Building and Environment 126 (2017) 119–131

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

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

Jennifer K. Vanos [a, c, *], Alexandria J. Herdt [a], Marc R. Lochbaum [b, d]

[a] Atmospheric Science Research Group, Department of Geosciences, Texas Tech University, Lubbock, TX, United States
[b] Exercise & Sport Psychology, Texas Tech University, Lubbock, TX, United States
[c] Climate, Atmospheric Science, and Physical Oceanography, Scripps Institution of Oceanography and Family Medicine and Public Health, School of Medicine, University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093, United States
[d] Research Institute for Olympic Sports, Jyväskylä, Finland

A R T I C L E I N F O

Article history:
Received 27 May 2017
Received in revised form
8 August 2017
Accepted 21 September 2017
Available online 23 September 2017

Keywords:
Children
Thermal comfort
Heat stress
Physical activity
Radiation
Bioclimatic design

A B S T R A C T

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 heartrate 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.

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

* Corresponding author. Climate, Atmospheric Science, and Physical Oceanography, Scripps Institution of Oceanography and Family Medicine and Public Health, School of Medicine, University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093, United States.
E-mail addresses: jkvanos@ucsd.edu (J.K. Vanos), alexandria.herdt@ttu.edu (A.J. Herdt), marc.lochbaum@ttu.edu (M.R. Lochbaum).

https://doi.org/10.1016/j.buildenv.2017.09.026
0360-1323/

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 Höppe [22]; Universal Thermal Climate Index (UTCI; [23,24]), with many assuming the 'average man' (1.8 m^2 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