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Schoolyard Shade and Sun Exposure: Assessment of Personal Monitoring During Children's Physical Activity

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ABSTRACT

Childhood exposure to ultraviolet radiation (UVR) is a major risk factor for the development of melanoma later in life. However, it is challenging to accurately determine personal outdoor exposure to UVR, specifically erythemally weighted UVR (UV_{Ery}), due to technological constraints, variable time–activity patterns, and the influence of outdoor environmental design. To address this challenge, this study utilized mobile and stationary techniques to examine the UV_{Ery} exposures of 14 children in a schoolyard in Lubbock, TX, in spring 2016. The aims of the study were to examine the influence of artificial shade on personal UV_{Ery} exposures and to assess full sun exposure ratios (ERs) within the same playground microenvironment. On average, personal wrist dosimeters worn during play in the sun measured 18% of the total onsite UV_{Ery} measured by a stationary UV pyranometer. Shade was found to significantly reduce the personal UV_{Ery} exposures by 55%, $UVB_{280–315\ nm}$ exposures by 91%, and the overall solar radiation by 84%. Substantial benefits can be garnered through focused design of children's recreational space to utilize shade—both natural and artificial—to reduce UVR exposures during play, and to extend safe outdoor stays. Finally, although the wrist is a practical location for a dosimeter, it often underestimates full exposures, particularly during physical activity.

INTRODUCTION

Personal exposure to ultraviolet radiation (UVR) as a function of activity has been investigated in many studies, largely in the adult population (1–4). Further studies examining personal exposures in youth or children's populations have been completed by Downs and Parisi (5,6) and Pagels *et al.* (7). It is well known that human exposures to UVR can vary significantly outdoors, with the strength of UVR largely dependent on latitude (8), weather conditions (9), and seasonality (7,8). The design of outdoor spaces also significantly influences exposure to global solar radiation (direct plus diffuse), including select portions of UVR. True exposures to UVR are often unknown due to the large variations in time–activity patterns of children and the cost and complexity of personal sensors. Few studies have assessed personal UVR exposures—specifically erythemal UV (UV_{Ery}) exposures—in relation to design of the outdoor built environment.

UVR, which is neither felt nor seen, can cause sunburns, eye cataracts, skin damage, and skin cancers, including melanoma (10,11). Compared to adults, children are at a higher risk of sunburn due to less adaptive behavior, intermittent exposures, and more sensitive skin at a young age (12). Studies have shown that overall rates of skin cancer are increasing (13). For example, from 1973 to 2001, the incidence of melanoma in U.S. children rose 2.9% annually (14). Of those with melanoma, many adult cases can be traced back to childhood exposures (12); thus, childhood exposure to solar UV_{Ery} radiation can induce long-term health effects. However, few studies have investigated children's personal exposures to UV_{Ery} radiation under real-world conditions in playgrounds, largely due to costs and the impracticalities as compared to the use of manikins (15).

Many studies have tested and applied small sensors to collect personal exposure data, including time–activity patterns of time spent indoors *versus* outdoors, within subpopulations at various latitudes. Studies most commonly take place during the summer season to assess overexposure to UVB or UV_{Ery} (*e.g.* 16,17), temporal differences (6,7,18), and comparisons by sensor type (*e.g.* polysulphone (PS) and electronic UV dosimeter [19]. Studies also utilize dosimeters to address the fundamental questions concerning the influence of sensor location on a subject's body. Weihs *et al.* (17) performed a personal UV exposure study using 10 dosimeters fixed to a single subject and found fluctuations in UV exposure depending on the subject's body orientation. The subject experienced the highest exposure on the shoulders while walking and on the legs while seated or lying down (17). An earlier study by Rosenthal *et al.* (20) highlighted the need for personal activity exposure research due to the large intersubject variability found using PS dosimeters on children in the United States, with differences also found between wrist and face locations. Dosimeters attached to wristbands have shown great utility for group exposure evaluations (4,16,21,22) and have been used for a large nationally representative study of sunlight exposure in Denmark (23). There are considerable opportunities for the use of such monitoring tools in child health studies, particularly at schools (24). Finally, dosimeters have been used alongside time

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diaries to investigate outdoor sun-related behavior in different population groups (25).

Many of the above studies were completed to compare actual exposures *versus* that reported to the public using the UV index (UVI), which provides a value of UVR strength based on sunburn potential for a given region/location in open sky situations. However, UVR levels within the built environment are variable and dependent on factors such as surface reflectance and reflection from building materials (26), as well as levels of air pollution (10). Various small-to-large-scale urban design interventions are available (*e.g.* shaded play areas and lowered sky view factors (SVFs)) to reduce exposure to radiation in high-activity locations (27). Such interventions have the ability to increase skin safety and lengthen the amount of outdoor activity (7,28). Although many studies have addressed the collection and validity of individual UV exposure, few studies have paired microscale, personal sensing with physical activity in playgrounds to understand the impacts of design on UV_{Ery} exposures experienced by children.

Within playgrounds, many design factors (*e.g.* tree or shade structure orientation, SVF, ground albedo, water sources) have a large influence on the amount of total solar radiation (including UV and visible radiation). Open, unshaded parks with high radiant heat loads are less conducive spaces for safe physical activity and thermal comfort (29–31). Common strategies to lessen exposure to solar radiation are well known (32,33), and there is a progressive increase in the use of shade sails in hot, dry areas (34). However, applications of such strategies are limited in practice, which emphasizes the need to provide an evidence base of the public health benefits of trees and other sources of shade in public schools (35). Real-world evidence from active play situations is needed to improve risk assessments and enhance the understanding of design on exposures so that appropriate measures can be implemented to prevent increased UV_{Ery} exposure (7).

This study utilizes two *in situ* measurement techniques (stationary and personal) to assess real-world UV_{Ery} experienced by children during one hour of physical activity on warm/hot sunny days. We set forth to (1) examine how shade within the built schoolyard environment affects UV_{Ery} exposure, (2) assess the variability of UV_{Ery} exposures within the schoolyard, (3) compare the two types of *in situ* measurements, and (4) assess the potential for personalized techniques to measure UV_{Ery} exposure within child populations.

MATERIALS AND METHODS

Field campaigns and study population. The current pilot study took place in Lubbock, Texas (33.567°N, 101.883°W), at an elementary school in a poverty and educationally stricken area of the city. Fourteen physically active and healthy subjects (eight females and six males) between the ages of 9 and 13 participated in the survey, with approximately 10 receiving UV_{Ery} dosimeters (Scienterra, New Zealand) each day. Children were selected based on their age and consistent availability in the after-school physical activity program. The racial breakdown was as follows: Hispanic (2), African American (11), and Caucasian (1). Given the low number of subjects in this study, subject group or interindividual statistical comparisons were not performed. With a high sample rate (10 s) providing over 3000 data points per day, and a large effect size, we were able to perform the direct sun *versus* shade comparisons.

The field testing occurred during six days from 4 to 13 May 2016 as part of the children's after-school physical activity program, between approximately 15:45 and 16:45 h daily with solar angles ranging from 53.9 to 55.0°. See Tables 1 and 2 for exact time periods and solar angles. The study design was created in combination with the physical activity goals for the day, and thus, each child also wore a Polar HR monitor (36), which recorded accelerometry information to provide a proxy for movement due to activity. The research was approved by the Texas Tech University Institution Review Board.

The study site was located in a schoolyard (Fig. 1), which consisted of multiple play areas over different surfaces: concrete sidewalk, asphalt basketball court, grass field, and a playground with a woodchip surface cover. Between the concrete sidewalk and asphalt basketball court, a large shade sail covered an elevated concrete platform (Fig. 1b). The grass field contained two small and one medium sized tree. See Supporting Information Video S1. For the given six-day experiment during the time periods for testing in the sun, the children were asked to refrain from standing under the small portion of tree shade, as it would affect the study results.

Table 1. List of days and times of physical activity during which testing took place, including activity type and length, surface type for given activity, as well as surface temperatures and albedos.

Date	Start/Stop time (hr)	Activity	~Time spent at activity	Surface type and sun exposure	Surface temperature (°C) Sun	Surface temperature (°C) Shade	Solar albedo of surface	UVB albedo of surface
4-May	15:40/16:15	Four Square	15 min	Concrete (sun/shade)*	40.0	29.2	0.34†	0.15‡
4-May		Four Square	15 min	Concrete (sun/shade) *	43.8	32.7		0.15‡
5-May	15:40/16:25	Kickball	20 min	Grass (sun)	32.8	–	0.26	0.03§
5-May		Four square	18 min	Concrete (sun)	42.7	–	0.33	0.15‡
5-May		Four Square	18 min	Concrete (shade)	–	27.1	0.57	0.15‡
9-May	15:40/16:20	Four Square	22 min	Concrete (sun/shade)*	44.4	34.1	0.35 (sun)	0.15‡
9-May		Four Square	20 min	Concrete (sun/shade)*	40.5	32.5	0.52 (sh)	0.15‡
10-May	15:35/16:40	Four Square	26 min	Concrete (sun)	47.5	–	0.32	0.15‡
10-May		Basketball	16 min	Asphalt (sun)	53.5	–	0.13	0.04¶
10-May		Kickball	15 min	Grass (sun)	35.1	–	0.24	0.03‡
11-May	15:45/16:45	Baseball	26 min	Grass (sun)	32.5	–	0.25	0.03‡
11-May		Four Square	14 min	Concrete (sun/shade) *	41.2	25.3	0.34 (sun)	0.15‡
11-May		Four Square	14 min	Concrete (sun/shade) *	45.1	35.4	0.51 (sh)	0.15‡
13-May	15:40/16:20	Four Square	10 min	Concrete (sun)	44.9	–	0.35	0.15‡
13-May		Baseball	12 min	Grass (sun)	31.3	–	0.24	0.03§
13-May		Four Square	12 min	Concrete (sun)	45.5	–	0.35	0.15‡

*Half of the group played in concrete sun, while the other half played in concrete shade. †Did not measure albedo in shade with net radiometer. ‡Feister and Grewe (58), Castro *et al.* (59). §Blumthaler and Ambach (60), Feister and Grew (58), Castro *et al.* (59). ¶Castro *et al.* (59).

Table 2. Descriptive statistics of average weather conditions (±SE) recorded by microclimate station during the six test days in May 2016. $UVB_{280–315\ nm}$ and UVI (obs) are from UVB pyranometer weather station. Radiant fluxes are in W m^{-2} (or J s^{-1} m^{-2}).

Date	Time	T_a (°C)	K_{in} (W m^{-2})	K_{up} (W m^{-2})	Solar Angle* (°)	$UVB_{280–315\ nm}$ (W m^{-2})	UVI (obs)*	UVI†
5/4/16	3:40–4:15	27.3 ± 0.23	898.6 ± 26.2	302.0 ± 9.9	53.9	2.50 ± 0.01	10.6	10
5/5/16	3:40–4:25	30.6 ± 0.24	880.6 ± 36.2	241.8 ± 20.5	54.0	2.48 ± 0.01	10.5	10
5/9/16	3:45–4:40	28.3 ± 0.45	709.2 ± 140.7	245.5 ± 49.2	54.6	1.87 ± 0.04	7.2	9
5/10/16	3:35–4:40	33.0 ± 0.21	854.7 ± 50.2	205.1 ± 9.3	54.7	2.33 ± 0.01	9.7	10
5/11/16	3:45–4:50	29.9 ± 0.47	819.1 ± 41.8	231.3 ± 32.0	54.9	2.24 ± 0.01	9.2	9
5/13/16	3:40–4:30	31.6 ± 0.36	845.3 ± 38.8	234.2 ± 38.5	55.1	2.36 ± 0.01	9.8	9

*Solar angle and UVI (observed at station) are for 4:00 pm. †UVI provided for region at 13:00.

Personal Electronic UV Dosimeters. Personal exposures to UV_{Ery} radiation were recorded by electronic UV dosimeters worn concurrently during physical activity. The UV dosimeters are miniature electronic sensors that measure the erythemally weighted UVB with a spectral response of 230–320 nm (37,38). Developed at the University of Canterbury, New Zealand (manufactured by Scienterra, New Zealand), the UV dosimeters utilized in this study have been used in numerous behavioral studies to digitally measure personal UV exposures (23,25,39,40). The dosimeters are lightweight, compact (36 mm diameter, 12 mm breadth), battery operated (3-volt coin cell), and weatherproof (see Fig. 2). The dosimeters are based on a visible-blind AlGaN photodiode, maintaining a spectral response that closely matches the International Commission on Illumination (CIE) erythema action spectrum (41), and a UV diffuser to mimic the cosine response of human skin (38,39). Dosimeter UV_{Ery} data were collected at 10-s intervals during each field campaign and worn on each child's wrist for uniformity between subjects (see Fig. 2b). The wrist has been previously validated as a reliable site for personal dosimetry (*e.g.* 22). The spectral and cosine response of the device is described in detail by Allen and McKenzie (42) and used by others (24,25,39).

Calibrations were performed for each sensor in March 2016 by Scienterra in Auckland, New Zealand. For calibrations, the Tropospheric Ultraviolet and Visible (TUV) radiative transfer model, which was first validated against a UV spectrometer at the National Institute for Water and Atmospheric Research (NIWA) Lauder atmospheric observatory (43) was used for clear-sky conditions. The variation between model and observations is <4%. A quadratic function with the intercept forced to zero was used to avoid errors with integrating individual measurements over time due to the dosimeters spending a lot of time inside. The raw dosimeter data collected from the field in 10-s doses were converted to an energy flux in W m^{-2} of erythemally weighted irradiance using the provided dosimeter-specific calibration equations. This erythemal UV irradiance was also converted into UVI (1 UVI = 0.025 Wm^{-2}), and calculations were performed for standard erythemal dose (SED) (where 1 SED = 100 J m^{-2} of erythemally weighted UV radiation) and minimal erythemal dose (MED) (where 1 MED = 210 J m^{-2}) (41,44,45).

Microclimate Data. Microclimate data were collected within the schoolyard in an open location using a high-end portable weather station positioned over grass, asphalt, or concrete (sun and shade), depending on the type/location of play each day. Net radiation and albedo were measured parallel to the ground surface using a CNR4 net radiometer (Kip and Zonen, Delft, the Netherlands) mounted parallel to the ground surface, with four flux components (incident and reflected or emitted short- and long-wave radiation) in W m^{-2}. Surface temperature (T_s) was measured with a DeltaTrak ThermoTrace Handheld Infrared Thermometer (Pleasanton, CA), and air temperature was measured using an HCS3 Temperature probe (Campbell Scientific).

UVB radiation (280–315 nm) was measured parallel to the ground surface using an SKU 430 pyranometer (Skye Instruments, Llandrindod Wells, UK). The SKU pyranometer has a spectral response of 280–315 nm as per CIE standards. The pyranometer is cosine corrected, with minimal errors at zenith angles up to 70°, and individually calibrated for an exposure output in W m^{-2}. It was ensured that no shadows were cast on the station while in the sun. All instruments were mounted 1.5–2.0 m above the ground surface on a portable tripod for easy movement over different play surfaces. All meteorological data were collected with a CR1000 datalogger (Campbell Scientific, Logan, UT) at 10-s intervals for comparative purposes with the UV dosimeters. To obtain measurements in the shade without disrupting play, the station was moved under the shade sail directly before or after play. This allowed for the measurements of shade sail transmissivity at high sun angles and, although not a simultaneous direct comparison, we were able to determine the general effect of the shade sail in reducing UVB during the study period as compared to open sky.

Data Interpretation and Statistical Analysis. Given that we measured two types of UV information (*i.e.* UV_{Ery} with the dosimeters and $UVB_{280–315\ nm}$ with the pyranometer), we applied the approximations put forth by McKenzie *et al.* (46 in sun conditions), where:

$$UVB_{280-315nm} = 7.505 \times UV_{Ery} \quad (1)$$

$$UVB_{280-315nm} = (W \cdot m^2) = 18.9 \times UVI. \quad (2)$$

According to McKenzie *et al.* (46), these approximations generally hold true within ±10% under solar angles >20°. As Eq. (1) and (2) are applicable to only open sun conditions, the shaded stationary data were not converted from $UVB_{280–315\ nm}$ to UV_{Ery}.

Finally, to compare differences between UV_{Ery} measured by the station's pyranometer and the UVB dosimeters (similar to that of Weihs *et al.* 17), we employed an exposure ratio (ER) for direct comparisons of full sun measurements. The ER (also termed percent ambient exposure) is defined by Vernez *et al.* (47) as the ratio between the dose received at a specific body site and the corresponding dose received on a flat horizontal surface at ground level. For our purposes, we used the ER as a metric to compare personal dosimeter SED measurements during activity (SED_{DOS}) to stationary SED measurements from the pyranometer (SED_{PYR}) under full sun conditions, as follows:

$$ER_{SED} = \frac{SED_{DOS}}{SED_{PYR}}, \quad (3)$$

where the SED_{PYR} is calculated subsequent to the conversion in Eq. (1).

Time series for each day were smoothed using a 120s moving average (10 data points). Box and whisker plots were created to display interquartile ranges of both personal dosimeter and stationary pyranometer observations. Daily comparisons (means ± standard errors) of the sun *versus* shade UV measurements over concrete were made using independent sample *t*-tests (P-value < 0.05). Outliers were removed for *t*-tests to meet significance testing assumptions, and all samples were tested for normality. Statistical analysis and plotting were completed in SPSS Statistics V23 and Python 2.7.10.

RESULTS

Onsite weather and UVB observations

Average weather conditions recorded by the microclimate station during each time period and activity are presented in Table 2. Daily observed temperatures and relative humidity ranged from approximately 27.3–33.0°C and 10.4–26.5%, respectively. All days were relatively clear, with incoming solar radiation ranging from 709.2 W m^{-2} (or J s^{-1} m^{-2}) on 9 May to 898.6 W m^{-2} on 4 May 2016. The UVB pyranometer recorded the highest UVIs on May 4 and May 5 (UVI = 10.5 and 10.5, respectively) and the lowest UVIs on May 9 and May 11 (UVI = 7.0 and 9.2, respectively). Surface solar albedos obtained by the net

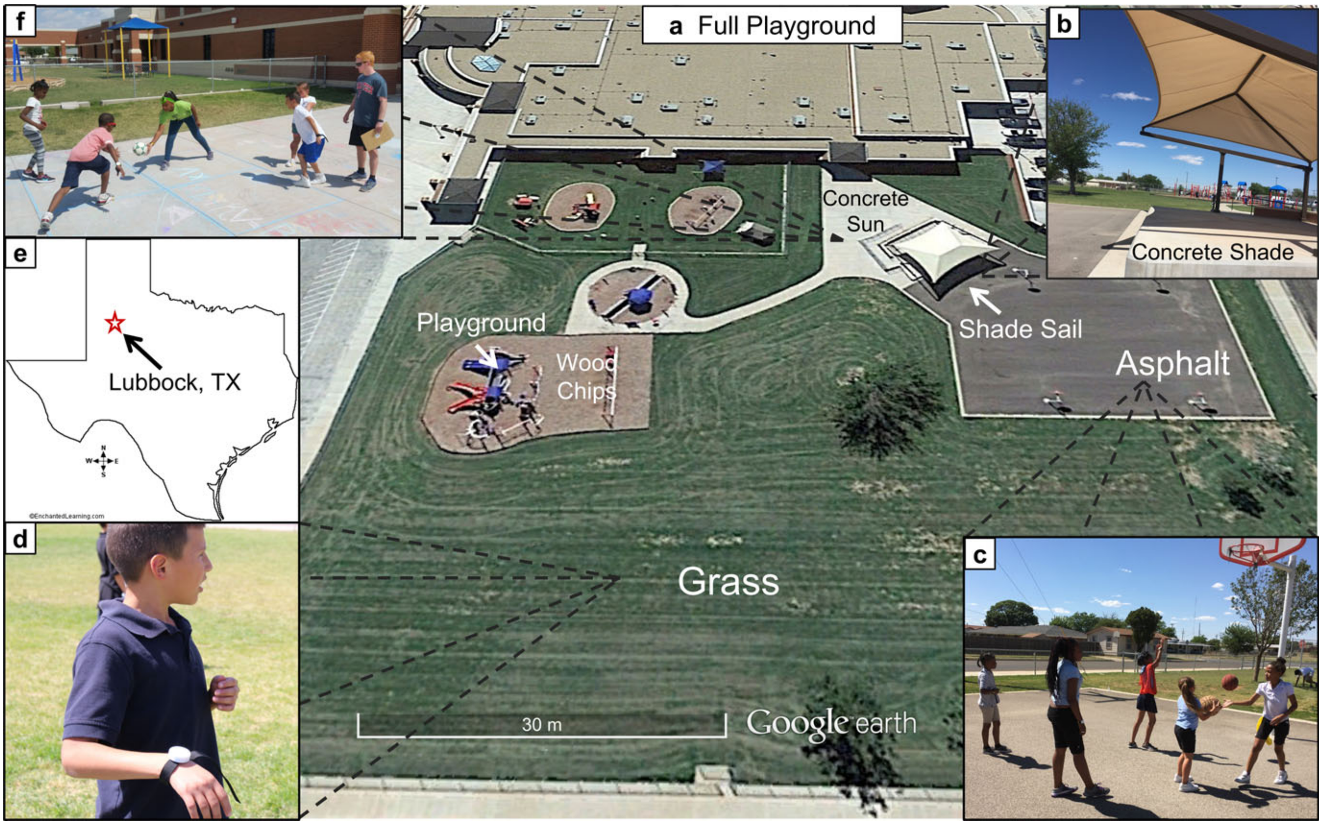

Figure 1. Study photographs: (a) Map of the study area: an elementary schoolyard in Lubbock, TX, containing play areas with various surface types, (b) the shade sail above an elevated concrete platform, (c) subjects playing basketball over asphalt, (d) a subject wearing a wrist dosimeter, (e) map of the location of the city of Lubbock within the State of Texas United States, and (f) subjects playing foursquare over concrete in the sun.

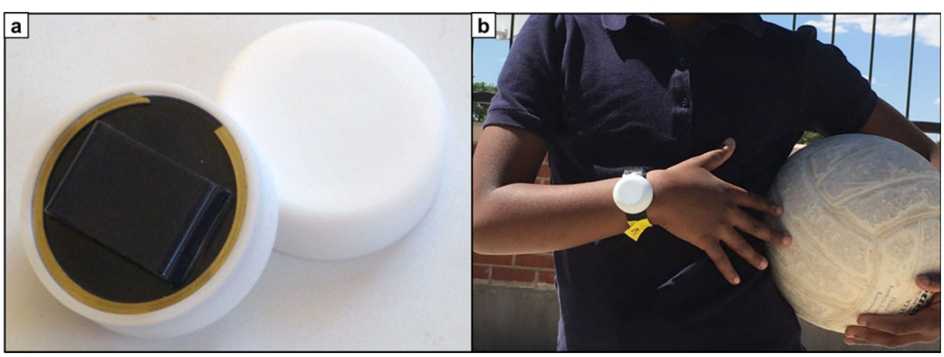

Figure 2. (a) Digital UV dosimeters utilized in the current study (Scienterra, NZ); (b) Digital UV dosimeter on a subject's wrist.

radiometer ranged from 24% on grass to 35% on concrete in the sun, while in the shade, the albedos were much higher (51%) due to the limited incoming radiation.

UV_{Ery} exposures in sun and shade

Individual UV_{Ery} exposures from the wrist dosimeters displayed significant decreases ($P < 0.05$) when under the shade sail as compared to in the direct sun (Table 3). Under the shade sail, 10-s doses from the wrist dosimeters ranged from 0.31 to 0.46 J m^{-2}, while in the shade, the mean 10-s doses were significantly less, averaging 0.17 J m^{-2} (range: 0.15–0.20 J m^{-2}). These differences are also shown by subject, day, and activity in the time series presented in Fig. 3. A depiction of the 10-s SED values from the sun and shade wrists dosimeter exposures is presented in Fig. 4a, where significant variability is found in the sun, as shown by the larger interquartile range and confidence intervals.

The sum of SED and MED varied between days due to the incoming UV_{Ery}, as well as the variation in playtime over which the total values were summed (Table 4). For example, the lowest total average SED was recorded on May 11 when each child spent a total of approximately 40 min playing in the sun. Reasons for this low value on a day with a "very high" UVI (9.2) are provided in the discussion. The highest average total SED was recorded on May 10 (SED = 1.57) when the children spent 65 min in the sun, also at a "very high" UVI of 9.65. These wrist SED values were again significantly less than that recorded by the stationary pyranometer, which reached a maximum of 9.46 SED on May 10 (65 min of play) and a minimum of 2.54 SED on May 4 (15 min

Table 3. Average UV_{Ery} exposures and standard errors (SE) from dosimeters in sun ($UV_{Ery(SUN)}$) and shade ($UV_{Ery(SH)}$), UV_{Ery} from station pyranometer in sun, and difference between sun and shade dosimeters exposures ($\Delta UV_{Ery} = (UV_{Ery(SUN)}–UV_{Ery(SH)})$), in J m^{-2} for a 10-sec dose. Statistical analysis assesses differences in sun *versus* shade exposure over the same surface. There were no significant differences found when comparing within sun exposures and within shade exposures.

Date	Wrist dosimeters				UVB Pyranometer
	Surface type†	$UV_{Err(SUN)}$ (J m^{-2})	$UV_{Ery(SH)}$ (J m^{-2})	$\Delta UV_{Ery} \pm$ SE (J m^{-2})	UVB_{Ery} (sun) $\pm$ SE (J m^{-2})
4-May	C	0.44 ± 0.01	0.20 ± 0.04	0.24 ± 0.015*	2.64 ± 0.01
5-May	Gr	0.47 ± 0.03	–	–	2.62 ± 0.01
	C	0.46 ± 0.02	0.15 ± 0.03	0.32 ± 0.015*	
9-May	C	0.36 ± 0.01	0.16 ± 0.03	0.20 ± 0.010*	1.81 ± 0.05
10-May	C/Gr/A	0.46 ± 0.08	–	–	2.42 ± 0.02
11-May	Gr	0.41 ± 0.09	–	–	2.30 ± 0.01
	C	0.31 ± 0.10	0.18 ± 0.04	0.013 ± 0.011*	
13-May	Co/Gr	0.32 ± 0.07	–	–	2.46 ± 0.02

*Significant difference at $P < 0.05$. †C—concrete; Gr—grass; A—asphalt.

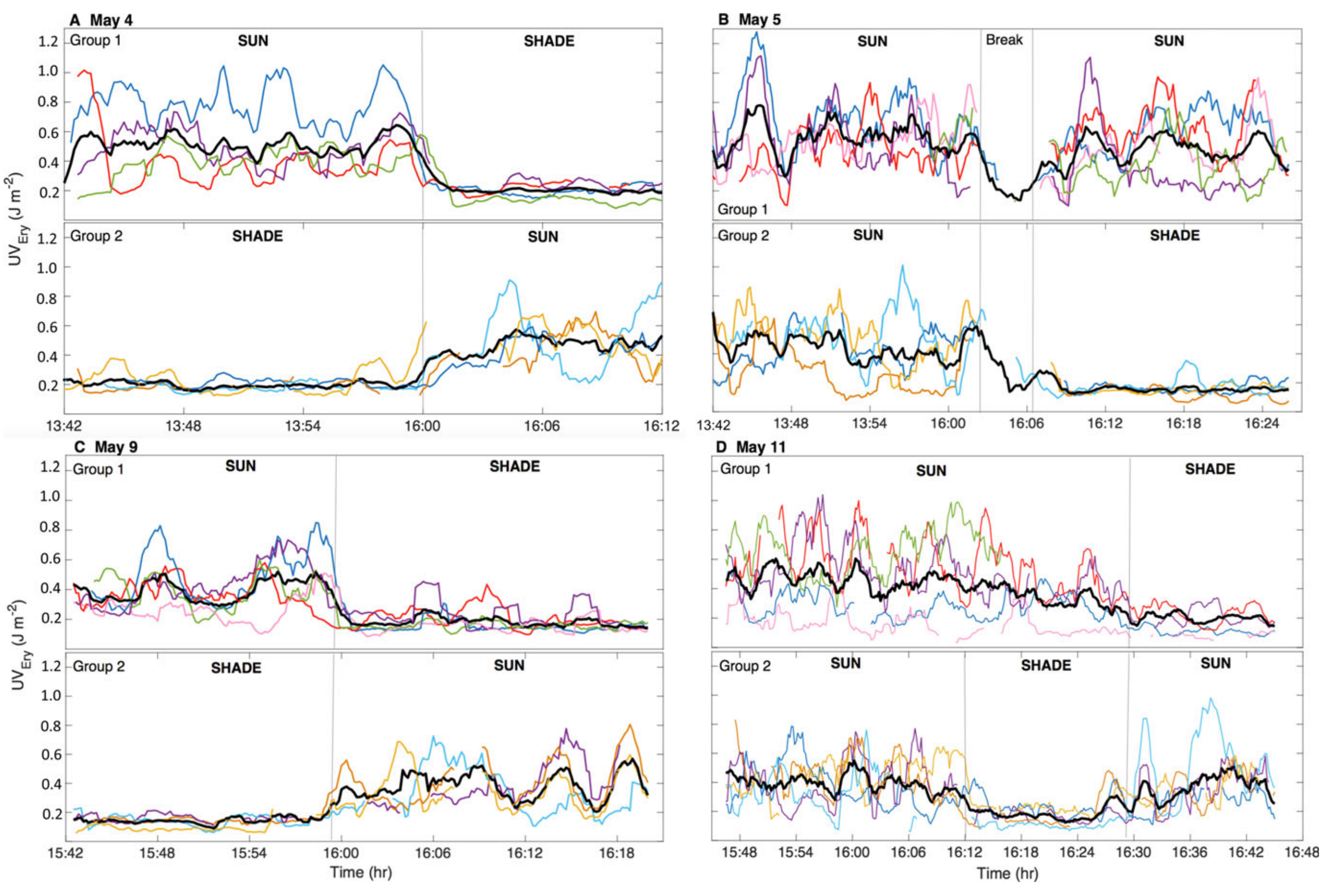

Figure 3. UV_{Ery} variation of wrist dosimeters by subject and day obtained for each individual participant. (a) May 4, (b) May 5, (c) May 9, and (d) May 11.

of play in sun). Overall, the stationary observations were more closely related to the length of play, and secondarily to the UVI, than to the dosimeter observations. Finally, the overall reductions under the shade sail of the $UVB_{280–315\ nm}$ and solar radiation were by 91% and 84%, respectively.

Exposure ratios

There were significant differences between wrist dosimeter measurements and the calculated stationary $UV_{Ery.}$ The stationary UV_{Ery} doses (J m^{-2}) recorded were 6.2 times higher on average than that of the dosimeters in the sun (ranging from 5.0 to 7.7 times greater on average). The pyranometer UVI averaged 9.5 ("very high") in the sun (closely matching regional UVI values given in Table 2) and are thus substantially greater than the UVIs observed by the dosimeters in the sun (UVI range of 1.34–1.78). Figure 4 demonstrates these significant differences in 10-s SEDs.

ERs comparing the SED from the dosimeters to the stationary observations display a mean of 17.5% for all subjects of the six days (median daily ERs ranged from 16 to 20%). However, daily variations in the maxima are present (Fig. 5) as exhibited by the extended interquartile ranges (IQR), the positive skew in all

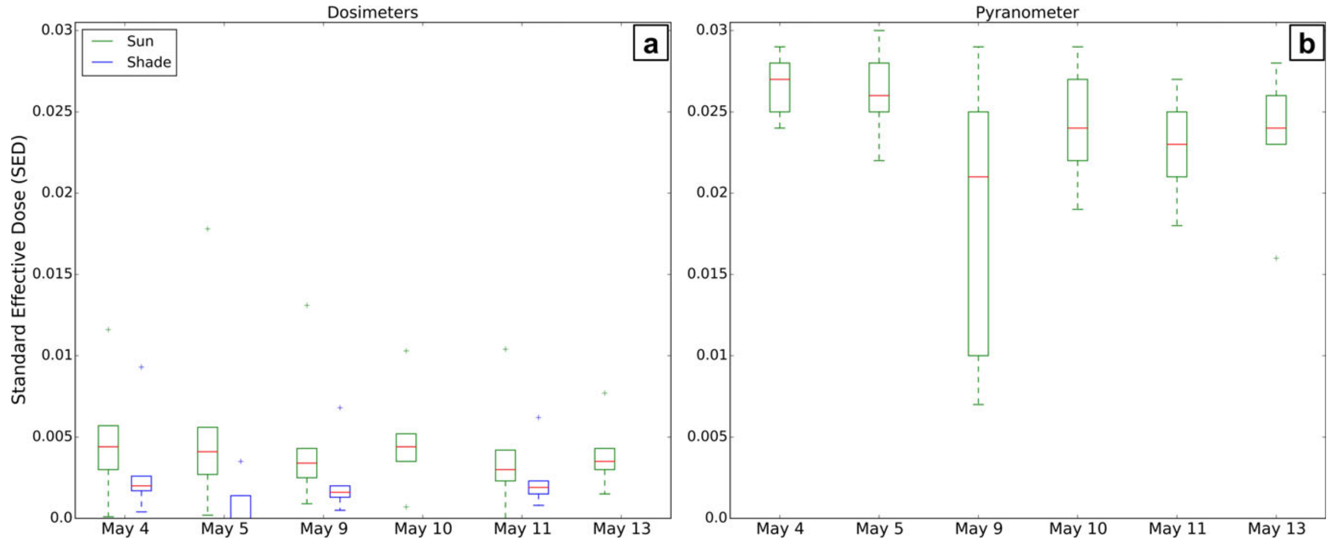

Figure 4. Box plots of total standard erythemal dose (SED) for each study day, displaying measurements taken in both sun (green) and shade (blue) from (a) the wrist dosimeters and (b) the UVB pyranometer mounted on the microclimate station.

Table 4. Averages of the total standard erythemal dose (SED) and minimal erythemal dose (MED) for time period in sun, as well as average Ultraviolet Index (UVI) recorded by the two instruments in sun and shade. The effect of the shade using the personal dosimeters was tested on four days.

		Total SED			Total MED			Average UVI		
		Dosimeters UV_{Ery}		UV_{Ery} Pyranometer	Dosimeters UV_{Ery}		UV_{Ery} Pyranometer	Dosimeters		Pyranometer
Date	Time in Sun	Sun	Shade	Sun	Sun	Shade	Sun	Sun	Shade	Sun
4-May	15 min	0.85	0.46	2.45	0.41	0.22	1.22	1.78	0.95	10.56
5-May	38 min	1.22	0.16	4.79	0.58*	0.08	2.28	1.76	0.23	10.48
9-May	20 min	0.85	0.43	2.12	0.40	0.21	1.01	1.45	0.74	7.23
10-May	65 min	1.57	–	9.46	0.75*	–	4.50	1.74	–	9.65
11-May	40 min	0.58	0.35	6.14	0.28	0.17	2.92	1.34	0.79	9.21
13-May	40 min	0.86	–	5.92	0.41	–	2.82	1.43	–	9.83

*Indicates a UV dose that would cause slight erythema if skin type was based on base MEDs. There were no instances where burning would occur for skin types II-IV in the given study using Fitzpatrick skin types (45), where a threshold of 0.5 is used for slight erythema.

distributions, and many high outlier values. May 9 presented the highest ER (20% median) when the children played Four Square on concrete, with a large positive skew and wide IQR of 19%. The instances of high ER values in Fig. 5 are indicative of the dosimeters facing the sun, although the dosimeter values did not go above that of the pyranometer as shown by ERs consistently <1.0. Over a 10-s sampling interval, there is a low likelihood of a dosimeter facing the sun the entire 10-s due to high activity levels, and thus, ERs <1.0 are expected. Overall, the stationary horizontal exposures were significantly higher than that received by the wrist dosimeters, which may have implications for the use of wrist dosimeters for dose–response studies.

DISCUSSION

The rapid acceleration of environmental sensing technology offers vast opportunities to improve individual and collective decision-making, and thus increase opportunities to improve our understanding of UV exposures at younger ages—a time when UV exposures have been linked to skin diseases later in life (20). Given the potential of personal sensors to provide estimates of more representative exposures in children's populations (*e.g.* 5,6), as well as the known influence of environmental design on exposures (28), we assessed how stationary *in situ* playground UV_{Ery} data relate to personalized UV_{Ery} exposures of 14 children (the "human scale" of observation), with 10 subjects wearing dosimeters on each day. The 10 subjects were not present on all days, and within a day, some subjects were removed from one activity due to not feeling well, 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 to real-world conditions and rules. Thus, although the real-world nature of the study is a strength, it also results in such limitations. The use of personal dosimetry is a promising method to advance our knowledge of how the design of outdoor spaces influences exposures to sunlight, specifically harmful UV_{Ery}. We have quantified exposures using three types of data, as put forth by Rosenthal *et al.* (20): (1) ambient Uv_{Ery} measurements, (2) exposure ratios, and (3) assessment by time spent outdoors.

Influence of shade

As many children attend schools and play outside mid-day when the sun intensity is highest, their outdoor playground

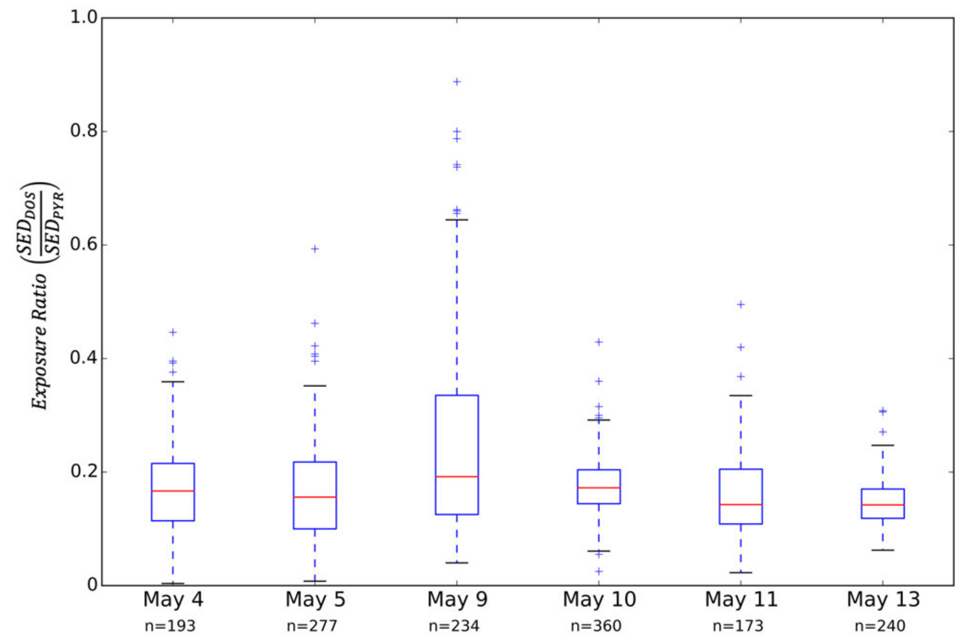

Figure 5. Box plots displaying exposure ratios (dosimeters SED/pyranometer SED) for each study day, sun observations only.

environments (created largely for promoting physical activity and creativity) may be a powerful determinant in the risk of receiving acute and long-term damage associated with UV exposure (5,28). Thus, the impact of sun protective behavior and changes in the built environment have been thoroughly investigated in the literature (*e.g.* 5,7,24,28,48–50). The current study demonstrated the effectiveness of an artificial shade sail in a playground, which effectively filtered out 91% of $UVB_{280–315\ nm}$ radiation, and reduced the SED by 60%. These reductions lengthen the time that children may safely play outdoors based on UV exposure, even on "very high" UVI days. Similar reductions in UVB dose were found by Heisler and Grant (51) who measured pedestrian level UV under trees and tested the shade provided by trees at various sun angles.

While the overall doses in the sun for the given time periods did not reach levels resulting in burns (based on the MED values for skin types II–IV (52)), by extrapolating to longer time periods in the sun, the exposures identified in this study would lead to sunburns. For example, extrapolating to time periods >1 h would result in burns for skin types II–III based on the Fitzpatrick scale assuming nonscaled base MEDs. This study shows, however, that by allowing the children to make use of the limited shade in the schoolyard, and thus reducing their time in direct sunlight, the MEDs would be concurrently reduced so that there would be no chance of sunburn. As all children but one in the current study had skin types of III or greater, there was no risk of burn for the given time periods and conditions.

Lower variability in the dosimeter readings under the shade sail was due to an overall lower SVF while children played under the shade sail, and relatively consistent UVR filtering through the shade sail and/or being scattered horizontally. The shade sail was able to significantly reduce the incoming solar and UVB radiation, which is largely a function of its size, orientation, color, transmissivity, and sky coverage, all elements that are critical to incorporate into the design of any urban area to obscure both the sun and sky (51). The current study did not measure personal UV_{Ery} under trees due to their small size, limited shading, and low number (three) on the playground. This lack of vegetation for shading is common in, open areas in arid and semiarid regions. The current study highlights that architectural solutions exist (*e.g.* shade sails, building passageways) that can combine with play-friendly vegetation to promote physical activity and also provide UV protection.

A related study by Milne *et al.* (49) found that the presence of shade in a schoolyard was not associated with children's sun exposure under free play, yet the current study controlled the play location of the children and thus we could directly assess, for a set time period, the direct differences between a group of children playing in the sun *versus* the shade. We also did not find a difference in exposure based on surface albedo, which aligns with Downs and Parisi (5) who similarly tested exposures over a basketball court and grass field. Although a more careful design of shade structures at schools is an important step forward (27), this study asserts that reducing direct overhead solar exposures should be the main focus of schoolyard design because exposures—regardless of activity—are significantly higher in open, unprotected spaces. Incorporating bioclimatic design techniques that lower SVF (*i.e.* vegetation, terrain) have been shown to effectively reduce UV exposures, extend outdoor stays, and increase physical activity (7,48). Boldemann *et al.* (48) showed that children are attracted to vegetation such as trees and shrubbery for play, which decreased their overall UV and global radiation exposures to 43% of available onsite UV, with exposures strongly correlated to SVF lowered by the vegetation (r = 0.80). Altin *et al.* (50) evaluated the implementation process of design changes within Swedish preschools for promotion of sun protective behavior and physical activity, where management and support of the design changes was a critical factor for success. Finally, the current study highlights an important area of research applications in low-income urban areas, such as the neighborhood within which the current study, which have lower proportions of tree canopy cover (53,54), and thus higher heat and radiant exposures.

Individual exposures and average ratios

The amount of time spent in the sun was an important indicator of the total SED and MED. The average time spent in the sun was 35 min per day (ranging from 15 to 65 min). However, the maximum average SED from the dosimeters was reported at 0.86 during 30 min of play on May 13 (UVI = 9.8), while a minimum average SED of 0.58 was recorded on May 11 during 40 min of play (UVI = 9.2). A high degree of intra- and interindividual variability was found, as is shown in Fig. 3, and found by Rosenthal *et al.* (20).

These total SEDs are similar to that of Wright *et al.* (24) who found an average SED of 0.90 experienced by children for 2.3 h of play per day in the summer and fall seasons (activity in both sun and shade), also using electronic UV dosimeters. Our SED results were lower than that found by Downs and Parisi (5), who measured maximum facial UV_{Ery} exposures ranging from 1.4 SED to 9.0 SED (minimum of 0.5 SED) on children in Australia for 1 h. However, given the different geographical location, length of time, and exposure location on the body, it is difficult to compare the two studies. The face also has the advantage of always being exposed to the sun with less variability due to movement, hence the lower values at the wrist are expected. However, some studies show lower exposures at the face as compared to the wrist (20).

The stationary pyranometer provided a good baseline indication of the UV_{Ery} dose that the children's dosimeters would "see" if perpendicular to the ground, facing upwards, and not moving. General findings of ERs show that the stationary pyranometer (ambient UV_{Ery}) was exposed to a significantly higher amount of UV_{Ery} than the wrist dosimeters. Measurements at the wrist were shown to constitute approximately 18% of the ambient UVB radiation measured by the on-site pyranometer, which is lower than the 50% average found in a similar study by Thieden *et al.* (22) in Copenhagen and Rosenthal *et al.* (20) in Massachusetts. These studies compared wrist to head exposures and also used different sensor types (spore-filter and PS sensor types, respectively), which have differing dynamic ranges. The current study also assessed children at a younger age, a factor that has been shown to affect ER results (24) and increase physical activity. For example, a study by Diffey *et al.* (55) compared the ERs during the following activities (ERs): sunbathing at a beach (0.80), sitting by a pool (0.42), skiing (0.22), and sightseeing (0.17), and found that more movement indicated lower ERs. Similar ER ranges during sporting activities (0.24–0.70) were found by at the wrist by Holman *et al.* (56). Given that the children in the current study were exercising at an "intense activity" level based on their metabolic equivalent values determined from the Polar heart rate monitors (3.8–6.8 METs), there are likely higher variabilities due to body part movements and changing orientations. Thus, the movement during various activities is shown to reduce the ERs, changes which were well documented by specific body part in a controlled study by Weihs *et al.* (17).

Overall, the ERs found in studies assessing physical activity are largely influenced by (1) the wrist sensor not facing directly perpendicular to the sun rays (*i.e.* how the UVI is measured), (2) body movement, and (3) the children not always in a location with a full SVF (22), and may further differ due to latitude, ambient conditions, and time of year. It is important to account for issues that may result in higher than experienced values UV_{Ery} by the pyranometer (*i.e.* always in sunlight, clothing protection), and potential under predictions of UV_{Ery} by the dosimeters. These underpredictions may be due to the dosimeter only measuring exposures at the wrist at a low angle of incidence and the observation that they can turn upside down or be covered by a hand or shirt. Such issues were addressed quickly if noticed by the researchers.

Additionally, we must also acknowledge the fact that at any moment during a high dosimeter reading (spikes up to 0.80 ER) —which could be assumed *more* accurate—countless other spots a child's body are facing away from the sun, yet this will not be evident from the exposures presented in the time series of data (Fig. 3). Likewise, we would see the opposite when the wrist sensor is faced away from the sun. Within these movements, Weihs *et al.* (17) demonstrated that the angle of incidence is first affected by the inclination of the body parts (such as wrist) and second by the orientation of the body compared to the sun. By assuming an evenly distributed (random) pattern of orientation throughout playtime, these peaks and valleys will average out, and the integral of the data points will be representative of a child's overall exposure. Therefore, wrist exposures are expected to be highly variable, and while they effectively account for indoor *versus* outdoor exposures (*e.g.* Køster *et al.* 23), they also underestimate ambient outdoor exposures; thus, ERs should be taken into account when assessing UV_{Ery} doses and SEDs so that underestimations do not occur. Finally, low-cost dosimeters, while useful for examining patterns in personal UV exposures, should not be regarded as a replacement for high-end UVR sensing instruments (19).

The current study is novel in the use of electronic UV monitors to measure both ambient and personal exposures at high sampling rates, and in the real-world testing of children during physical activity, which is indicative of outdoor exposures experienced by most children. Finally, many studies examining high personal UV exposures originate from New Zealand and Australia and are largely confined to studies later in childhood or adolescence (57); thus, the current study, which took place in a predominantly sunny, semiarid area of the United States in a child population, provides new insight into exposure modeling.

CONCLUSIONS

Overexposure to UVR in outdoor play spaces is a major risk to children's health. We have investigated the effect of shade on children's personal UV_{Ery} exposures in an elementary schoolyard and also assessed differences between personal and stationary (ambient) measurements (*i.e.* exposure ratios (ERs)) in a semiarid city. The technologies utilized in this study offer a complement of direct experience of the natural world under sun/shade exposure conditions: (1) personal erythemal UV dosimeters on the wrist (denoted UV_{Ery}), and (2) on-site UVB monitoring with a high-end pyranometer measuring UV between 280 and 315 nm ($UVB_{280–315\ nm}$). Results demonstrate that shade is as an effective design tool to substantially limit effective doses of harmful UVR and solar radiation, extend playtime, and limit erythema. The wrist-mounted electronic dosimeters used in this study were effective in measuring UV_{Ery} as a function of time with high temporal resolution (10 s), accounting for movement, behavior, and sky conditions. However, the use of such sensors must be employed with caution during physical activities due to underestimated observations, where an average ER (or percent ambient exposure) of 18% is found in this study. We also provide new information at high resolution in an underserved children's population in a region where personal UVR exposures have been relatively unstudied. Finally, this research expands new information regarding real-world application of personal dosimeters for both exposure assessments and effective urban design initiatives, thus contributing to healthy development through limiting skin damage in children and providing comfortable play environments for physical activity.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Video S1. Photographs and video footage of the study site, participants, and equipment.

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