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Effects of physical activity and shade on the heat balance and thermal perceptions of children in a playground microclimate

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ABSTRACT

Outdoor thermal comfort (TC) is an important parameter in assessing the value and health utility of a recreational space. Given the public health significance of child heat illness, the ability to model children's heat balance and TC during activity has received little attention. The current pilot study tests the performance of an outdoor human heat balance model on children playing in warm/hot outdoor environments in sun and shade. Fourteen children aged 9–13 participated in the 8-day study in Texas in spring 2016, performing physical activity while wearing heart rate monitors and completing thermal perception surveys (e.g., actual thermal sensation (ATS)). Surveys were compared to predicted thermal sensation (PTS) based on principles of human-environment heat exchange using personal data and a suite of on-site microclimate information. Results demonstrate the model to significantly predict ATS votes (Spearman's $\rho = 0.504$). Subjective preferred change was also significantly correlated to modeled PTS ($\rho = -0.607$). Radiation, air temperature, windspeed, and level of tiredness were significant predictors of ATS. Finally, the mean human energy balance was significantly lower in the shade (-168 W m^{-2}), thus lowering heat stress potential, with the model predicting ATS with little-to-no error (0.2 and 0.0 scale error units in sun and shade, respectively). This study demonstrates an ability to estimate a child's heat balance while accounting for changes in major heat contributors (e.g., radiation, metabolism), and is the first study to evaluate TC of children during activity in outdoor built environments. New insights of heat perception may aid in recognition of often under-recognized heat stress.

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1. Introduction

Human thermal comfort (TC) assessed through heat balance modeling and/or subjective surveys varies across age, sex, activity level, and location, yet few models have examined TC in children and youth during physical activity in outdoor spaces. Outdoor TC is also an essential parameter to assess the value of an outdoor recreational space based on intended use and health benefits (e.g., activity types) [1,2], to improve urban well-being using urban

microclimatic design [3], and to guide sustainable urban development [4]. The majority of TC models are based on indoor studies and stem from TC perceptions and physiological parameters of adult subjects [5–7], with little-to-no certainty that the models can be applied to children [8]. Moreover, the dynamic, non-steady-state nature of outdoor environments becomes more complex during physical activity. The resulting variation in heat exchanges, such as evaporative and radiative heat, are important factors governing rapidly changing outdoor TC [9]; therefore, it is not always appropriate to apply the most well-validated TC models for sedentary activity (e.g., [6,10]) to the outdoor environment during physical activity.

Children are widely regarded as having inferior thermoregulation during extreme heat to that of adults, and thus experience differing TC and responses [11–13]. Increasingly, literature has asserted that children are more vulnerable than adults to extreme

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heat (e.g. [14–16]), yet there is a paucity of both epidemiological and physiological evidence as compared to adults to fully support this claim. Falk and Dotan [13] highlighted that heat thermoregulation studies involving children account for less than 10% of all published articles, including those on adults (~1200 adult articles before 2006).

The most striking difference between young children and adults is a lower sweat production in children [12,13,17,18]. Children also experience a quicker rise in core temperature [19], are less efficient at cooling through evaporation [20], and present a higher body surface area (BSA) to body mass (BM) ratio. This final difference can implicate thermoregulation under extreme conditions when the surrounding air temperature (T_a) is higher than the skin temperature (T_{sk}), and thus the 'dry' heat fluxes (i.e., convection and radiation) become a heat gain rather than loss [13] proceeding at a greater rate. Yet when $T_{sk} > T_a$, children lose a relatively greater amount of heat through dry heat dissipation because of their higher BSA-to-BM ratio, requiring less evaporation to cool [21] and allowing for better water conservation [13]. These differences may result in variations from TC models tested and created for adults (e.g., Physiological Equivalent Temperature by Hppe [22]; Universal Thermal Climate Index (UTCI; [23,24]), with many assuming the 'average man' (1.8 m² body surface area, resting heat production of 90 W or 50 W m⁻²) [25,26]. In the original TC chamber tests by Fanger, children were not included, thus leading Fanger to state that more research would be required to apply the results to (young) children [6], yet a general lack of such studies remains [27]. Finally, research shows that children perceive thermal environments differently than adults [28]; hence, psychological perceptions of what is 'warm' or 'hot' to children may vary widely from what adults perceive. Children also have minimal experience in dealing with extreme heat which creates underdeveloped psychological and behavioral adaptations [8,28,29].

The heat load experienced by any individual is related to local weather, but also to the design of the built environment that partially controls the microclimate, and can thus be altered through design interventions [2,30]. Playgrounds represent one of the many spaces purposed for outdoor physical activity, yet many contain artificial surfaces with high heat capacities and/or heat conductivities (e.g., artificial turf, asphalt, concrete, metal, rubber) and lack shade [31,32].

Within the previous decade, multiple studies have compared the effects of adult TC to outdoor human physical activity using survey-based approaches, such as attendance counts, questionnaires, and interviews [2,33,34]. Few studies have incorporated outdoor field tests with physical exercise (e.g., running, walking, cycling). Those which have completed such testing have largely focused on validating the actual and predicted thermal sensation (TS) of adults (e.g., [35–40]), finding a 'skewing' in TC to the warm end of the scale (i.e., adults are comfortable with being slightly warm during exercise outdoors [36]).

Although adult TC studies have created well-established techniques for understanding the influence of the microclimate on humans, such estimations have not been applied to children exercising outdoors. Therefore, the goals of this pilot research study were to 1) test the performance of the COMFA (COMfort Formula) energy budget model on children (aged 9–13) playing in warm/hot outdoors environments, and 2) determine the influence of shade on TC. Although the assessment of the thermal environment within indoor classrooms has been studied since the 1960s (e.g., [41–43]), this is the first study to evaluate the use of an energy budget (heat balance) model on children exercising outdoors. This experiment further seeks to demonstrate the potential of personal monitoring methods in both heat stress prediction and playground design related to children's actual and perceived TS.

2. Materials and methods

2.1. Outdoor field tests

The current study took place from April 28–May 13, 2016 in Lubbock, Texas (33.5667°N, 101.8833°W) at an elementary school. The climate is semi-arid (tropical/subtropical steppe). Average weather conditions during each study period are shown in Section 3.1.

Fourteen active and healthy subjects (8 female, 6 male) between the ages of 9 and 13 participated in the field study. The children were part of an after-school physical activity program taking place between approximately 15:45 and 16:45 h daily. Descriptive characteristics are listed in Table 1. The field study design was created in combination with the daily goal of 60-min of moderate-to-vigorous physical activity, with each hour split into two or three activity types (Table 2). The test subjects were instructed to complete each activity with the full group of participants based on the planned activities (games) for the day. The activities lasted approximately 10–20 min each to allow the children to equilibrate with the changing activity and/or microclimate. A mixture of four types of games and surfaces were used: kickball (grass), American football (grass), baseball (grass), four-square (concrete sun and shade), basketball (asphalt), and free play (wood chips) (see Figs. 1 and 2 and Table 2). This mixture of activities ensured a range of environments and metabolic rates for the modeling of each child's energy budget at 10-s intervals (Table 2). Four-square was the only activity where children played in sun for one time period, and in the shade of a shade sail for another (Fig. 2C). During such tests, half of the group played in the sun, while the other half performed the identical activity in the shade. The groups then switched. This allowed determination of the effect of shade on TC, energy budget, and thermal perceptions. Children were provided water during breaks as necessary; activity transitions/breaks between activities were not considered in the analysis. The research was approved by the Texas Tech University Institutional Review Board.

At the end of each period of activity, children were asked to rate their *actual* TS (ATS) on a 7-point psychophysical scale (hot, warm, slightly warm, neutral, slightly cool, cool, cold; Fanger 1970), preferred change (PC) in thermal sensation (i.e., would you like to feel much warmer, warmer, slightly warmer, no change, slightly cooler, cooler, much cooler [44]), whether they are comfortable (yes/no), and their energy levels (very tired, a bit tired, not tired), following guidelines and design of surveys used to assess TC of children by Teli et al. [8] and of the general population by Stathopoulos et al. [45] (see Supplemental Material 1). Children were asked to focus on overall feelings thermal sensation and exertion, rather than specific body areas. Two or three surveys each day were completed each period on the surface of play at the end of the activity, depending on the number of activities completed (Table 2), so as to avoid interfering with play.

Table 1
Descriptive characteristics of the study population displaying mean, standard deviation (SD), and ranges in each sex.

Variable	Mean	SD	Min–Max
Female (n = 8)			
Age (yr)	10.4	1.42	9–13
Height (cm)	141.8	15.41	124.5–176.5
Weight (lbs)	66.8	9.74	56–79
BMI	15.4	3.07	9.0–20.5
Male (n = 6)			
Age (yr)	10.2	0.75	9–11
Height (cm)	141.9	12.41	132.1–161.3
Weight (lbs)	88.9	33.9	65–139
BMI	19.5	4.37	16.1–26.9

Table 2Experimental setup for the eight test days showing the time period, surface, surface temperature (T_{sfc}), and surface solar albedo for each activity.

Date	Start/Stop time (hr)	Activities	Approx. activity time	Surface Type	T_{sfc} (°C)		Solar Albedo
					Sun	Shade	
28-Apr	15:50/16:45	Football	20 min	Grass	23.1	—	0.22
		Basketball	15 min	Asphalt	34.6	—	0.24
		Free Play	20 min	Woodchips	30.2	—	0.13 ^c
29-Apr	15:40/15:45	Basketball	20 min	Asphalt	46.0	—	0.24
		Free Play	20 min	Woodchips	37.5	—	0.13 ^c
		Kickball	25 min	Grass	25.5	—	0.24
4-May	15:40/16:15	Four Square	15 min	Concrete (sun/shade) ^a	40.0	29.2	0.34 (sun)/0.58 ^b (sh)
		Four Square	15 min	Concrete (sun/shade) ^a	43.8	32.7	
5-May	15:40/16:25	Kickball	20 min	Grass (sun)	32.8	—	0.26
		Four Square	18 min	Concrete (sun)	42.7	—	0.33
		Four Square	18 min	Concrete (shade)	—	27.1	0.57
9-May	15:40/16:20	Four Square	22 min	Concrete (sun/shade) ^a	44.4	34.1	0.35 (sun)/
		Four Square	20 min	Concrete (sun/shade) ^a	40.5	32.5	0.52 ^b (sh)
10-May	15:35/16:40	Four Square	26 min	Concrete (sun)	47.5	—	0.32
		Basketball	16 min	Asphalt (sun)	53.5	—	0.13
		Kickball	15 min	Grass (sun)	35.1	—	0.24
11-May	15:45/16:45	Baseball	26 min	Grass (sun)	32.5	—	0.25
		Four Square	14 min	Concrete sun/shade	41.2	25.3	0.34 (sun)
		Four Square	14 min	Concrete sun/shade	45.1	35.4	0.51 (sh)
13-May	15:40/16:40	Four Square	10 min	Concrete (sun)	44.9	—	0.35
		Baseball	11 min	Grass (sun)	31.3	—	0.24
		Four Square	12 min	Concrete (sun)	45.5	—	0.35

^a Half of the group played on concrete in the sun, while the other half played on concrete in the shade.^b Based on station data under shade sail.^c Estimated from Oke (2003).

Fig. 1. A) Map of the location of the City of Lubbock, TX, USA; B) children playing four square on concrete (sun) with weather station in foreground; C) full aerial picture of playground (Google Maps) containing play areas with various surface types; D) the shade sail covering an elevated concrete platform; E) female subjects playing basketball over asphalt; F) high-end microclimate station over grass powered by solar panel.

2.2. Microclimate data collection

The microclimate of the schoolyard was quantified using a high-end portable weather station collecting a full suite of ambient

variables. Net radiation was measured using a CNR4 net radiometer (Kip and Zonen) mounted parallel to the ground surface, with four flux components (incident and reflected or emitted short- and long-wave radiation) measured simultaneously. It was ensured that

Fig. 2. A) Children playing four-square in sun on concrete. B) Shade sale and shade on concrete at low sun angle. C) Children playing kickball on grass.

no shadows were cast on the radiation instruments. Wind velocity (v_w) was measured using an 03101 three-cup anemometer (R.M Young), and relative humidity (RH) and air temperature (T_a) were measured using an HCS3 Temperature and Relative Humidity Probe (Campbell Scientific). All instruments were mounted 1.5–2.0 m in height on a portable tripod for easy movement over different ground surfaces. Meteorological data were collected with a CR1000 datalogger (Campbell Scientific) at 10-sec intervals. Finally, the surface temperatures (T_{sfc}) were measured during each activity with a handheld DeltaTrak ThermoTrace Infrared Thermometer (Pleasanton, CA).

2.3. Modeling thermal comfort using the comfort formula (COMFA) energy budget model

The energy budget in $W m^{-2}$ for each participant was calculated at 5-min intervals during the exercise session using the COMFA outdoor energy budget model [35,37,38]. The COMFA model has been applied and/or reviewed in the research literature numerous times over the last decade (e.g., [4,46–50]). As a rationale index, it incorporates various environmental and physiological variables into a heat balance equation:

$$EB = M + R_{abs} - E - C - L_{emit} \quad [1]$$

where M is metabolic heat conducted to the body surface, R_{abs} is absorbed radiation, and E , C , and L_{emit} are evaporative, convective, and emitted longwave heat losses, respectively, in $W m^{-2}$. The COMFA model requires the following inputs: T_a ($^{\circ}C$), RH (%), v_w ($m s^{-1}$), static clothing resistance (r_{co} , $s m^{-1}$), static clothing vapor resistance (r_{cvo} , $s m^{-1}$), metabolic activity (M_{act} , $W m^{-2}$), activity velocity (v_a), incoming and outgoing shortwave radiation (K_{in} and K_{up} , respectively), and atmospheric and ground longwave radiation (L_a and L_g , respectively), in $W m^{-2}$. We present an overview of the

main calculations in the model that are critical for the current study. For further details on all equations within the COMFA energy budget model, see Refs. [35–40].

2.3.1. Modeling absorbed radiation

The R_{abs} represents the combination of long and shortwave radiation fluxes absorbed by a human body in $W m^{-2}$. Absorbed radiation was estimated using inputs from the CNR4 net radiometer based on methods by Kenny et al. [51] for outdoor environments. This method models a human as a cylinder [52,53], and is calculated based on the absorbed shortwave and longwave radiation in Equation (2) as follows:

$$R_{abs} = A_{eff} \frac{L_{g(abs)} + L_{a(abs)} + K_{up(abs)} + K_{in(abs)}}{A_{cyl}} \quad [2]$$

where $K_{in(abs)}$ and $K_{up(abs)}$ are incoming and ground reflected shortwave solar radiation absorbed by the person, respectively, and $L_{a(abs)}$ and $L_{g(abs)}$ are absorbed atmospheric and ground surface longwave radiation, respectively [39,51], in Watts. A_{cyl} is the outer surface area of the body cylinder (m^2) based on a height to diameter ratio of 1:10. A_{eff} is the effective area factor of a human, which is 0.78 when standing [53].

2.3.2. Metabolic activity & body temperatures

Test subjects wore Polar Team Pro heart rate (HR) sensors [54], which measured HR (bpm), activity speed (v_a , $m s^{-1}$), acceleration ($m s^{-2}$), and distance (m) at 1-s intervals, converted to 10-s averages to align with weather station data. Missing data, which comprised <2% of data, were removed. A general energy expenditure estimation method by Strath et al. [55] was implemented for M_{act} estimation, which is appropriate for application to the average population. Resting heart rates (RHR) were determined for each child based on the 8-day average RHR that was recorded while

children sat resting quietly indoors. Using inputs of age, RHR, activity HR, and sex, the energy expenditure of the children was estimated by determining an activity volume of oxygen $\text{VO}_{2\text{act}}$, which is divided by 3.5 to provide output in metabolic equivalent of task (MET) units ($1 \text{ MET} = 58.15 \text{ W m}^{-2}$) (see Refs. [39,55]). HR monitoring is found to be a valid method for estimating oxygen consumption during child play [56] and thus metabolic intensity of the activity (M_{act}). The final value of M in Eq. (1) is determined after subtracting the fraction (f) of total metabolic energy that is consumed by respiratory heat loss [35].

T_{sk} was estimated using Eq. (3) as follows:

$$T_{\text{sk}} = \left(\frac{T_c - T_a}{r_c + r_a + r_t} \right) (r_a + r_c) + T_a \quad [3]$$

where the clothing resistance, r_c , is provided by Eq. (5), r_a is boundary layer aerodynamic resistance [57,58], and r_t is tissue resistance [36,59]. All resistances to heat transfer are in s m^{-1} . Eq. (3) has been tested outdoors and found to reproduce measured values during exercise [38], and is consistent with related outdoor heat balance research [60–62]. T_c was estimated based on the M_{act} [53,63] as follows:

$$T_c = 36.5 + 0.0043 M_{\text{act}} \quad [4]$$

2.3.3. Clothing

The test subjects generally wore standard cotton collared T-shirts as school uniforms with either pants or shorts. The static clothing resistance (r_{co} , s m^{-1}) input into the COMFA model was assigned in accordance with Havenith et al. [64], ISO9920 [65], and Kenny et al. [36]. The two different ensembles, with r_{co} values, were: 1) T-shirt, long pants, socks, shoes ($r_{\text{co}} = 93 \text{ s m}^{-1}$); 2) T-shirt, regular walking shorts, socks, shoes ($r_{\text{co}} = 77 \text{ s m}^{-1}$). Clothing insulation is represented in the current study using units of clo, where $1 \text{ clo} = 186.6 \text{ s m}^{-1}$ (or $0.1555 \text{ m}^2 \text{ }^\circ\text{C}^{-1} \text{ W}^{-1}$). All days during the test period were of moderate to high wind speeds (see Table 3). Based on the known maximum reduction factor for r_{co} of 37% and the fact that v_a plays a large role due to the ‘pumping effect’ in reducing clothing insulation [64,66], the following equation was utilized [36]:

$$r_c = r_{\text{co}} \left(-0.37 \left(1 - \exp^{-\frac{v_a}{0.72}} \right) + 1 \right) \quad [5]$$

2.4. Translation of the COMFA budget & statistical analyses

All microclimate and physiological data were collected at 10-s intervals. As the surveys were provided at the end of an activity, the final 5 min of these data from each activity were averaged to

estimate the mean 5-min heat balance experienced by each subject at assumed equilibrium. The energy budget was translated into onto a 5-point TS scale (Table 4) to provide a predicted thermal sensation (PTS) and compare to the ATS votes reported by the child. Using the last 5-min period of the activity for linking to the ATS votes allowed for more direct comparisons of PTS with ATS. Wider comfort limits are often found outdoors as well as during physical activity, thus active individuals have been found to have wider ranges of TC [33,37,67,68]. Based on results from the testing of the COMFA model under outdoor conditions and during physical activity in adults [36,38], and that acceptably comfortable outdoors conditions include slightly warm (+1) and slightly cool (−1) [69,70], the neutral category was collapsed to include +1, 0, and −1. The final two columns in Table 4 display this collapsed neutral category of the PTS and ATS scale units (altered from 7-point to 5-point scales), and the translation into an energy budget to create the PTS values.

The relationships between the PTS, ATS, and preferred change (PC) were assessed using non-parametric Spearman's rho rank correlations as the three variables were ordinal (rank position) [74]. An ordinal regression was employed using specified predictor variables of ATS based on an iterative process to maximize the log likelihood of a given ATS outcome and the relationship. Differences between exposure conditions (sun/shade), subjects, and sex were statistically compared using analysis of variance. Each survey response and data point were treated as independent, giving sufficient power for statistical analysis between sun/shade exposures, energy fluxes, and thermal perception across days. A p-value of 0.05 was used for significance tests. A direct assessment of the impacts of sun and shade on the ATS, PTS, and PC scales was accomplished by comparing only instances when subjects were over the concrete surfaces (i.e., we compare concrete in sun versus concrete under shade sail). Analyses were completed using MATLAB R2015b and SPSS Statistics V23.

3. Results

3.1. Daily weather and energy budget variability

A total of eight field test days were conducted with 14 children during the afternoon hours (minimum activity length of 35-min, maximum of 65-min) under clear sky or partly cloudy conditions. The number of subjects tested per day varied from 8 to 14. The T_a , RH, and wind speed ranged from $27.3 \text{ }^\circ\text{C}$ to $33.0 \text{ }^\circ\text{C}$, 5.8% to 37.2%, and 0.3 and 5.5 m s^{-1} , respectively (Table 3). Mean incoming solar radiation ranged from 360.8 to 898.6 W m^{-2} . These observations provide a suitable range of testing conditions for warm-to-hot conditions for the given location and time of year, and presented a relatively normal distribution of energy budgets (Supplemental Material 4). As the field tests occurred at the very start of the warm season and the climatological average maximum T_a for these

Table 3

Descriptive statistics of average weather conditions ($\pm$ standard error) recorded by the microclimate station during the eight test days in spring 2016. T_a (air temperature), RH (relative humidity), K_{in} and K_{up} (incoming and outgoing shortwave radiation, respectively), v_w (wind speed), L_{in} and L_{up} (incoming and outgoing longwave radiation, respectively).

Date	Time (hr)	T_a ($^\circ\text{C}$)	RH (%)	K_{in} (W m^{-2})	K_{up} (W m^{-2})	v_w (m s^{-1})	L_{in} (W m^{-2})	L_{up} (W m^{-2})
4/28/16	15:50–16:45	28.0 ± 0.67	37.2 ± 0.90	360.8 ± 134.4	80.6 ± 31.4	1.6 ± 0.88	402.9 ± 7.82	457.2 ± 6.16
4/29/16	15:40–16:45	27.7 ± 0.27	5.8 ± 0.30	862.8 ± 45.9	211.1 ± 9.3	5.5 ± 1.07	323.9 ± 2.17	471.7 ± 2.90
5/04/16	15:40–16:15	27.3 ± 0.23	16.0 ± 0.87	898.6 ± 26.2	302.0 ± 9.9	1.4 ± 1.14	347.2 ± 1.48	518.5 ± 1.21
5/05/16	15:40–16:25	30.6 ± 0.24	11.6 ± 0.62	880.6 ± 36.2	241.8 ± 20.5	1.3 ± 0.38	361.3 ± 1.40	512.0 ± 12.56
5/09/16	15:45–16:40	28.3 ± 0.45	15.4 ± 0.46	709.2 ± 140.7	245.5 ± 49.2	4.2 ± 0.68	369.0 ± 3.89	510.1 ± 2.19
5/10/16	15:35–16:40	33.0 ± 0.21	10.4 ± 0.49	854.7 ± 50.2	205.1 ± 9.3	3.4 ± 0.88	372.7 ± 0.91	522.5 ± 4.39
5/11/16	15:45–16:50	29.9 ± 0.47	18.8 ± 0.81	819.1 ± 41.8	231.3 ± 32.0	0.3 ± 0.25	369.6 ± 3.14	525.2 ± 15.90
5/13/16	15:40–16:30	31.6 ± 0.36	26.5 ± 0.91	845.3 ± 38.8	234.2 ± 38.5	1.4 ± 0.72	397.9 ± 3.60	531.4 ± 4.93

Table 4
Depiction of the comfort sensation (a) and zone of thermal effect (b) coinciding with (c) the 7-point thermal sensation (TS) scale created for non-exercising individuals. The collapsed and skewed 5-point TS scale adapted for exercising individuals is displayed in (d) [36]. The 5-point TS scale and corresponding COMFA budget outputs were applied in the current study

(a)	(b)	(c) Non-exercising		(d) Exercising	
Comfort Sensation	Zone of thermal effect	7-point TS Scale & Vote	Energy Budget Value 7-point scale	5-point TS Scale & Vote	Energy Budget Values 5-point scale
Very Uncomfortable	Incompensable Heat				
Uncomfortable		Hot (+3)	$\geq +201 \text{ W m}^{-2}$	Hot (+3)	$>250 \text{ W m}^{-2}$
Slightly Uncomfortable	Sweat Evaporation	Warm (+2)	$+121 \text{ to } +200 \text{ W m}^{-2}$	Warm (+2)	$151 \text{ to } 250 \text{ W m}^{-2}$
Comfortable	Vasomotor Compensable	Slightly Warm (+1)	$51 \text{ to } +120 \text{ W m}^{-2}$	Neutral (+1 to -1)	$-20 \text{ to } +150 \text{ W m}^{-2}$
		Neutral (0)	$-50 \text{ to } +50 \text{ W m}^{-2}$		
		Slightly Cool (-1)	$-51 \text{ to } -120 \text{ W m}^{-2}$		
Slightly Uncomfortable	Shivering	Cool (-2)	$-200 \text{ to } -121 \text{ W m}^{-2}$	Cool (-2)	$-20 \text{ to } -150 \text{ W m}^{-2}$
Uncomfortable					
Very Uncomfortable	Incompensable Cold	Cold (-3)	$\leq -201 \text{ W m}^{-2}$	Cold (-3)	$<-150 \text{ W m}^{-2}$

(a), (b) based on Epstein and Moran [71] and Shapiro and Epstein [72] corresponding to 7-point ASHRAE scale. (c) 7-point thermal comfort scale based on ASHRAE [73]; corresponding energy budget values by Kenny et al. [36] adapted from Harlan et al. [46]. (d) 5-point skewed TS scale and energy budgets from Kenny et al. [36].

eight days is 27.2°C (average daily mean of 19.4°C), it was expected that the children would not be acclimatized to the relatively hot weather during this study.

The daily average energy budget value and each energy flux (i.e., convection, evaporation, etc.), averaged for all children, are displayed in Fig. 3. The greatest variance in the energy fluxes was found in the metabolic heat load and R_{abs} , while convective and longwave heat losses had minimal variation. Evaporative heat losses varied moderately from 83 to 156 W m^{-2} , with the greatest sweat loss (based on modeled evaporative heat losses) found on days when the metabolic outputs were high due to the higher generation of sweat for cooling. Overall, the mean of the energy budgets from summing the energy fluxes (Eq. (1)) ranged from 161 W m^{-2} ('warm') to 309 W m^{-2} ('hot'). Significant between- and

within-day variations of M_{act} and T_{sk} were found by gender ($p < 0.05$), where males had a higher metabolic level, on average, than females, resulting in higher T_{sk} . Wide variations in M_{act} were also present between rest and activity periods in the sessions. The daily time series of metabolic heat (M) and T_{sk} are presented by subject in the Supplemental Material 2 and 3. The average metabolic activities translate into MET intensities (min–max) of 3.8 – 6.8 METs, which falls within 'intense activity' for children's play listed by the World Health Organization [75].

3.2. Comparing actual thermal sensation votes and predicted thermal sensation

As shown in Fig. 4, the overall ATS votes (both sexes) were

Fig. 3. Stem and leaf box plot depicting the range of the energy budget values (EB) on each date averaged for all subjects. Energy flux gains and losses also shown: metabolic heat gain (M), absorbed radiation heat gain (R_{abs}), convective heat loss (C), evaporative heat loss (E), and longwave emission heat loss (L_{emit}), in W m^{-2} . The interquartile range (IQR) is indicated by the length of each box plot (25th to 75th percentiles), with outliers (values 1.5–3 IQRs from box end) marked by $\circ$. The area above the orange and red dashed lines displays 'warm' and 'hot' energy budgets, respectively, with neutral values beneath the orange line. The purple line indicates the lower limit of 'extreme danger' according to the COMFA-model-based HTCI by Harlan et al. [46] (human thermal comfort index), which some EBs briefly reached on two days. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Frequency histograms of actual thermal sensation (ATS) votes from subjects and predicted thermal sensation (PTS) based on the COMFA energy budget model on a 5-point scale (see Table 3). Data divided by gender, with percentages representing a fraction of the total responses.

skewed to the left, ranging from <1.0% of participants stating 'cold' (−3) to 42.3% stating 'hot' (+3). By sex, females declared a TS of 'hot' at a frequency of 52.2% (versus 47.7% for males). The PTS values (translated from EB values) (Fig. 4B) were significantly and positively correlated to the ATS votes shown in Fig. 4A ($\rho = 0.504$, $p < 0.01$). All Spearman's correlations for ATS, PTS, and PC are displayed in Table 5. In sun-exposed conditions only, the ATS-PTS relationship was also strong and significant ($\rho = 0.418$, $p < 0.01$). Additionally, the ATS values were significantly negatively correlated with the PC (i.e., a greater perceived warming created increased preference to be cooler). Interestingly, when children stated a preference to be 'a lot cooler' due to warm or hot ATS votes, they also stated satisfaction with the environment ('thermally comfortable') 36.4% of the time (see Fig. 5A); only in 18.8% of instances did subjects report both preference to be 'a lot cooler' and thermal discomfort. This unexpected finding is further discussed in Section 4.

Although the predicted budget values were significantly and positively correlated with ATS ($\rho = 0.500$, $p < 0.01$) (Table 5), there is overlap in the thermal sensation categories (Fig. 6) (i.e., the range of each ATS may overlap with more than one PTS value) creating difficulty in distinguishing a TS 'category', even after

collapsing the energy budget values into five categories. All predicted EB fluxes were greater than 0 W m^{-2} , and thus the 'cool' and 'cold' responses from the subjects are outliers and were not predicted by the model. Moreover, the subjective responses were primarily found in the 'neutral' and 'hot' categories, indicating the subjects followed less of a continuum along the TC scale as predicted by the PTS with the COMFA model (Fig. 4A) and as found in earlier TC studies on adults indoors [6]. The model also had a higher performance when predicting the ATS votes of females compared to males ($\rho = 0.561$ and 0.416 , respectively), although no significant difference was found by gender.

3.3. Factors affecting actual thermal sensation & the influence of shade

An ordinal regression with independent weather variables, tiredness level, and metabolic activity as predictors of ATS, as well as sex and exposure type as controlling factors, is displayed in Table 6. The overall model fit showed a significant prediction of the ATS values, with significant predictors of air temperature, solar radiation, and level of tiredness (causing an increase in ATS votes towards the hot end of the scale) and wind speed decreasing the

Table 5

Spearman's rank correlations (ρ) between Actual Thermal Sensation votes (ATS), Predicted Thermal Sensation (PTS) from model, and Preferred Change votes (PC) for all conditions, sun (all surfaces), sun (concrete), and shade (concrete).

Condition		ATS	PTS
All ($n = 261$)	ATS	1.00	—
	PTS	0.504**	1.00
	PC	−0.607**	−0.377*
Sun All ($n = 224$)	ATS	1.00	—
	PTS	0.418**	1.00
	PC	−0.606**	−0.318**
Sun* ($n = 38$)	ATS	1.00	—
	PTS	0.409*	1.00
	PC	−0.609**	−0.361*
Shade ($n = 37$)	ATS	1.00	—
	PTS	0.361*	1.00
	PC	−0.362*	−0.168

*Rho correlation is significant at the $p < 0.05$ level.

**Rho correlation is significant at the $p < 0.01$ level.

Fig. 5. Preferred change (PC) in thermal sensation based on (A) binary thermal comfort responses and (B) sun versus shade exposure.

ATS votes as wind aids in heat loss *via* convection. Children indicated a preference for 'more wind' 83% of the time based on data from days 7 and 8 of testing. Metabolic activity and RH were not significant predictors but strengthened the model when included. Similarly, sex and exposure were not significant controlling factors in the model prediction of ATS. Energy fluxes were not included in the model as they were not independent of the predictor weather variables.

Through direct comparison of the influence of full shade and full

sun on the subjects' TC during the 'four-square' activity (Table 7), we found energy budgets to be significantly higher in the sun ($+168 \text{ W m}^{-2}$), which is largely due to the increased R_{abs} in the sun ($+164 \text{ W m}^{-2}$, $p < 0.05$). No significant differences were found in the average metabolic output, evaporative, convective, and long-wave heat losses between the sunlit and shaded conditions. The COMFA model adequately predicted the ATS in both the sun and shade with minimal error: the PTS and ATS in the sun differed by 0.2 scale units (1.5 versus 1.3, respectively), with 0.0 units of error in the shade (Table 7). These results demonstrate the model's ability to predict a child's actual TC while also accounting for major contributors (i.e., metabolic heat and radiation) to the energy budget. The Spearman's rho rank correlations (Table 5) indicated a significant relationship between ATS and PTS votes in the sun (0.409, $p < 0.01$), and a slightly weaker, yet also significant relationship in the shade (0.362, $p < 0.05$). As in the overall sun conditions, the children had a significant preference for cooler conditions in the sun while playing on concrete (-0.609 , $p < 0.01$); however, this relationship was weaker and less significant while playing on concrete in the shade (-0.362 , $p < 0.05$). This indicates that the children had a lower preference for cooling while in the shade.

The subjective preferences for thermal change in sun versus shade (Fig. 5B) showed a greater preference for cooling when playing in the sun (29.3% of instances) versus 13.3% preferring to be 'a lot cooler' when in the shade. These preferences are corroborated by a preference to have 'less sun' and 'less temperature' 83.3% of the time while in the sun.

4. Discussion

4.1. ATS and PTS comparison

The current paper set out to test the ability of the COMFA outdoor energy budget model to predict children's perceptions of TC during exercise in warm-hot conditions, and also to determine the influence of full shade on TC. As children are considered a special population in TC modeling studies [5], the novelty of the current study—being the first to apply energy budget modeling and TC surveying to children in warm-hot outdoor conditions during exercise—has potential to begin answering larger questions with

Fig. 6. Scatter plot displaying the range of the COMFA budget values for each of the actual thermal sensation (ATS) votes given by participants for all days and activities listed in Table 2, split by female (yellow fill) and male (hollow). The area above the orange and red dashed lines displays 'warm' and 'hot' energy budgets, respectively, with neutral values beneath the orange line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 6Ordinal regression model assessing the dependence of the subjects' actual thermal sensation votes on various recorded predictors and factors ($n = 261$).

Variable	Estimate	Std Error	Sig.	95%	CI ^c
Wind Speed	−0.461	0.135	0.001*	−0.725	−0.197
Metabolic Activity	0.000	0.002	0.917	−0.003	0.003
Air Temperature (°C)	0.135	0.068	0.049*	0.001	0.269
Relative Humidity (%)	−0.004	0.030	0.900	−0.063	0.055
Solar Radiation ($W m^{-2}$)	0.004	0.001	0.003*	0.001	0.007
Tiredness Level (0–2)	0.590	0.227	0.009*	0.146	1.035
Sex (Male-Female)	−0.315	0.289	0.277	−0.882	0.252
Exposure (sun-shade)	−0.323	1.073	0.763	−2.426	1.779
Model Fit Information ^a	ChiSquare	df	Significance		
	117.86	8	0.000*		
Pseudo R ^{2b}	Cox and Snell	Nagelkerke	McFadden		
	0.368	0.389	0.157		

*Significant at a $p < 0.05$ level.^a The significant Chi-Square being significance shows that the model fit with multiple predictors is better than the model without predictors (null hypothesis).^b Further statistical measures of association or explained variation based on predictor variables tested.^c Confidence Interval.**Table 7**Mean, standard error (SE) of the mean, and range (min–max) for energy budget (EB), predicted thermal sensation (PTS) and actual thermal sensation (ATS) votes, energy streams [M (metabolism), C (convection), E (evaporation), L_{emit} (emitted longwave radiation), R_{abs} (absorbed radiation)] compared between sun (n surveys = 38) and shade ($n = 37$). Significant differences between sun and shade tested using an ANOVA where $p < 0.05$.

		EB ($W m^{-2}$)	PTS	ATS	M ($W m^{-2}$)	C ($W m^{-2}$)	E ($W m^{-2}$)	L_{emit} ($W m^{-2}$)	R_{abs} ($W m^{-2}$)
Sun	Mean $\pm$ SE	258.8 $\pm$ 11.66	1.5 $\pm$ 0.11	1.3 $\pm$ 0.19	276.8 $\pm$ 14.60	44.7 $\pm$ 2.77	105.7 $\pm$ 6.37	370.8 $\pm$ 1.48	512.9 $\pm$ 3.25
	Range	(63.5–400.2)	(0 to +3)	(−3 to +3)	(124.6–489.7)	(16.9–74.8)	(40.8–203.8)	(358.0–383.9)	(458.3–531.2)
Shade	Mean $\pm$ SE	90.8 $\pm$ 6.04	0.1 $\pm$ 0.07	0.1 $\pm$ 0.17	255.6 $\pm$ 13.05	42.0 $\pm$ 2.84	96.9 $\pm$ 5.69	371.3 $\pm$ 1.39	348.6 $\pm$ 1.42
	Range	(28.5–186.0)	(0 to +3)	(−3 to +3)	(126.9–499.5)	(15.9–74.1)	(40.8–204.2)	(359.6–385.3)	(341.6–367.5)
Difference		168.0**	1.4**	1.2**	21.2	2.7	8.8	0.5	164.3**

**Significantly difference between sun and shade ($p < 0.05$).

respect to children's outdoor environments, thermal perceptions of heat, heat stress, and the link to physical activity.

Given that numerous studies have demonstrated that outdoor physical activity leads to greater thermal acceptance and thus minimal objection to 'slight warmth' [33,68,76,77], we assumed a similar preference in children and collapsed the 'neutral' category to include both 0 and +1 for the current analysis, as given in Kenny et al. [36]. Results are also set in the context of above average temperatures for the time of year in the City of Lubbock, TX (−1–6 °C higher). Air temperatures during play ranged from 27.7 °C to 34.2 °C. At such air temperatures, where T_a is much less than or similar to T_{sk} , children can tolerate at least 1-hr of moderate exercise [78,79].

Recent studies have addressed TC in children in classrooms utilizing similar survey methods (e.g. Refs. [8,28,80,81]). Many studies assessing the TC of children find the need for adaptive models due to the fact that children are more sensitive than adults to both temperature changes [29] and higher temperatures [8]. The ATS votes provided by children displayed such thermal discomfort ('hot') with the relatively hot weather conditions. A curious finding, however, was the subjects' indication of being 'thermally comfortable' even though they largely preferred to be much cooler. This finding demonstrates that children may have a different perception of 'thermal (dis)comfort' than adults, and that an absence of comfort based on ATS and PC votes may deter them from taking proper heat precautions (i.e., seeking shade, cooling, water, or stopping physical exertion) in hot weather. This finding may be explained by the children's general lack of experience and knowledge of the consequences resulting from high environmental heat loads. Psychological variations in TS of the average population occur due to an individual's thermal history, expectation, and time (day, season) of exposure [76,82]. Children lack decision-making

capacity as well as experience as compared to adults when dealing with environmental heat, thus increasing their vulnerability to heat.

Humphreys [83] completed the first study assessing the capability of young children (elementary school) to participate in surveys using conventional TC rating scales, and found encouraging results. The current study also found that children could adequately answer questions provided both visually and verbally on the questionnaire. Although we found outliers in the ATS responses and moderate similarities between the ATS values between subjects, the subjective responses indicate the presence of wide TC variations in the younger ages, particularly with increased physical activity, as found by Gavhed and Holmer [84]. It remains, however, that the budget categories used to interpret the COMFA model may need to be further adapted for children, yet more testing under a wider range of conditions is needed to do so.

4.2. Heat stress prediction

Energy budget models can be more useful for holistic predictions of heat stress compared to individual indices (such as air temperature) because heat stress—particularly during exercise—is seldom caused by high air and/or dew point temperatures alone [85]. Energy budget values can be taken as rational indicators for potential heat stress given all contributing factors, where values above the level of 340 $W m^{-2}$ indicate possibly dangerous energy budgets if maintained [46]. In the current study, 13% of the energy budgets were recorded at or above this level (see Supplemental Material 4). Children were given water breaks and allowed to rest from exercise when requested, thus such high energy budget values were not maintained. The children also reported higher rates of 'tiredness' in proportion to increasing ATS values.

Furthermore, the current results are merely applicable to a specific time of year in semi-arid environments for elementary-aged children, and thus further testing is needed for wide-scale applicability. Methodological advances applied in the current study include the use of HR monitors also measuring activity speeds, both of which are key measurements to accurately model the heat balance of an individual. Activity speeds are shown to provide important information that affect aerodynamic resistance and thus T_{sk} , clothing insulation reduction factors, and evaporation [36,39,64].

The highest average energy budget values were found on May 10th and May 13th (309 and 276 W m⁻², respectively) and the overall energy budget outputs were most sensitive to changes in R_{abs} and metabolic activity (Table 6). Therefore, the most impactful options to lessen the energy budget of the subjects in the current study were shade and a lower physical activity level. However, the metabolic rate did not affect the subjects' perceived TC (or ATS vote). Similar to that of Gagge et al. [86], T_{sk} was significantly related to perceived TC, where heat-induced discomfort was related to physical mechanisms such as sweating, T_{sk} , and skin conductance, and not related to metabolic output.

A practical benefit from these results is in the interpretation of the individual energy budget fluxes (i.e., L_{emit} , R_{abs} , etc., shown in Fig. 3) to indicate the greatest contributor to heat gain, and thus provide information that may influence a change in micro-environment and/or activity level to reduce heat gain. For example, the current study demonstrated that the R_{abs} was 168 W m⁻² lower in the shade than in the sun (Table 7), which alone would lower the mean energy budget from 'hot' to 'neutral'. Numerous other studies have found similar correlations between radiation (or proxies of solar radiation such as the globe temperature) in predicting TC [82].

Results further demonstrate the presence of high heat and radiant loads in a location where the children participate in the majority of their daily physical activity (i.e., playground/schoolyard). This finding is in contrast to the overall goal of the after-school activity campaign, which is designed to help all children meet their required minutes of daily physical activity. Females were slightly less active in general (1.4 METs less on average than males), which resulted in a slightly lower ATS (<0.1 ATS points) in females than males, a gender-based finding similar to that of Humphreys [83].

4.3. Park bioclimatic design for hot conditions

On clear, warm days with abundant direct solar radiation, surface and human exposure to the mean radiant temperature—the combination of all short- and long-wave radiant fluxes [70]—becomes the most significant agent of heat gain [40,87]. Although such information on heat exposure and perception is well-known in the literature, specifically for adults, little is known concerning how children perceive enhanced body heat and radiative changes in outdoor environments; how said exposures affect activity behavior (levels); and in turn how the interactions of heat and radiation with perception and behavior affect their vulnerability during exercise in warm environments. The simple fact that the core of a child's body is closer to hot surfaces, which emit high sensible heat loads, creates heightened vulnerability for children, yet the presence of shade significantly reduces surface temperatures as shown through the use of a shade sail [30]. The shade sail in the current study significantly reduced the predicted energy budgets, improved perceived comfort, and also lessened UVB exposure [88]. Nasir et al. [68] also found improved TC and park use related to shaded conditions in hot conditions in the summer.

Many practitioners, policy managers, and urban planners work

to design usable and aesthetically pleasing outdoor spaces, and may or may consider how design affects health and/or include current and future climate (or urban 'micro'-climate) in their applications [47,89,90]. Such oversight can be detrimental for the intended use of the outdoor space when uncomfortable spaces are designed [91], and future climate variability and urban growth are important considerations when planning urban areas for the coming century [92]. For example, passive cooling design options exist for creating cool streets [93], ameliorating impacts of radiation is achievable through urban design [30,94,95], and implementing effectively designed 'park cooling islands' with shade is a well-documented cooling strategy [40].

Studies also suggest that the amount of time spent outdoors is a significant predictor of physical activity in children [96,97], and the outdoor thermal environment correlates with occupant behaviors in open spaces [2]; thus, it is of utmost importance for outdoor open spaces in warm climates to be designed with heat mitigation in mind. Recently, Huang et al. [2] renovated a playground in Wuhan, China (humid subtropical climate), added shade and vegetation, and employed the Universal Thermal Climate Index (UTCI) to model TC in an attempt to find a correlation with park attendance. The researchers found that the renovated playground attracted 80% more occupants in the warm season, lowered heat stress, and increased length of stay. The study also found that children were more likely to be present in the park under wider thermal ranges than adults and the elderly, directly linking design to attendance for physical activity purposes. Future studies addressing the TC of children within activity-based environments will allow scientists to make urban bioclimatic design recommendations to landscape architects and urban planners for improving TC, and thus length of stay, amount of activity, and frequency of use, all of which can have significant public health benefits.

4.4. Limitations

Given the real-world nature of the current study, many limitations were present that were difficult or could not be controlled based on resources and/or ethics approvals. In addition to that addressed within the methodology and/or discussion, we identify the following study limitations:

- The children were directed as to which activities to complete and when, and for the most part followed directions well; however, because of these directions from coaches, we cannot directly determine a correlation between physical activity level and environmental factors (such as heat load influencing amount of physical activity).
- The results and TS agreement are applicable to semi-arid regions in the mid-spring season, and children aged 9–13. Further testing is needed to create an adaptive model based on age and time of season combined with exercise.
- The fourteen subjects were not present on all days, and within a day some subjects were removed from one activity due to not feeling well (complaints of being too hot or cannot breathe well, for example), being picked up early by parents, or bathroom breaks. We tried to minimize these issues as much as possible, yet also had to remain adaptive in a real-world study and follow rules. Thus, although the real-world nature of the study is a strength, it also results in such limitations.
- Other activities during the day and variations in daily stress or mood may have impacted the children's physical activity levels.
- As in any survey-type study, it is difficult to know fully that responses are answered in an objective manner. Researchers allowed students time to think when needed. If students were uncooperative, their responses were not recorded.

- The weather station was moved to the current play surfaces when possible. At times [such as over the woodchips or when the children were split into two groups (sun and shade)], we estimated K_{in} with shade sail transmissivity and used the T_{sfc} to estimate L_g , which minimizes the variation of the emitted radiation during the given activity.

This pilot study clearly demonstrates that the real-world data gathered provides detailed information and methodological advances for TC studies in playground (or related) built environments that are designed for exercise and the effectiveness of bioclimatic design techniques to lessen heat exposure. However, future research will address the issue of sample size needed for model adjustments for the child subpopulation.

5. Conclusions

As cities grow and temperatures are projected to rise, the importance of understanding the overall influence of heat on human health is growing. Children are vulnerable to the heat, yet a paucity of research exists in holistically assessing the thermal experience of children when exercising outdoors. We have provided the first study to apply energy budget modeling to children during outdoor exercise. The performance of the COMFA energy budget model was tested on children playing in warm-hot, sunny outdoor micro-environments in both sun and shade. The model was able to adequately predict the inter- and intra-individual thermal sensations of the children, and performed strongly when accounting for variable biophysical energy fluxes that are altered by activity and/or urban design (e.g., metabolic heat and radiation, respectively). However, further research under a wider thermal range is needed to determine the most accurately adapted energy budget categories associated with ATS values for children, as well as differences in perception from that of adults when in the heat and/or during physical activity.

Findings also demonstrate the important role of urban design in lessening heat and radiant exposures to mitigate heat stress in a vulnerable population during the warm season. Insights from bioclimatic design for heat mitigation will play an increasingly large role in minimizing high urban temperature extremes to provide maximum public health utility of outdoor recreational spaces in the warm season. A playground is a microcosm of urban areas—complex designs are used with many types of natural/artificial surfaces, orientations, and purposes, yet are created for active use. We can therefore learn a great deal from the influence of design on microclimates at a small scale (playground) to improve perception and lessen radiant heat exposures, in turn reducing heat stress potential. Such design lessons translate across urban spaces. Enhanced focus on bioclimatic design is necessary for creating playground spaces that are more conducive to *active* play, where children can thrive within safe thermal conditions for longer periods of time. In turn, heat stress potential can be substantially lessened and children will gain increased benefits from exercise even during the warm season.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.buildenv.2017.09.026>.

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