Thermal Comfort in a Naturally Ventilated and Air Conditioned Urban Arcade

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ABSTRACT

Thermal comfort research in office buildings has led to developments in new thermal comfort standards. Yet a review of thermal comfort research reveals a lack of information on human response to conditions in *transitional spaces*: courts, atria, and arcades; spaces influenced by the outdoors, but bounded by a building or conditioned space. This study focuses on one type of transitional space, the urban arcade.

Adapting methods from past field research of indoor thermal comfort, we collected data using two techniques: survey questionnaires and physical measurement. Subjects walked through two arcades and completed a thermal comfort survey. To quantify the thermal conditions of the arcade, we designed a measurement cart, containing equipment and sensors that took measurements of the physical environment as subjects completed surveys.

The arcades of Cleveland, Ohio served as a case study in which 25 occupants completed questionnaires in two arcades, one naturally ventilated, the other air-conditioned. In general, the thermal environmental conditions of the arcades met the specifications of current thermal comfort standards. A wide range of votes and large deviation between votes characterized thermal sensation voting of occupants.

INTRODUCTION

An urban arcade is a glass-covered passageway that connects two or more city streets, lined on both sides by shops. Arcades host a multitude of activities such as retail establishments, serve as passageways for pedestrians between streets, and provide protection from inclement weather. At the scale of the city, arcades play a major role in the energy use of parent buildings. Understanding the environmental conditions that produce human thermal comfort in arcades is critical to design an optimized, energy efficient arcade, but has greater implications in the design of buildings of similar type, and the construction of the urban fabric.

Past research of urban arcades has documented the thermal environment of arcades, and attempted to predict the subjective response, or vote, of occupants through mathematical modeling. (Potvin 1999, 2000) This study adds to the current body of knowledge of thermal comfort, transitional spaces, and arcades via a field study that characterizes the thermal

environment of arcades, and documents actual subject response through surveys. The primary questions of this study ask:

1. *What are the ranges of thermal environmental conditions found in urban arcades?*
2. *What are the characteristics of thermal sensation voting in arcades?*

The results of this field study provide thermal comfort data for the study of arcades and transitional spaces, and quantify thermal sensation voting in arcades, potentially shaping the way we craft future thermal comfort standards and design urban form.

CONTEXT

The Climate of Cleveland, Ohio

Cleveland, Ohio is in a temperate zone of the United States at 42ºN, 82ºW. Cleveland's climate has two distinct seasons: a hot-humid summer, and a cold-dry winter. The shift in temperature between the high of summer and low of winter is extreme, averaging 52ºC.

The summer design dry bulb temperature of Cleveland is 32ºC, with a wet bulb of 22ºC. (ASHRAE, 1997) Summer design temperatures generally reach their highs in mid to late August. Field surveys of the arcades took place during Cleveland's hot season. After reviewing climate summaries and coordinating schedules with arcade management, the first survey took place on September 7, 2001. A second survey took place the following day. Temperatures on both test days reached 30ºC, 2º short of the summer design dry bulb temperature. (NOAA Climate Summary) Tests were coordinated to coincide with the warmest part of the day, early to mid-afternoon.

Arcades Surveyed

Several criteria provided the basis for selection of arcades in this study. These criteria included the selection of an air-conditioned and naturally ventilated arcade, close proximity of one arcade to the next such that subjects could walk between spaces, permission and accessibility granted by arcade owners, availability of subjects, budget, logistics, and time. Preparation for the study included researching past field studies of arcades and transitional spaces, finding and compiling a list of extant arcades, recruiting a subject group, documenting the history and original design of the arcades, and documenting changes to the ventilation and conditioning systems of the buildings. Two arcades volunteered to participate in the study, one mixed mode and the other fully conditioned.

The first of the two arcades, the Euclid Arcade, is a one-story passage connecting two 5-story office structures. The arcade is a straight corridor 400 feet long, 15 feet wide. Constructed in the beginning of the 20th Century, around 1910, it features a double shell glass roof along its full length. Currently, the arcade operates as a mixed mode space, using air-conditioning in shops, and in the main arcade space only on days in which the temperature or humidity are excessively high. (Marcus, 2001) For the purpose of the study, the HVAC system in the mixed mode arcade was disabled throughout testing with subjects, simulating the original, naturally ventilated nature of the space.

The Cleveland Arcade is a three building complex that joins two 9-story office buildings with

a 5-story arcade. The arcade was completed in 1891, the collaboration of an architect and structural engineer. (Schofield, 1966) Within the last year, a private development corporation has purchased the Cleveland Arcade, investing over 50 million dollars to restore its interior. Installation of an air conditioning system was part of the renovation to the arcade's interior. The air-conditioning functioned as designed throughout testing, at set points normally used in summer. (Goeden, 2001)

METHODS

Thermal Comfort Cart

An indoor thermal comfort cart, designed for compactness to facilitate easy air travel from Oregon to Ohio, as well as mobility on site, took measurements at 1.1 meters above the floor while subjects filled out the comfort surveys. The thermal comfort cart automatically measured ambient air temperature, relative humidity, and globe temperature. Ground surface temperature, solar radiation, and air velocity were measured with hand held equipment, also at the 1.1m height. The instrument cart rolled from location to location in the arcade, and subjects filled out specific survey pages at locations in the arcade while standing in close proximity to the cart.

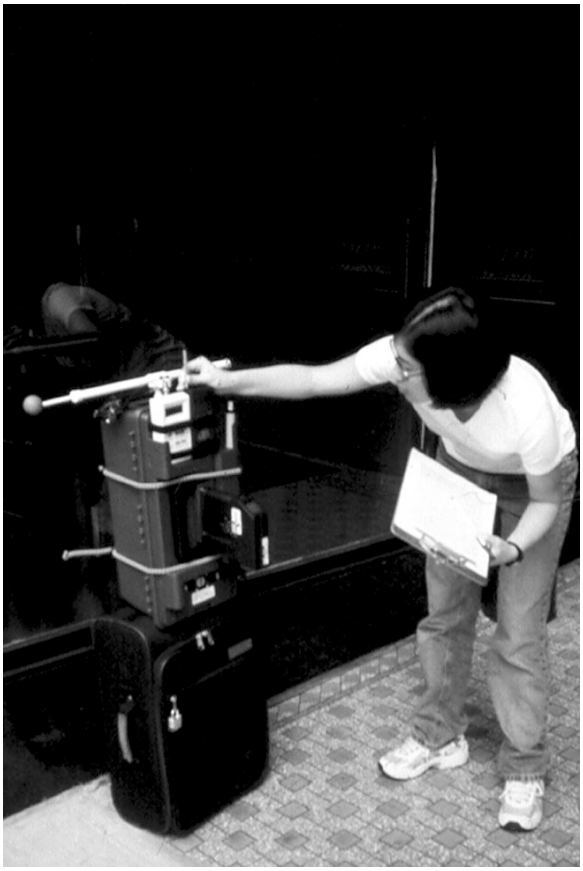

Figure 1: The Thermal Comfort Cart

The ambient air temperature probe was constructed with a Type-T thermocouple, and was accurate to 0.2ºC. The relative humidity sensor, constructed by Vaisala, was rated to be better than 5% accurate. The globe thermometer was constructed from a 38mm ping-pong ball, painted gray, with a Type-T thermocouple at the center. Measurements were recorded and stored in a Campbell 21X data logger, which was downloaded post survey to a computer for analysis.

Ground surface temperatures were measured with a Raytek Raynger infrared pyranometer, at accuracy better than 0.5ºC. Solar radiation was recorded with a Li-Cor hand held pyranometer, at an approximate accuracy of 5%, and air velocity was measured with a Vaisala hot wire anemometer, with high accuracy. These measurements were taken by hand, and entered onto preformatted data record sheets on-site.

From this data, and data from the surveys, indoor climate indices such as mean radiant temperature, operative temperature (Top) and new effective temperature (ET*) were calculated. These indices were calculated by inputting thermal environmental data from the thermal comfort cart, and data from the subjective surveys into the UC Berkeley Thermal Comfort Program, version 1.03.

Arcade Comfort Survey

The comfort survey covered four main sections, 1) demographic information 2) current status of thermal comfort, 3) thermal expectation, and 4) thermal memory. Demographic questions recorded information such as age, sex, and length of time lived in Cleveland, clothing levels, and level of activity before the survey. Current status of thermal comfort questions used standard comfort scales common to field studies of thermal comfort such as the ASHRAE 7pt. Thermal Sensation Scale, the McIntyre 3pt. Preference Scale, a 6pt. General Comfort Scale, and questions about direct acceptability in which subjects were asked to reply "acceptable" or "unacceptable" about their current thermal conditions. Questions about humidity, air movement, and direct sunlight also used preference and acceptability scales. Thermal expectation questions asked the subject to anticipate their thermal sensation before entering or exiting the arcade by recording a vote on an ASHRAE 7pt. Thermal Sensation Scale. Thermal memory questions asked the same questions as the "current" thermal comfort questions, but asked the subject to reflect on the conditions they had experienced after they had left the space.

For analysis, metabolic heat production was assumed equal in all subjects, and equivalent to walking at a steady 2km/h, which corresponds to 1.9 met or 110 W/m^2.

Table 1: Summary of Subject Samples

Arcade, Date	All	Cleveland Arcade, 9/7/01	Euclid & Cleveland Arcades, 9/8/01
Conditioning	NV & AC	AC	NV & AC
Sample Size	25	9	16
Gender (% of sample)			
Male	60.0	77.7	50.0
Female	40.0	22.3	50.0
Age (years)			
Mean	51.2	41.9	56.5
Std Dev	14.2	13.2	12.1
Maximum	80.0	59.0	80.0
Minimum	28.0	28.0	45.0
Height (cm)			
Mean	172.5	175.4	170.8
Std Dev	9.9	9.3	10.1
Maximum	190.5	189.2	190.5
Minimum	157.5	157.5	157.5
Weight (kg)			
Mean	78.0	75.3	79.7
Std Dev	18.6	21.1	17.5
Maximum	123.6	118.2	123.6
Minimum	50.0	50.0	56.8
Number of years in Cleveland			
Mean	34.9	21.7	42.4
Std Dev	16.9	12.6	14.5
Maximum	80.0	40.0	80.0
Minimum	7.0	7.0	24.0
Clothing Levels (clo)			
Mean	0.44	0.50	0.40
Std Dev	0.11	0.10	0.11
Maximum	0.73	0.73	0.62
Minimum	0.28	0.41	0.28

Subjects

Table 1 presents a statistical summary of the respondents to the arcade survey. This table describes the 9 occupants who took the survey in the fully conditioned Cleveland Arcade on September 7, 2001, as well as the 16 occupants who took the survey in the naturally ventilated Euclid Arcade and fully conditioned Cleveland Arcade on September 8, 2001. The total sample size was 25 people; none of the survey respondents took the survey more than once, and none took the survey on both days.

The majority of the survey respondents have lived in Cleveland for more than ten years. None of the respondents lived in Cleveland for less than 7 years. These results indicate that the survey respondents are familiar with Cleveland's climate, and are therefore acclimatized to Cleveland's climate.

MEASURED THERMAL CONDITIONS

Table 2 presents a statistical summary of the thermal environmental and comfort indices by arcade and date tested. These indices include operative temperature t_{op} (average of t_a and t_r), and new effective temperature (ET*).

Table 2 indicates that, the average ET* in the naturally ventilated arcade was 26.2ºC, 0.2ºC higher than the 26ºC ET* upper boundary of the *Standard 55* comfort zone. (ASHRAE, 1992)

Table 2: Summary of Indoor Climate Indices

Arcade Name	All (AC+ NV)	Cleveland Arcade (AC)		Euclid Arcade (NV)
Date of Visit		9/7/01	9/8/01	9/8/01
Number of Visits		1	1	1
Sample Size (Top)	15	5	5	5
Sample Size (ET*)	205	45	80	80
Operative Temperature (ºC)				
Mean	25.1	24.7	24.7	26.0
Std Dev	0.7	0.2	0.2	0.1
Maximum	26.2	25.0	25.0	26.2
Minimum	24.5	24.5	24.5	25.9
New Effective Temperature (ET*)				
Mean	25.3	24.8	24.8	26.2
Std Dev	0.7	0.2	0.2	0.2
Maximum	26.4	25.2	25.2	26.4
Minimum	24.6	24.6	24.6	25.9

Comparison to The Comfort Zone

Figure 2 presents operative temperature and humidity data for each arcade plotted on a psychometric chart and compared to the criteria specified by *ASHRAE Standard 55-1992* for summer conditions. Each series represents one pass through each arcade, from street, to inside the arcade, and back to the street.

After completing the surveys and thermal sweeps through all of the arcades, it was determined that the response time of the globe thermometer on the thermal comfort cart was unacceptably slow in situations of large step changes (>2ºC), and therefore could not be considered accurate at the first point of entry into each arcade. These measurement points (3 in total) are included as outliers in all figures in this paper.

Nearly all of the indoor climate measurements (92%, or 11/12 points) fell within the boundaries of the *Standard 55* comfort zone. No data points fell below the cool boundary prescribed by *Standard 55* (<23ºC ET*), or exceeded the upper humidity limit of 20ºC wet bulb. Nearly all of the outdoor climate measurements (83%, or 5/6 points) fell outside the boundaries of the *Standard 55* comfort zone. No points fell below the cool boundary prescribed by *Standard 55*, but nearly all points exceeded both the upper humidity limit of 20ºC wet bulb, and upper temperature limit of 26ºC ET*. As expected, the thermal environmental conditions in the naturally ventilated Euclid Arcade were markedly warmer than those of the conditioned Cleveland Arcade, hovering at the 26ºC ET* upper boundary of the summer comfort zone.

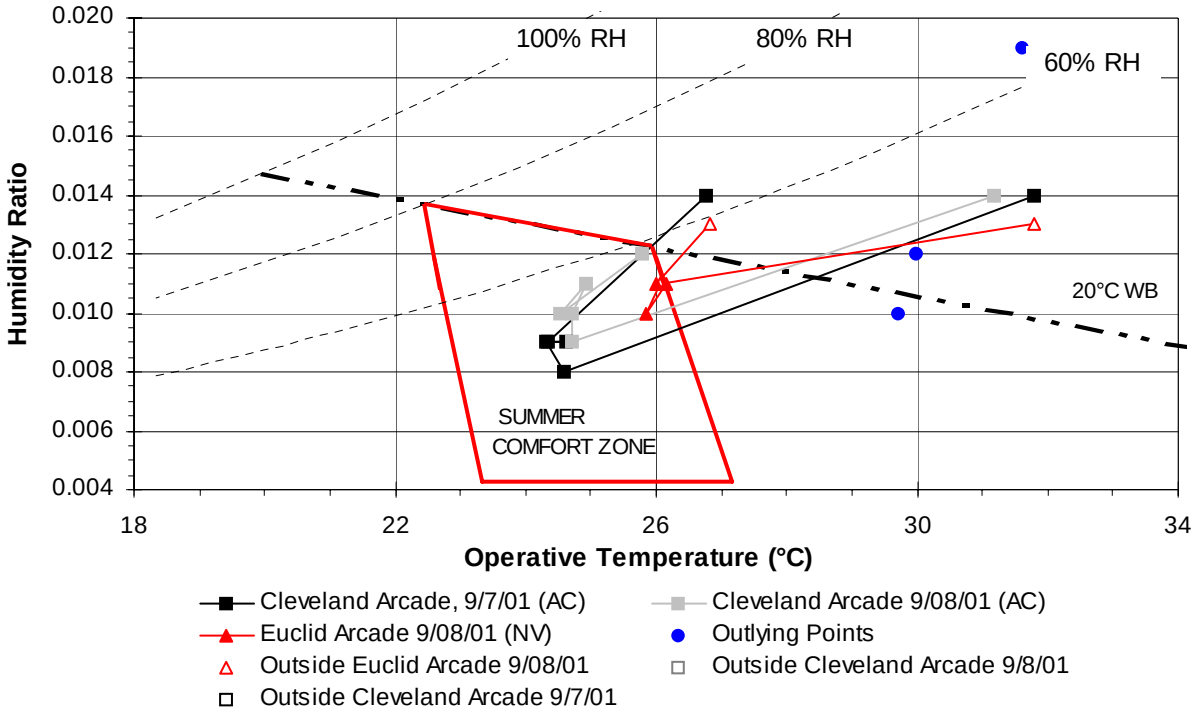

Figure 2: Comparison to the *Standard 55* Comfort Zone

THERMAL SENSATION VOTING

The mean thermal sensation vote for the subjects in the air-conditioned Cleveland Arcade was close to neutral (0.2), while subjects in the naturally ventilated Euclid Arcade had a mean thermal sensation vote close to slightly warm (1.3). The range of votes in the conditioned Cleveland Arcade was wide, from cool (-2) to hot (3). The range of votes in the naturally ventilated Euclid Arcade was slightly smaller, from slightly cool (-1) to between warm and hot (2.5).

Figure 3 is a frequency distribution of thermal sensation voting for both arcades. The top of the distribution curve for air-conditioned arcades centers on neutral (0), while the top of the curve for naturally ventilated arcades centers between slightly warm (1) and warm (2). This is consistent with the plot of thermal environment conditions on the psychometric chart of Figure 1, where the conditioned Cleveland Arcade data is centered in the

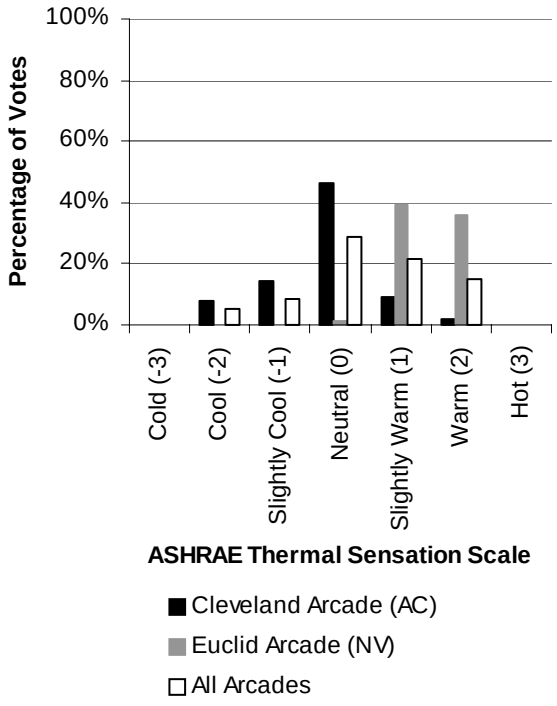

Figure 3: Frequency Distribution of Thermal Sensation Votes

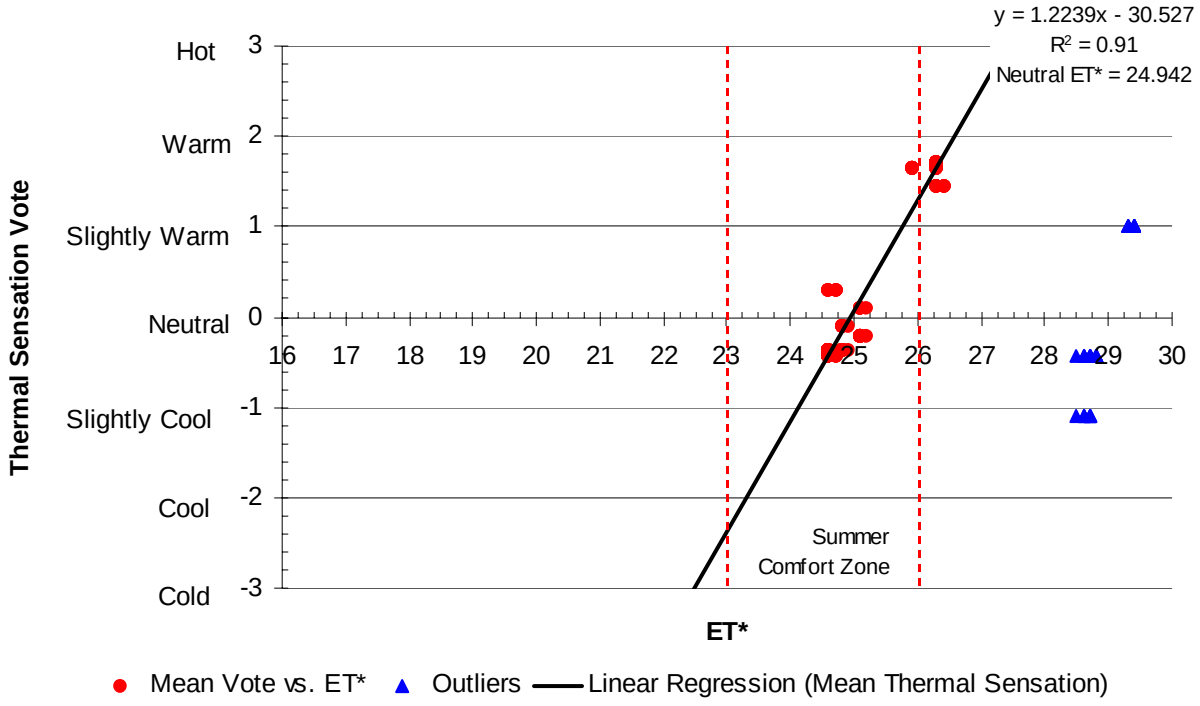

Figure 4: Linear Regression of Thermal Sensation Voting

comfort zone, and the naturally ventilated Euclid Arcade thermal environment edges towards the top of the thermal comfort zone, at 26ºC ET*.

The strength of association and sensitivity of thermal sensation votes to an indoor climate index can be quantified by using a linear regression technique. This type of analysis is common to field studies of thermal comfort. The analysis of arcade thermal sensation vote data proceeded by taking mean votes at each point in the arcade as a dependent variable, and comparing it to an independent variable, new effective temperature (ET*).

Figure 4 presents the results of this comparison, for all arcades. (Because of the small size of the subject sample, not enough data was available to create a statistically significant linear regression model for the two ventilation modes.) The regression line fitted to the data was statistically significant; the R^2 coefficient was 0.91. The subjects in all arcades had a gradient coefficient of 1.22 thermal sensation units per ºC ET*. Therefore, the subjects will experience a one-unit change in their thermal state for every 0.8ºC change in ET*. The neutral temperature of the subject sample was 24.9ºC ET*.

CONCLUSIONS

The ASHRAE 55-1992 Standard uses 23 and 26ºC ET* lines to delineate the temperature boundaries of the comfort zone on the psychometric chart. Compliance to the standard given these sets of conditions was good. Over 90% of the points measured inside the arcade complied with the standard, even though outdoor temperatures were at or exceeding the summer design dry bulb temperature.

The average ET* in the naturally ventilated arcade was 26.2ºC, 0.2ºC higher than the 26ºC ET* upper boundary of the *Standard 55* comfort zone. The average ET* in the air conditioned arcade was 24.8ºC, with a range of 24.6 to 25.2ºC.

The mean thermal sensation vote for the subjects in the air-conditioned Cleveland Arcade was close to neutral (0.2), while subjects in the naturally ventilated Euclid Arcade had a mean thermal sensation vote close to slightly warm (1.3). A regression line fitted to mean thermal sensation vote data was statistically significant; neutral temperature of the subject sample was 24.9ºC ET*, and the subjects in all arcades had a gradient coefficient of 1.22 thermal sensation units per ºC ET*.

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