortable constructions in Madagascar and other countries of the Indian Ocean. Experimental and subjective data were collected in 67 traditional habitats and 25 public and private schools, located in 25 districts of urban communes in the Northern Madagascar. Mathematical modelling was based on Rohles approach. At total of 992 questionnaires were collected and analysed during rainy and dry seasons. The results showed that traditional buildings were more comfortable than schools. Comfort temperature varied from 24.6 to 28.4 °C during both seasons in residences and schools. When the indoor air temperature varied in the 24.5–27.5 °C range, more than 80% of peoples were satisfied.

1. Introduction

Temperature often significantly varies in naturally ventilated buildings (Lu, Xia, Wei, Fang, & Qi, 2016). Natural ventilation is an important sustainable building design strategy, known to mankind for centuries (Fergus Nicol and Michael Humphreys, 2012; Lu et al., 2016). In some studies, it is recommended to improve indoor air for building natural ventilation (Nematchoua, Tchinda, Djongyang, & Ricciardi, 2014a) and, according to other researches, the energy consumption in building can be minimized, also by exploiting natural ventilation (De Dear, Brager, & Cooper, 1997). The results of surveys still depend on several parameters coming from studied place and the obtained data cannot always been extended to different regions (Fergus Nicol and Michael Humphreys, 2012). Thermal comfort heavily depends not only on environmental factors, but also on physical, physiological and psychological aspects (Fergus Nicol and Michael Humphreys, 2012). Thermal sensations and preferences of occupants are always different in a same environment (Nematchoua, Tchinda, Orosa et al., 2014) and a comfortable and healthy environment is a prerequisite (De Dear et al., 1997). The concept of thermal comfort is quite complex and varies according to each subject (CIBSE and CIBSE Guide A, 1999), however,

although many international standards define the range of comfort conditions, opinions still stand widely divided (Yau, 2008). Worldwide researchers are presently focusing on the energy efficiency of buildings (Nematchoua, Tchinda, & Orosa, 2014a).

Several Literature works testify the importance of the adaptive approach. van der Linden, Loomans, and Hensen (2008), aiming to study the linkage between the predicted mean vote (PMV) and the adaptive thermal comfort (ATC) model, showed that, for a moderate outdoor climate as in The Netherlands, the PMV-approach is well able to explain the results derived from the ATC approach. Tan and Kosonen (2003), by studying many buildings in the tropical hot-and-humid climates, showed that the adaptive approach to thermal comfort is also suitable in tropical hot-and-humid climate, providing the means to determine the thermal comfort requirement of occupants. Halawa and van Hoof (2012) looked critically at the foundation and underlying assumptions of the adaptive model approach and its findings. They found that this new approach may take credit for widening the range of acceptable comfort temperature, which allows to obtain more energy savings in buildings.

Adaptive comfort concerns have already been introduced in ASHRAE Standard 55, but just as an option in certain conditions. Hong,

Nomenclature		Temp	Temperature(°C)
		Tint	Indoor temperature
ASHRAE	American Society of Heating, Refrigerating and Air	T_u	Uniform air temperature
	Condition Engineers	T_r	Mean radiant temperature
ATC	Adaptive thermal comfort	Trad.build	Traditional building
I_{cl}	Insulation (Clo)	T_{sens}	Thermal sensation
M	Metabolism(met)	TWI	Thermal preference index
MAX	Maximum	Va	Air speech(m/s)
Med	Medium		
Min	Minimum	*Greek symbols*	
PMV	Predicted mean vote		
PMV*d*	Adaptive PMV	β_S	Proportion of occupant having voted "comfortable"
PMV*q*	Predicted mean votefrom questionnaire	α	Slope
Pv	Air vapour partial pressure(pa)		
RH	Relative humidity(%)	*Subscripts*	
RHint	Indoor relative humidity		
TAI	Thermal acceptability index	t_n	Neutral temperature
TC	Comfort temperature	t_o	Operative temperature

D'Oca Yan, and Chen (2017) analysed some questions and suggested a method to improve energy savings and occupant behaviour in buildings. The new methods suggested by the researchers allow to increase energy efficiency and to reduce energy use in residences. Karyono (2000), after a study in 596 offices in Jakarta, found that comfort conditions could be achieved without unnecessary cooling in air conditioned buildings. The research carried out in some schools by Nematchoua, Tchinda, and Ricciardi (2014) showed that the increase of air velocity is an essential phenomenon for obtaining thermal comfort. Jentsch, James, and Bahaj (2018), after several investigations carried out in an UK primary school, suggested that children have a different thermal perception than adults. Sullivan and Trujillo (2015) showed that in a given environment, when the air temperature is so high or very weak, a majority of occupants are uncomfortable. Other studies were applied in schools and buildings in several places with different climates (Deuble and Johnde Dear, 2012; Fahmy and Sharples, 2009; Jensen, 2008; Lan, Wargocki, & Lian, 2011 ;Sekhar, 1995; Tablada, De Troyer, Blocken, Carmeliet, & Verschure, 2009; vander Lindena, Boerstra, Raue, & Kurvers, 2002; Wong and Khoo, 2003).

In Sub-Saharan Africa and Indian Ocean, some studies were carried out in this field (Nematchoua, Tchinda, Orosa et al., 2014; Nematchoua, Tchinda, Ricciardi et al., 2014; Nematchoua et al., 2014a; Nematchoua, Tchinda, & Orosa, 2014b; Noël, René, & Donatien, 2010; Noël, René, & Donatien, 2012; Ogbonna and Harris, 2008), but they need to be improved in order to allow the development of specific standards for these regions. Today, the modern buildings are in many cases built by means of imported materials. The choice of Madagascar as the place for this study was not carried out randomly. It is the biggest island of Indian Ocean and the 4th in the world. Madagascar, according to the World Meteorological Organization, is considered as the third-ranking country in the world that is most vulnerable to climate change. This change affects indoor air in buildings.

Madagascar is ranked among those countries that are rich in solar energy, with an estimated potential of around 2000 kWh/m²/year. Madagascar's largely rural population mainly depends on subsistence agricultural activities, which contribute to habitat degradation, especially the loss of forests (Tadross, Randriamarolaza, Rabefitia, & Yip, 2008). Several areas of the island have over 2800 h of sunshine per year. According to the report of the Diagnosis of Energy Sector (Madagascar National Communication, 2004), Madagascar has a potential of over 2000 MW of wind power. The country fragility in the face of multiple climates and crossing cyclone motivates the population of the Northern Madagascar to build with temporary materials and with the cheapest on the market, generating uncomfortable residential buildings. The choice of traditional residences and schools as subjects of

the research is due to their excellence because they host people of different ages and from all parts of the country. Moreover, no investigations on thermal comfort have been carried out previously in regularly-occupied buildings such as traditional habitats and schools in Indian Ocean with new adaptive approach, except for those in (Nematchoua, Ricciardi, Reiter, Asadi, & Demers, 2017; Rakotondramiarana, Ranaivoarisoa, & Morau, 2015; Razanamanampisoa, Randriamanantany, & Rakotondramiarana, 2018). The researches carried out this last decade in Sub-Saharan Africa had some limits: they were only referred to sedentary activity and to a fixed range of thermal clothing insulation. It is important to study the action of physical parameters on the health and productivity of occupants. This study analyses the influence of gender, clothing, activities, participants' mind state, and occupants' control strategies on adaptive comfort assessment.

Physical measures were also carried out, while questionnaires were simultaneously distributed to the occupants. The analysis of the indoor air data gave some information about the studied environments. Furthermore, for studying the variation of the effect of indoor parameters on the participants' health and productivity, a statistical analysis of the subjective questionnaires was carried out. An adaptive approach to the thermal comfort assessment is necessary because of the growing interest in the energy performance of buildings related to the envelope characteristics and to the occupants' satisfaction.

The overall purpose of the research is to create an important database on thermal comfort in Indian Ocean and to suggest another approach of thermal comfort studies based on the analysis of the subjective responses of occupants and mathematical models, in order to suggest the development of a standard norm more suitable for these countries. Results could help building designers to be more efficient and to help the regions with similar climates to expand their database.

2. Materials and methods

2.1. The studied region

Located between 20°00S and 47°00E, Madagascar lies almost entirely within the tropical region. It has an area of 592.000 km². The island is separated from Africa by the Mozambique Channel by about 400 km. There are two main seasons in Madagascar: dry, from May to October, and rainy, from November to April. Two short seasons of approximately 1-month duration separate these two seasons. From May to October, the climate is characterized by an anticyclone to the Indian Ocean, that directs a wind regime of trade winds from South-Eastern Madagascar. During this season, the eastern part of the island

experiences a humid climate "in the wind", while the western part undergoes a drought-like climate termed "down wind". The study was conducted in the tropical city Antsiranana (Northern Region), (Fig. 1).

Antsiranana is the largest city in Northern Madagascar and is the capital of the province of Diego-Suarez. Its population was estimated at 257,163 inhabitants in 2014. The town of Antsiranana is sheltered by the bay of Diego-Suarez (156 km of coast) the second port of the country. It is the second largest bay in the world after Rio de Janeiro. About 25 districts constitute the Urban Commune of Antsiranana, which extends over 47 km². The town is bounded to the north by the coves of the Dordogne and Melville, to the south and South-East by the plateau of Antanamitarana, to the east by the bay of the French, and to the west by the deltaic plain of Antomboko and the plateau of Cape Diego. Detailed characteristics of the studied area are reported in Table 1. Average rainfall of 12.4 mm makes the month of June the driest one, while in January rainfall is the highest in the year with an average of 204.9 mm.

2.2. Experimental campaign

An experimental campaign was carried out in 67 traditional habitats or residential buildings, and in 25 private and public schools, elementary and high schools, located in 25 districts of the urban commune of Antsiranana. Most of the selected traditional habitats were older than 70 years; traditional houses were built using local materials, such as dry bamboo, red earth, straw leaf, enamelled iron, and sometimes using provisional materials. Their heights vary between 1.9 and 4.5 m. Most of the buildings have square or rectangular plans, and their roof are formed of dry straw leaves, more than 5 cm thick, with an inclination of 45 °C and, sometimes, covered by old rusted metal sheets (Fig. 2).

These types of habitats are mostly located in the peripheral quarters of the town and often grouped near the main road. Some of them include sheet fences and earth block walls around. Other habitats are open to the public, allowing the indoor natural lighting during the day. These buildings have small verandas on the main façade that are used for rest and protection against sun and rain. The height or the length of

most of the doors are less than 1.77 m. In the majority of cases, the windows are on the main façade and oriented to North East, with a small area of about 0.12 m². The provisional materials are similar to wall, such as bamboo and plank.

The schools are mostly located in densely populated neighbourhood and close to roads. Most of them were built between 10 and 150 years ago, with plastered and painted walls and, sometimes, with earth block walls. In Table 2, the physical parameters evaluated for the different buildings are reported.

Traditional buildings are characterized by bamboo, steel sheets and planks, while schools are constructed with parpen bricks and earth block wall.

Data reported in Table 2 show that the habitats with steel sheet material present the worst thermal performance while the ones with bamboo material present the highest thermal performance. In all the different studied schools, there were at least 50 students per classroom (Fig. 1b). During this study, for both schools and traditional houses, the occupants were not subjected to any constraints, except for the complete interruption of the cooling and heating systems. The study was conducted during the periods reported in Table 3.

2.3. Instruments and questionnaires

The maximum, minimum, and mean air temperature, relative humidity and air speed were measured by a probe thermometer, thermo-hygrometer and anemometer. All these parameters allow to characterize the studied physical indoor environments (ASHRAE, 2004). The characteristics of the instruments are reported in Table 4. Before each experimental campaign, the equipment was calibrated in order to ensure reliability and precision in the readings taken (Feriadi and Wong, 2004; Roaf, Fuentes, & Taylor, 2001; Wong et al., 2002).

The sensitive infrared thermometer allowed to detect the maximum, minimum and mean temperature inside the wall. Some of the specific characteristics of this infrared thermometer are the especially clear laser point; a wide range temperature and an adjustable emissivity (depending on the material). This device easily detects
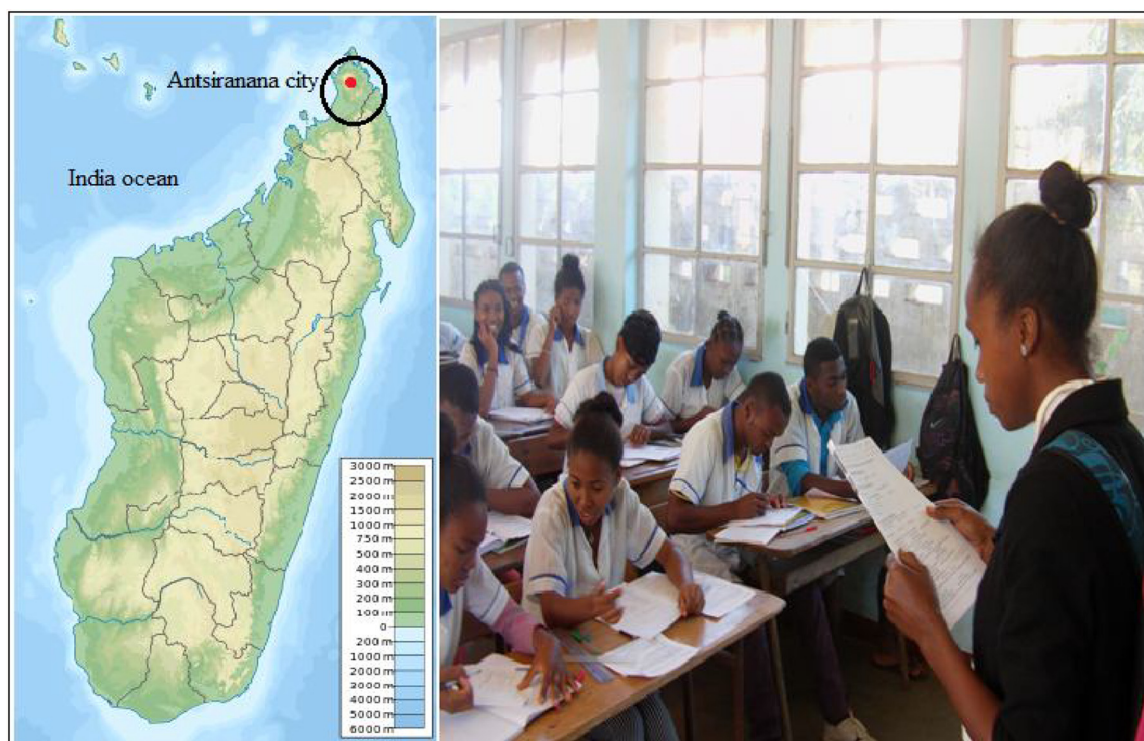

Fig. 1. Map of the place of study (left) and photos of an example of investigated school (right).

Table 1
Some climatic characteristics of Antsiranana city.

City	Latitude	Longitude	Altitude(m)	Temp. (°C)		RH(%)		Wind Speed (m/s)		precipitation (mm)	
				Max.	Min.	Max	Min.	Max	min	Max	Min
Antsiranana	12°16′S	49°17′E	43.0	33.5	20.0	85.5	60.5	9.0	4.5	338.0	0.0

Fig. 2. An example of traditional habitat in Madagascar.

the characteristics of objects at more than 10m.Measurements were taken every 5 min at a height of 1.5 m from the ground level, in strict compliance with the prescriptions of the ASHRAE Standard 55 and ISO 7730 Standard (UNI EN. ISO 7730, 2006). During the investigations, physical measures were carried out, while the questionnaires were simultaneously distributed, as suggested in (Brager and de Dear, 1998; De Dear, 2004; ; De Dear and Brager, 2001). The probes were installed far from heat sources, but next to strong people's concentration. A total of 22 students were selected and trained to conduct the surveys. For each campaign,data was collected continuously from 8:00AM to 6:00 PM The measurements provided three of the six parameters of interest: air velocity, relative humidity, and air temperature inside the buildings. They were used in order to calculate the PMV and PPD indices, in compliance with Finger's model. Just 30 min after the beginning of the lesson, both measurements and questionnaire distribution took place, in order to allow the students, villagers, and instruments to adjust to the environmental conditions.

The opinions and feelings of individuals were obtained by a careful analysis of questionnaires. They were developed in previous works (Buratti, Ricciardi, & Vergoni, 2013; Ricciardi and Buratti, 2012). A total of 992 questionnaires were collected during both seasons: 25 students for each of the 25 schools (625) and the remaining in traditional buildings (367). Questionnaires were written in French and Malagasy language, which are the country official languages. The language preferences of the occupants were

Table 3
Periods of study.

		Dry season			Rainy season		
city	Time	Month	Years	Time	Month	Year	
Antsiranana Traditional habitat	3 weeks	May–June	2016& 2017	1 week	December	2016	
School	2 weeks	September	2016	1week	November	2016	

considered while distributing questionnaires. The questionnaire was subdivided into two different parts: a section with the personal data (age and sex) and one about the thermal aspects (judgement about tolerability of thermal environment, air movement, temperature difference between head and ankle, activity performed in the last period, etc.). A synthesis of measured data is reported in Table 5.

2.4. Characteristics of the voters

The school inhabitants were young and more capable of answering the questionnaires than the buildings occupants. The height of the voters varied in the 1.41–1.65 m range in traditional buildings and in the 1.55 m–1.89 m range in schools. The weights ranged between 35 and 95 kg. The thermal clothes varied according to sex and age of the occupants, with an average thermal insulation of 0,86clo in schools and 0.92 clo in traditional buildings. The activity level varied according to seasons, but it was noticed more intense activities in traditional habitats than in schools. The main characteristics of the voters are reported in Table 6.

2.5. Mathematical models

The mean radiant temperature (T_r) was estimated using the following regression model, as function of the measured air temperature (T_a), proposed in Djongyang and Tchinda (2010):

$$T_r = 0.99T_a - 0.01, R^2 = 0.99 \tag{1}$$

The operative temperature (T_o) was determined from the measured air temperature (T_a) and the mean radiant temperature (T_r) by the following relationship (De Dear and Brager, 2001):

$$T_o = A\,T_a + (1_a - A)\,T_r \tag{2}$$

where the weighting factor (A) depends on the air velocity(w).

A = 0.5 for w < 0.2m/s;A = 0.6 for 0.2 < w < 0.6m/s; A = 0.7 for 0.6 < w < 1m/s.

Table 2
Building thermal characteristics.

Building [Wall kind]	floor area (m²)	Windows surface (m²)	thermal transmittance of wall (W/m²k)	thermal transmittance of window(W/m²k)	heat flux w/m²	position
Parpen brick	9.5–18.5	0.5–1.5	0.001–0.025	0.35–0.7	0.95 – 1.55	NE,SO
Earth block	11.5–14.5	0.2 1.5	0.07–0.55	0.15–1.5	2.5 − 5.5	NE, NO
Bamboo	9.5–13.5	0.0.3	0.21–0.75	0.12–0.7	2.1–9.3	SE, NE
Steel sheet	8.5–12.5	0.1–0.3	$(1.5–2.8)*10^{-5}$	0.1–1.1	5.4–12.7	NO, NE
Plank	9.5–16.5	0.2–0.6	0.01–0.15	0.15–0.5	4.5- 10.5	SE, NO

Table 4
Characteristics of the measurement system.

EMC 50081-1(model)	Function	Range	Resolution	Accuracy
Infrared thermometer				
Temperature	-50 to + 1000 ºC	0.1ºC	± 1.5 % ± 0.2 ˚C	
Thermo-hygrometer				
	Temperature	0–50 ˚C	0.1 ˚C	± 0.5 ˚C
	Humidity	0.1% to 99.9%	0.10%	± 3% (10–90%)
Anemometer				
Model:DA01				
	Wind speed	0 to 30 m/s	0.1 m/s	± 5%
	Temperature	-10 to 45 ˚C	0.2 ˚C	± 2 ˚C

Table 5
Synthesis of measured data in traditional residential buildings and schools.

	Traditional residences		Schools	
Parameters	Min	Max	Min	Max
T_{int} [˚C]	20.5	31.5	20.7	32.4
RH_{int}[%]	45.5	77.5	51.5	70.5
Va [m/s]	0.0	1.0	0.0	0.65
Pv [pa]	1869.5	2104.6	1721.7	2506.6

Thermal neutrality temperature (T_n) was defined as the optimal temperature in order to guarantee the best comfort conditions (ASHRAE, 2004). It could be an useful tool in order to quickly estimate thermal comfort. The surveyed conditions could be considered in the comfort zone, assuming 80% of satisfied persons as a good design target. Some researches (ASHRAE, 2004) showed that it is possible to estimate T_n, adapted PMV and T_{sens} under basic of several formulas in the Literature, including the results of physical measurements and questionnaires. By means of the calculated T_n data, a correlation between T_n and operative temperature (T_o) was found (Mui and Chan, 2003):

$$T_n = 0.7677T_o + 4.5842 \tag{3}$$

Furthermore, the Neutral Temperature was correlated to the External Temperature T_e, by means of the following equation:

$$T_n = 0.1544T_e + 19.3520, \text{ with a good correlation } (R^2 = 0.56). \tag{4}$$

Adapted PMV (PMV_d) was estimated by means of the following Rohles equation (Rohles, 1971):

$$PMV_d = aT_a - bP_{va} - c \tag{5}$$

in which T is the air temperature, P_v is the air vapour pressure (which could be calculated by means of the relative humidity), and a, b, and c are coefficients calculated by the authors in Buratti et al. (2013), which depend on sex (male or female) and thermal clothing insulation. The Rohles model was only valid in the 0–0.5 clo range of thermal insulation of clothing; nevertheless, the new coefficients associated to the model developed in Buratti et al. (2013) could be employed with I_{cl} varying in the 0.25–1.65 clo range.

The thermal sensation air temperature (T_{sens}) was calculated according to Nematchoua et al. (2014b). It is described by the following

equation:

$$T_{sens} = 0.407 \cdot T_a - 9.855, \ R^2 = 0.937 \tag{6}$$

3. Results and discussions

Approximately 1100 questionnaires were distributed in 25 schools and 67 traditional habitats in 25 districts situated in the Northern part of the island, but only the 90.2% (992) of the questionnaires were collected and analysed. The 37% of the 992 received questionnaires were collected in traditional residences and the 63% in schools. It was very difficult to retrieve all questionnaires distributed in the study site, because of the high density of students per classroom. The low response rate (37%) for traditional habitats was due to motivation's lack of villagers, most of them require a salary at the end of survey. In total, the 9.8% (108) of the questionnaires distributed were not recovered from voters. Before suggesting an adaptive approach, it was very important to understand the voter responses to their environment. With this purpose, in the next sub-paragraph, statistics of the subjects of residential occupants and personal thermal variables were analysed.

3.1. Subjective approach

3.1.1. Habitat and personal data

In this study, the voter ages varied from 15 to 75 years (Fig. 3a). Among the voters, the 69.9% (male) and the 22.2% (female) have an age in the 15–24 years range and the 14.2% (male) and the 13.4% (female) an age in the 24–34 years range. In addition, the 4.4% (male) and the 1.5% (female) have an age in the 55–64 years range while no voter's female were in the 65–75 years range, but only the 1.8% (male). It may be concluded that more than the 80% of voters were young people.

The construction period of each studied place is indicated in Fig. 3b. No school built between 0 and 9 years ago were investigated, while the 36.4% of traditional residences, the 31.8% of traditional habitats and the 3.5% of schools were built in the 20–29 years ago range. The 3.1% of traditional habitats and in mean the 12.5% of both were built from 50 to 59 years ago. No one of the studied traditional habitats was more than 70 years old, while the 31.6% of schools were more than 60 years old. According to previous researches (McCartney and Nicol, 2001; Nicol and McCartney,

Table 6
Characteristics of the voters.

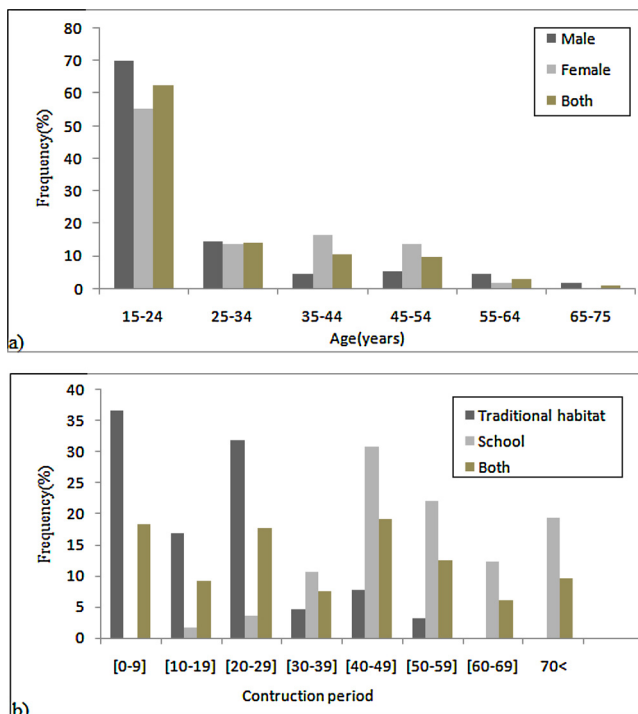| Occupants	Height(m)			Weight(kg)			I_{cl}(Clo)			M(met)			Age					
	M	F	T	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max
Trad.build.	137	230	367	1.41	1.59	1.65	55	60.5	95	0.5	0.92	1.5	1	1.1	1.2	18	38	64
Schools	250	375	625	1.55	1.65	1.89	35	59	79	0.4	0.86	1.45	1	1	1.1	14	18	25
Total/mean	387	605	992	1.41	1.62	1.89	35	59.8	95	0.4	0.89	1.5	1	1	1.2	14	28	64

Fig. 3. voter ages (a) and construction period of studied habitats and schools (b).

1999), the voters' age and the building construction period can be two precious parameters to be taken into account in the results analysis of thermal comfort.

3.1.2. Thermal acceptability (TAI) and thermal preference (TWI)

In this study, the thermal acceptability index (TAI) is defined as the ratio of persons who consider acceptable to the total number of persons who express an evaluation, and thermal preference index (TWI)as the ratio of persons who want to change to the total number of persons who express an appreciation for the environment, such as reported in Buratti and Ricciardi (2009).

According to the analysis carried out by Lu et al. (2016), it was found that the thermal sensation varied in function of voters sex. Data showed in Fig. 4 confirm this result: in the schools no males voted "cold", as thermal acceptability and only the 6.9% of females voted this index. The 35.7% of males and the 42.5% of females indicated "neutral" during both seasons. The 15.5% and the 27.4% of males voted " slightly warm and warm", respectively Furthermore only the 3.4% and the 17.2% of females indicated the same sensation. Generally, the 11.1% of persons voted "hot". On the other hand, in traditional habitats, no voters indicated "cold" for the thermal environment; however, the 6.4% of males, were voting "cool" and the 60.5% of females were sharing the same feeling during both seasons. The 8.5% of occupants voted "slightly warm", while the 35.4% of males and 23.6% of females were voting "warm". Taking into account both sex, approximately the 52.8% found the environment neutral, the 4.5% cool and the 29.6% warm during the two seasons. These results are almost the same as those obtained by Djongyang and Tchinda (2010) in North Cameroon, where they found that the 52.5% of occupants indicated that their residence was neutral during the studied period.

From Fig. 5, it appears that in traditional residences, when indoor air temperature varies in the 20–21.9 °C and in the 22 °C–23.9 °C ranges, no occupants wanted a "cooler" sensation. The 33.4% and the 100%,preferred no changes, while the 66.7% and the 0,4% of occupants voted, as thermal preference, "warmer"

in the same environment for habitats and schools respectively. In addition, in the 24–25.9 °C range, the 24.3%, the 67.6%, and the 8.1% of occupants wanted" cooler", "no change", and "more warm" respectively. In the 28 °C–30 °C range, the 90% and the 10% of inhabitants voted again "cooler" and "warmer" as thermal preference during both seasons. However, in schools (Fig. 5b), in the 20 °C–22 °C range, the 66.7% voted "warmer", the 16.7% voted "cooler and no changes", otherwise the 25.6%, the 58.1%, and the 16.3% voted as thermal preference "cooler", "no change" and "warmer", respectively. These results confirm that in both studied places, when air temperature is in the 24–26 °C range, more than the 60% of voters wanted as thermal preference "no changes", while when temperature is more than 28 °C, the 75% of occupants were preferring "cooler" for their environment. These findings confirm the results found in the Literature (Buratti and Ricciardi, 2009; Ricciardi and Buratti, 2012),which showed that thermal preference of people varies according to temperature. A great difference regarding the people's feelings can be due to activity level and clothing in this place. Data are reported in Table 7.

3.2. Adaptive approach

Before comparing the results obtained for traditional residences and schools, it was important to perform a Chi-square test or a t-test. The Chi-square test can be used to evaluate or to compare two groups (or two measures) and to easily take the best possible decision (Boslaugh, 2012; Lehmann and Romano, 2005). Generally, when the Chi-square test is applied for an analysis and a comparison of the results obtained in both the studied places, it allows to confirm whether they provide similar results or not and if there is a big discrepancy. All the statistical analyses were carried out by means of IBM SPSS 24.0 Statistical software. The 95% of confidence level (CL) assessed as level of significance was equal to 5%,which is majority used in t-test applications. The software allows to freely take, the value of the significance interval (called the p-value). Results are reported in Table 8.

The test is significant for p < 0.05 (5%),as above explained: in our case study, (p-value) is equal to 0.026. Thus it can be concluded
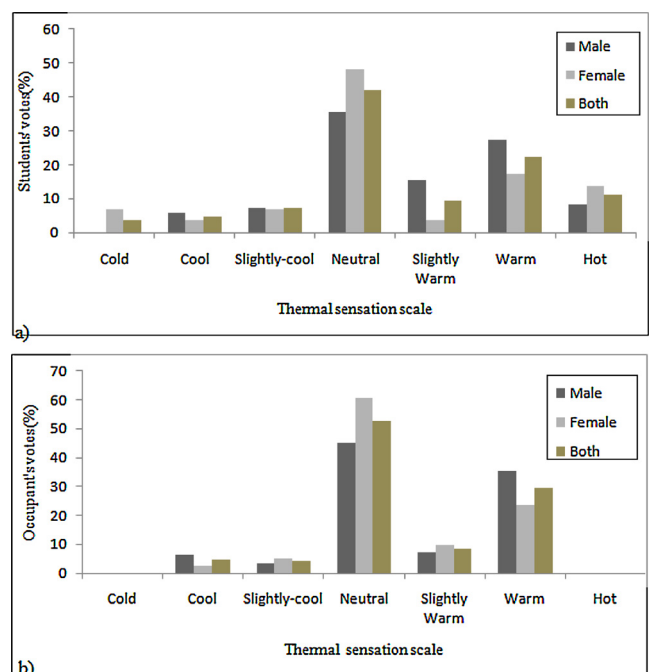

Fig. 4. Occupants' thermal sensation during both seasons in schools(a) and traditional habitats(b).
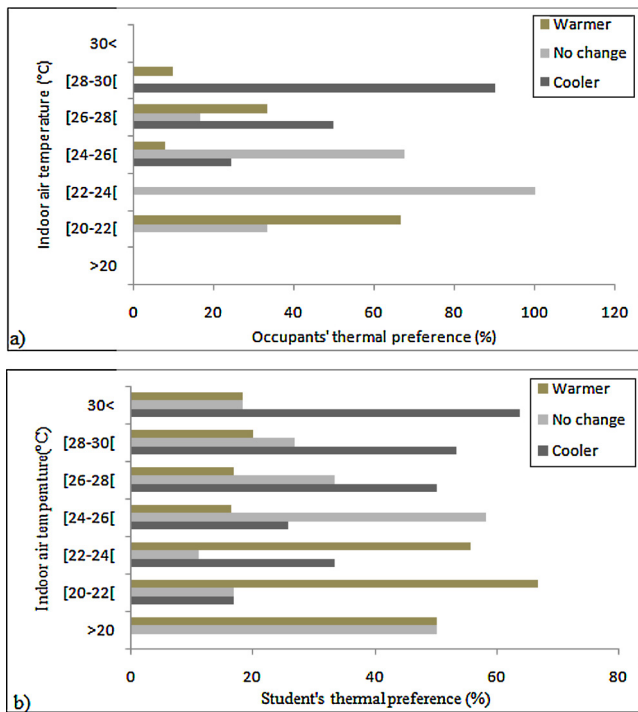
Fig. 5. Occupants' thermal preference as a function of air temperature values in habitats(a) and schools(b).

Table 7
summary of TAI and TWI.

Traditional buildings	Schools					
	Male	Female	both	Male	Female	both
Number of questionnaires	137	230	367	250	375	625
Average age	41	35	38	18	18	18
TAI	45.1	60.5	52.8	35.7	48.2	41.9
TWI	16.7	33.2	25.4	16.7	25.5	21.2

Table 8
Results of Chi-square tests in traditional residences and schools.

Datasets	value	df	asymp. Sig.(2-sided)
Pearson chi-square	66.500[a]	60	0.026
Likelihood ratio	46.168	60	0.905
Linear-by-linear association	0.973	1	0.324

Superscript (a) indicates that it is RC table Chi-Square Test, [a]Correlation is significant at the (P < 0.05), level (2-tailed) .
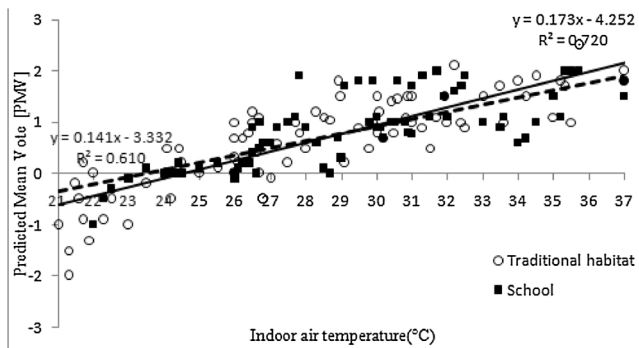
Fig. 6. The variation of PMV with mean indoor temperature in both seasons.

that thermal and indoor air sensations of the occupants are different in the two studied places. These discrepancies can be due to the strong activities in traditional habitats. Clothing and construction materials can also have a significant effect on heat transfer.

3.2.1. People and indoor climate

Fig. 6 shows the variation of Predicted Mean Vote (PMV) with the mean indoor temperature in traditional habitats and schools. Linear regression was used for the equations (6) and (7), as reported in another study (Kuchen and Fisch, 2009). Good correlations ($R^2 = 0.72$ and $R^2 = 0.61$) were found between the predicted mean vote (PMV) and the indoor air temperature (T_a):

$$PMV = 0.173\, Ta_a - 4.252, \ R = 0.85 \ \text{in schools} \tag{6}$$

$$PMV = 0.141 Ta_a - 3.332, \ R = 0.78 \ \text{in traditional buildings} \tag{7}$$

Correlations between T_a and PMV could also be evaluated good if regarding the main importance that mental and behaviour parameters have when data are coming from response to questionnaires (see Fig. 6).

When the air temperature was in the 21.1–35.5 °C range, the Predicted Mean Vote varied in the −1.5 to + 2.2 range in traditional buildings and in the −1 to +1.9 in schools. For PMV = 0, the neutral temperature was around of 24.57 °C in schools and 23.65 °C in traditional habitats.

According to the Literature review, it is possible to estimate the comfort temperature when more than 80% of occupants find the environment comfortable (De Dear et al., 1997). The experimental PMV values indicated that the thermal neutrality range is much higher than the one suggested by the direct votes. This seems to confirm the opinions by previous scientists regarding the restrictions of the PMV for predicting thermal comfort in naturally- ventilated residences (Nicol, 2004). In the Literature, it is important to notice that several adaptive comfort models were developed during the last two decades (Nguyen, Singh, & Reiter, 2012; Nguyen and Reiter, 2014a).

The following model defines the indoor comfort temperature (TC) as a linear function of the indoor air temperature found in this study, as showed in Fig. 7; the following equations were found:

$$T_C = 0.286 Ta + 18.86, \ R = 0.58 \ \text{in school} \tag{8}$$

$$T_C = 0.250\, Ta + 19.6, \ R = 0.78 \ \text{in traditional residence} \tag{9}$$

This model was based on data collected within this region.

When the indoor air temperature was in the 23.5–35.2 °C range, the comfort temperature was varies in the 24.6–27.6 °C range in traditional habitats and in the 24.9 −28.4 °C in schools. This result shows that the comfort temperature is higher in schools than in traditional habitats. The thermal neutrality temperature is around of 25.3 °C in both the studied places and during both the rainy and dry seasons.
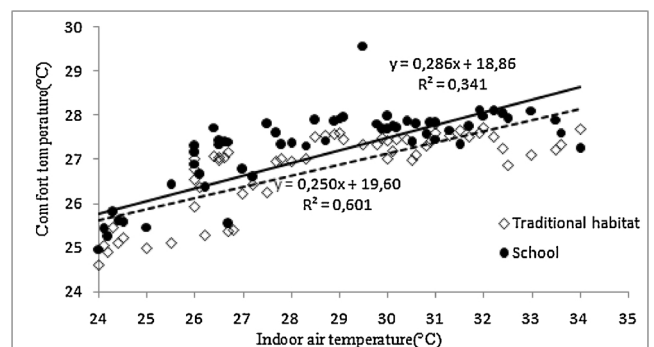

Fig. 7. The comfort temperature as function of the mean indoor temperature in both seasons.

According to field surveys conducted over a wide range of buildings and countries, it was found that the comfort temperature is closely correlated to the outdoor or indoor temperature. A similar result was found analysing the collected data throughout the year from a particular group of surveys in Pakistan and Europe (McCartney and Nicol, 2001; Nicol, Raja, Allaudin, & Jamy, 1999). At the time of the break between 12.00 and 2:00 PM, the comfort temperature was almost similar in all the schools and residences; it could be due to the absence of activity during these times.

As an example of how effectively adaptive actions can be used to achieve comfort, Fig. 8 shows the percentage of comfortable subjects (PMV = 0) among students and inhabitants in Madagascar (Antsiranana) at different indoor temperatures. Data were collected over dry and rainy seasons when the comfort temperature was continually changing, as it was the indoor temperature. Several good correlations ($R^2 = 0.82$ and $R^2 = 0.79$) between the percentage of occupants who found the environment comfortable, and the mean indoor air temperature are given in Eqs. (10) and (11).

$$\beta_S = -0.019\,T_a^2 + 1.014\,T_a - 12.52, \text{ R} = 0.91 \text{ in schools} \quad (10)$$

$$\beta_S = -0.013\,T_a^2 + 0.712 T_a - 8.347, \text{ R} = 0.89 \text{ in traditional buildings} \quad (11)$$

where β_S is the proportion of occupant having voted "comfortable" their environment.

These curves show the mean probability of comfort calculated using the regression method. Each point represents the percentage of comfort conditions in a particular place and during a given day (Fergus Nicol and Michael Humphreys, 2012).

With a continually changing indoor temperature and comfort temperature, Antsiranana residences were found comfortable at temperatures T_a ranging between 25.1 and 27.6 °C (comfort range for at least 80% acceptability). It was also noticed that on many studied places, the occupants recorded no discomfort. This result was almost similar to the ones by Nicol and McCartney (1999), who found when air temperature is in the 23–26 °C range, more than 80% of voters estimated the environment comfortable.

The next sub-section has the aim to study the relation between PMV from questionnaires and adaptive PMV, in order to understand the difference between voters opinion.

3.2.2. People and adaptive temperature

In Fig. 9, the difference between operative temperature (t_o) and neutral temperature (t_n) versus PMV (PMVq) from questionnaire for male and female in schools and traditional habitats or the respondents' thermal sensation was investigated. Three linear equations (from 12 to 14) were obtained, with significant correlations. In traditional buildings, it was noticed that all the correlation lines between both sex have the same slope ($\alpha = 0.486$) and similar coefficient ($R^2 = 0.79$):

$$PMV_q = 0.918\,(t_o\text{-}t_n) + 0.13, \text{ R} = 0.93 \text{ for female students} \quad (12)$$

$$PMV_q = 0.629(t_o\text{-}t_n) + 0.20, \text{ R} = 0.95 \text{ for male students} \quad (13)$$

$$PMV_q = 0.486(t_o\text{-}t_n) + 0.31, \text{ R} = 0.89 \text{ for traditional occupants (both male and female)} \quad (14)$$

PMVq varied in the −1.5 to +1.5 range, while ($t_{oa} - t_n$) were in the −2 to +2.5 range. When $t_o = t_n$, PMVq was expected to be very low or zero and people should feel neutral and wanted no change on thermal preference. However, when the neutral temperature is higher than the operative temperature, people should feel cold or sometimes slightly cool, and therefore PMVq is expected to be negative. Vice-versa in the case of $t_n < t_o$, people should feel hot or slightly warm and wanted their environment to be cooler. In this condition, PMVq is expected to be positive. These results are in agreement with those found by Ricciardi and Ziletti Buratti (2016),

who demonstrated that thermal preference and thermal sensation of inhabitants in residential buildings varied according to t_o and t_n. The neutral temperature(t_n), is one of the parameters depending on the studied environment and De Dear and Brager (2000) showed that the adaptation's behavioral mechanism can directly act on the thermal balance of human body, because of personal comfort given to this one.

Adaptive PMV (PMVd) as function of the uniform temperature is shown in Fig. 10. The different values of PMVd were estimated on the basis of the equation given in Buratti et al. (2013), with clothing resistance from 0.51 to 1.00. The following equations were obtained in this study, that will allow to improve the Literature with a new data base:

$$PMV_d = 0.269\,Tu_a - 6.115, \text{ R} = 0.99 \text{ female} \quad (15)$$

$$PMV_d = 0.142\,Tu_a - 3.141 \text{ R} = 0.94 \text{ male} \quad (16)$$

$$PMV_d = 0.183\,Tu_a - 4.087, \text{ R} = 0.97 \text{ both} \quad (17)$$

For uniform air temperature T_u in the 20.5–29.0 °C range, the obtained adaptive PMV varied in the −0.61 to +1.40 and in the −0.41 to +0.8 ranges, for females and males respectively. For PMVd = 0, (neutral environment),uniform neutral temperature was around 23.0 °C for both genders.

In addition, Fig. 11 shows the adaptive PMV versus equivalent uniform temperature in both seasons. The equivalent uniform temperature was obtained according to (ASHRAE, 2004; Ricciardi and Buratti, 2012). For both genders, the following equation was obtained:

$$PMV_d = 0.161 T_{uea} - 3.587, \text{ R} = 0.79 \quad (18)$$

When PMVd = 0, the equivalent uniform neutral temperature was about 22.5 °C. When equivalent uniform temperature varied in the18.5–22.1 °C range, people should feel cold and therefore PMVq is expected to be negative. On the other hand, in the 27.9 °C–31.5 °C range, people wanted colder environments, because indoor air was intolerable in residences.

In the Literature several studies (Buratti, Palladino, & Ricciardi, 2016; Nematchoua et al., 2015; Nguyen and Reiter, 2014b; Ricciardi and Buratti, 2015) showed that at a certain threshold temperature (greater than 30 °C), voters preferred their environment to be colder.

Correlation between adaptive PMV (PMVd) and PMV from questionnaires (PMVq) in traditional buildings and schools are given in Figs. 12 and 13, with clothing resistance in the 1.01–1.40 clo range. In traditional residences, for PMVq values in the −1.0 to +2.5 range, PMVd, oscillated in the 1.1–2.1 range. The following equations were obtained forum stable indoor temperatures:

$$PMV_d = 0.048(PMV_q)^2 + 0.050\,(PMV_q) + 1.621, \text{ R} = 0.72 \text{ for male} \quad (19)$$

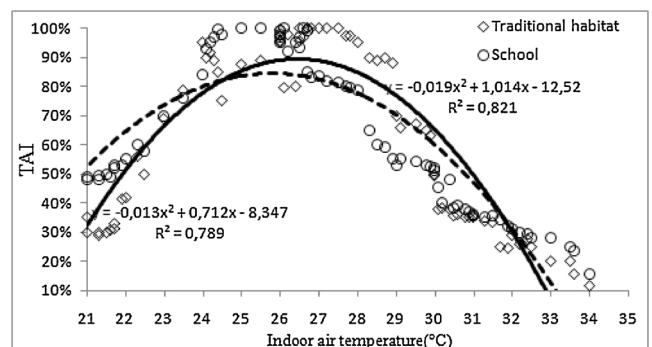$$PMV_d = 0.038(PMV_q)^2 + 0.126(PMV_q) + 1.292, \text{ R} = 0.54 \text{ for female}$$

Fig. 8. The percentage of occupants who were comfortable at different indoor temperatures in both studied places during the two seasons.
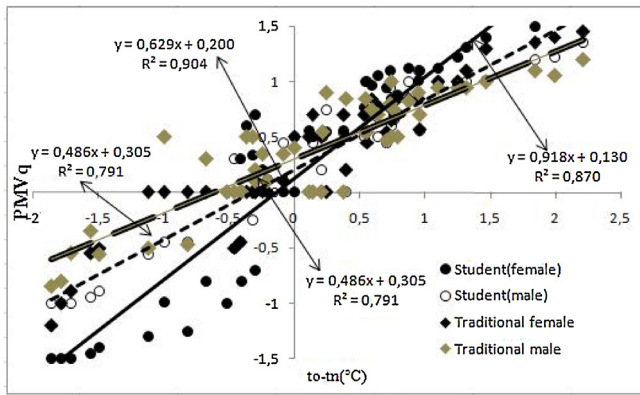
Fig. 9. PMV from questionnaires (PMV q) as function of the difference between operative temperature and thermal neutral temperature (analytical method) for males and females in both seasons.
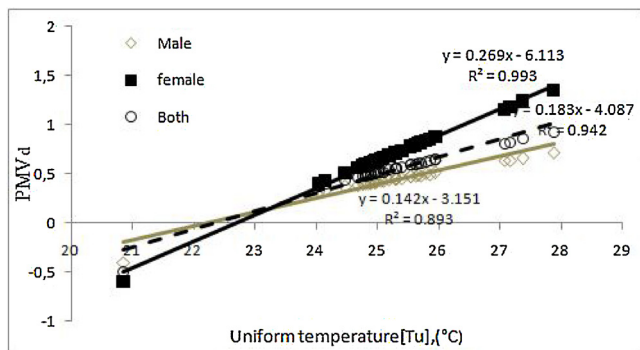

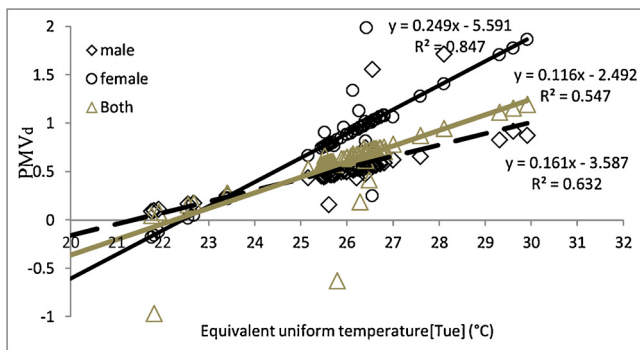**Fig. 10.** Adaptive PMV(PMVd) versus uniform temperature during both periods.

Fig. 11. Adaptive PMV versus equivalent uniform temperature during both periods.

$$(20)$$

$$\text{PMV}_d = 0.042(\text{PMV}q)^2 + 0.041\,(\text{PMV}q) + 1.493, \text{R} = 0.67 \text{ for both}$$

$$(21)$$

In fact, during the dry season (June), $\text{PMV}q$ varied in the 0.5–2.5 range for both genders, while PMV_d was in the 1.3–1.8 and in the 1.5–2.1 ranges for females and males respectively. In these conditions, the 81.5% of voters found the environment warm and would prefer a more neutral one. However, in rainy season (December), $\text{PMV}q$ varied in the −1.0 to 1.5 range for both genders, while $\text{PMV}d$ was in the 1.1–1.5 and in the 1.3–1.8 for females and males respectively. When $\text{PMV}q = -0.5$, PMV_d was 1.6 (females) and 1.2 (males); when $\text{PMV}q = 0$, $\text{PMV}d$ increased up to 1.63 (males) and 1.29 (females). In these conditions, the 44.5% of occupants were voting "warm" and
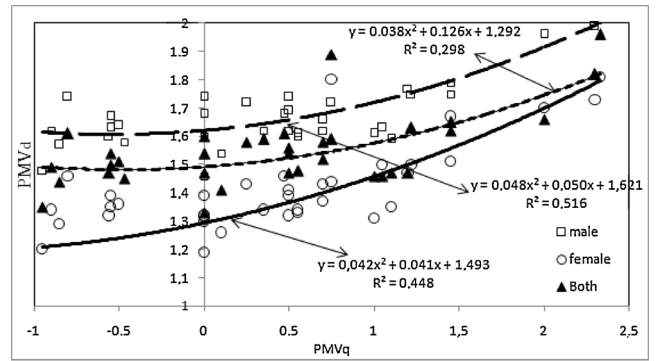

Fig. 12. Correlation between Adaptative PMV(PMVd) and PMV from questionnaire(PMVq) in traditional buildings.
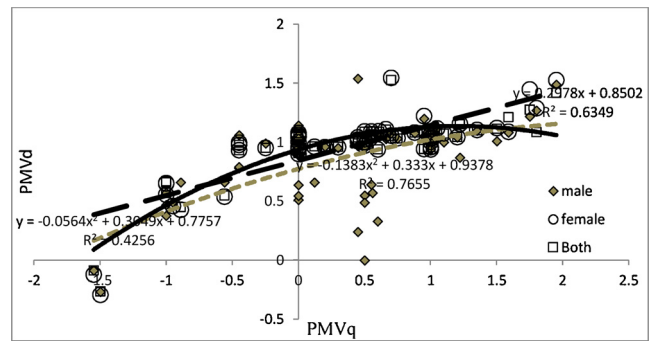

Fig. 13. Correlation between Adaptative PMV and PMV from questionnaire in Schools.

wanted a neutral environment.

From these results, it can be concluded that the adaptive PMV coming from mathematical models and subjective response of questionnaire (PMV_q) varied in the same direction. On the other hand, in school, PMV_d varied in the −0.5 to 1.5 range, while $\text{PMV}q$ was oscillating from −2 to +2. For $\text{PMV}_q = 0$, PMV_d was expected to be positive during both seasons. Generally, experimental results still depend on environmental climate. Exceptionally in this study, some findings were similar to results found by Buratti et al. (2013), who showed that PMV_q was within −1 to +2 range, corresponding to the +0.45 to +0.50 range for PMV_d. A great discrepancy was often noticed between objective results derived from measurements (PMV_d) and subjective ones from questionnaires (PMV_q). It explains why the sensation of neutral comfort is often majority in questionnaire answers, in comparison with the objective experimental results.

Thermal sensation (T_{sens}) was obtained from the questionnaires and other environment parameters, which allowed to obtain
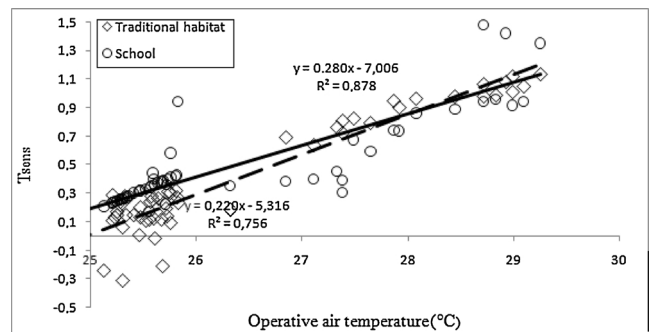

Fig. 14. Thermal sensation temperature versus operative temperature in traditional residences and schools.
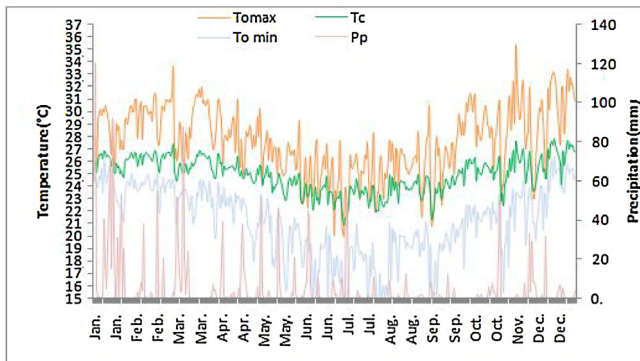
Fig. 15. The seasonal changes in mean comfort temperature TC in Antsiranana and its relation to mean daily maximum, minimum outdoor temperatures and precipitation.

Fig. 14, where the thermal sensation temperature was plotted versus operative temperature in traditional residences and schools during both seasons. By fixing relative humidity in the 55–75% range and air speed in the 0.15–0.55 m/s range, it is very interesting to notice that almost the same slope (around $\alpha = 0.2$) and good correlation coefficients ($R^2 = 0.88$ and $R^2 = 0.76$)were obtained. The following equations were applied:

$$T_{sens} = 0.28\, T_{oa} - 7.006, \ R = 0.94 \text{ in School} \tag{22}$$

$$T_{sens} = 0.22\, T_{oa} - 5.316, \ R = 0.87 \text{ in traditional} \tag{23}$$

In these equations, the good correlation can explain that there was not a great discrepancy between objective results, derived from measurements, and subjective ones, from questionnaires.

Clothing insulation is always the most difficult factor to be estimated in any field of investigation, due to the wide variety of clothing models and, consequently, it cannot be accurately estimated, in accordance with the clothing index tabulated by the ASHRAE and ISO standards (ASHRAE, 2004; UNI EN. ISO 7730, 2006). For values in the 0.51–1.50 clo range, the different T_{sens} obtained values varied from -0.47 to 1.13, with the average operative temperatures ranging from $22.4\,°C$ to $28.5\,°C$ in traditional residences and from -0.12 to 1.58 with the average operative temperatures ranging from $23.5\,°C$ to $29.5\,°C$ in schools. For $T_{sens} = 0$, the neutral temperature obtained in traditional buildings during both seasons was $24.5\,°C$, while in schools it was about $25.1\,°C$. With an operative temperature greater than $28\,°C$, T_{sens} was almost identical in schools and residences during rainy season. Similar results were found by Nematchoua et al. (2014b), who found that when the different T_{sens} values obtained vary from -2.03 to 2.05, the average internal temperatures range from $16.5\,°C$ to $28.5\,°C$ in the tropical wet warm climate of Douala.

3.2.3. People and the outdoor air temperature

The adaptive relationship between comfort temperature and the outdoor air temperature can be used for designing comfortable buildings. An example is shown in Fig. 15. It was noticed an instability of minimum, maximum, and comfort temperature. The trend of rainfall is also reported on the same figure. It was noticed that rainfall varied in the 0–120 mm range, when comfort temperature was in the24.5 $-27.5\,°C$ range.

Globally, in this study, it was found that more than 80% of voters have an age between 15 and 35 years. This can explain why, during the two seasons, more than 50% of occupants voted "neutral" as thermal sensation. It was saw that occupant's thermal preference varied according to studied place. Some researchers (such as Nicol and Cartney (Nicol and McCartney, 1999)) showed that the occupant's age and number of years spent in a dwelling can affect

thermal sensation and thermal preference of occupants. Roaf et al. (2001) showed that it is important to establish the relationship between outdoor and comfort temperature. In a previous study carried out in Cameroon, results confirmed that the comfort temperature ranged between $23\,°C$ and $28\,°C$ (Nematchoua et al., 2014a). Several researches considered by ASHRAE (ASHRAE, 2004) found that the comfort temperature is between $23\,°C$ and $26\,°C$. In this study, the comfort temperature was between 25.1 and $27.6\,°C$. All these above conclusions showed that comfort zone varied as function of the studied place. The thermal comfort range allows the selection of materials regarding micro-climate of environment. This choice is very important, keeping in mind the health and productivity of occupants in an environment. The experimental and simulation data can help the architects to build more modern buildings, with weak energy consumption. It is very interesting to note that the thermal modelling of the buildings could be useful to find solutions on how to manage the heat flux, so that the building performs better.

These results contribute to the advancement of the research because they propose a database on thermal comfort in an area that does not yet have a reliable construction standard.

4. Conclusion

In this study, an adaptive approach based on the analysis of questionnaires and mathematical models was applied, in order to evaluate thermal comfort in Madagascar. The experimental study was conducted in 67 traditional buildings and 25 schools in transition tropical climate of Indian Ocean. Some linear equations were obtained with significant correlations. The correlations could be evaluated good if considering the great importance that behaviour and mental parameters have when data are coming from questionnaires. The adaptive approach to thermal comfort reveals the new conditions of environment. It's interesting to study thermal comfort using adaptive approach because this method gives new results coming from studied environment. The variation of the air temperature has always significant effects on people's feeling, for example in this study, at more than $28\,°C$, the 75% of occupants preferred their environments to be "cooler". In this case, people should feel warm and therefore PMVq is expected to be positive.

The votes given in the questionnaires vary always in a wider range of values with respect to the measured data, due to the personal sensation.PMV from questionnaires varied from 0.5 to 2.5 for both studied places (traditional buildings and schools), while the adaptive PMV was in the 1. 3–1.8 range for females and in the 1.5–2.1 range for males. In these conditions, the 81.5% of voters found their environment warmer and preferred a neutral environment. Sometimes, when the operative temperature is equal to the neutral temperature, PMVq was expected to be very low or zero and people should feel neutral.

The results of the present can be useful for the development of sustainable standards for indoor climate for buildings in the future in several islands in the Indian Ocean.

Conflict of interest statement

The authors disclose any relevant associations that might pose a conflict of interest.

Acknowledgment

Appendix. Synthesis of the questionnaire

Note: This questionnaire is anonymous; the results of the statistical evaluation, the analysis and conclusions will be published. Please carefully read each question before answering and don't discuss with your friend who also filled this questionnaire.

*** Thanks you for your co-operation and the time you will have to devote to this questionnaire***

PART 1: PERSONAL DATA
(Please tick off the appropriate box,)
Age…………. Sex : M ☐ **F** ☐ height…………., weight…………
What is the type of building you study in? : Modern☐ Traditional☐

Is it with: mud ☐ wood☐ stone☐ glass ☐
Is it plastered ☐ Paint☐

How long did you live in the town?..
How long you live in your present house?..
How old is your house?...
What is the color of your house? ……………………………………………………………
How many rooms does it have?...
How many floors have your house?
PART 2: THERMAL
QUESTIONNAIRES (please tick off the appropriate box)

1) How do you feel about the temperature in this moment?
2) Cold ☐ , cool ☐ , Slightly cool ☐ , Neutral ☐ , Slightly warm ☐ , warm☐ , Hot ☐

3) How do you find it?
Acceptable☐ Slightly acceptable☐ Not acceptable☐ Slightly not acceptable ☐

4) What is your thermal sensation?
Comfort ☐ Light annoyance ☐ Annoyance ☐ Heavy annoyance☐

5) How would you like to feel?
Much too cool ☐ Too cool ☐ A little bit cool ☐ No change ☐ A little bit warm☐ Too warm ☐ Much too warm☐

6) On the basis of your personal preferences, how would you consider the room temperature?
Acceptable ☐ Not acceptable ☐

7) How do you consider this room?
Perfectly tolerable ☐ Slightly hard to tolerate☐ Hard to tolerate☐ Veryhardto tolerate ☐ intolerable ☐

8) How do you feel about the air flow in this moment?
Completely not acceptable☐ Not acceptable ☐ Slightly not acceptable ☐
Slightly acceptable ☐ Acceptable ☐ Perfectly acceptable ☐

8)Would you like to have an air mouvement
Smaller than now☐ Exactly how it's now☐ Greater than now☐

9) You find this Environment ?
Very Comfortable☐ Comfortable ☐ Slightly Comfortable☐ Slightly Uncomfortable☐ Uncomfortable☐ Very Uncomfortable ☐

10) How would you describe indoor humidity in your Building?
Very dry ☐ Moderately dry ☐ Slightly dry ☐ Neutral☐
Slightly humid ☐ Moderately humid ☐ Very humid ☐

11)Would you like to have an air humidity
Smaller than now☐ Exactly how it's now☐ Greater than now☐

Provide us indication regarding your clothing (e.g. Underwear, woman clothes, trousers, accessories, shirt, pullover etc.)
12)What was your occupation during last hour?

Occupation	Last 10 minutes	minutes ago	minutes ago	minutes ago
Doing Office job	☐	☐	☐	☐
Walking in slope	☐	☐	☐	☐
Walking in flat land	☐	☐	☐	☐
Walking in ascent	☐	☐	☐	☐
resting	☐	☐	☐	☐
running	☐	☐	☐	☐
seating	☐	☐	☐	☐
taking a bath	☐	☐	☐	☐
driving	☐	☐	☐	☐
reading	☐	☐	☐	☐
Doing something else	☐	☐	☐	☐
eating	☐	☐	☐	☐
washing dishes	☐	☐	☐	☐
cooking	☐	☐	☐	☐

PART 3: PERSONAL MICROCLIMATIC CONTROL (please tick off the appropriate box)

1) **How can you define the level of control of microclimatic conditions?**

No control ☐   Light control ☐   Medium control ☐   High control ☐   Total control ☐

2) **How do you feel about the possibility of controlling thermal comfort?**

Satisfied ☐   Not satisfied ☐

3) **Can you open/close the windows?**

No ☐   Yes ☐

4) **Can you open/close the external doors?**

No ☐   Yes ☐   there is no door ☐

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