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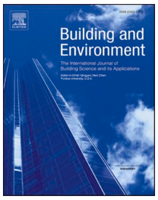

Outdoor playgrounds and climate change: Importance of surface materials and shade to extend play time and prevent burn injuries

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ABSTRACT

Surfaces in outdoor playgrounds get hot in the sun and can cause serious skin burns in children. *In-situ* measurements from 10 playgrounds in Sydney showed that the maximum and average surface temperatures of sun-exposed playground equipment and flooring surfaces were frequently above skin contact burn thresholds. Black and dark-coloured wet pour rubber and synthetic turf were the hottest floor materials, all having maximum surface temperatures ($T_{s\ max}$) > 80 °C. A blue rubber dolphin was the hottest piece of play equipment, with a $T_{s\ max}$ of 91.8 °C. A systematic assessment of common synthetic flooring materials exposed to full sun showed notable differences in $T_{s\ max}$ between material types and colour-tones. Synthetic turf with 40 mm long grass blades ($ST_{lng\text{-}GR}$) was the hottest material ($T_{s\ max} = 84.5$ °C), followed by dark blue styrene butadiene rubber ($SBR_{D\text{-}BL}$, $T_{s\ max} = 81.1$ °C), dark green ethylene propylene diene polymer ($EPDM_{D\text{-}GR\text{-}2}$, $T_{s\ max} = 77.8$ °C), dark brown thermoplastic vulcanizate ($TPV_{D\text{-}BR}$, $T_{s\ max} = 71.8$ °C), and intermediate blue thermoplastic polyolefin ($TPO_{I\text{-}BL}$, $T_{s\ max} = 65.0$ °C). All these materials were hot enough to cause contact burns on typical, warm summer days when children are likely to visit outdoor playgrounds. Surface temperatures were significantly reduced in the shade and never reached burn threshold temperatures. Selection of appropriate material type and colour-tone, together with the provision of shade can remove the hazard risk for contact skin burns from outdoor playgrounds. Results of this work will assist playground designers and managers to provide safer places for our children to play longer in increasingly warmer summers.

1. Introduction

1.1. The importance of outdoor play

Outdoor play is universally recognised as a vital element in healthy physical and emotional development in children [1–3]. The benefits to a child's physical development have long been recognised and are derived from increased activity levels and use of energy, growth and strengthening of large muscle groups through movements such as climbing, running, swinging, and jumping, plus an increase in cardiovascular endurance [4] and large and fine motor skills [5].

Despite the recognised importance of outdoor play for childhood health and development, the amount of time kids in the developed world spends playing outside is decreasing [1]. On average, children now spend around half the time outside that their parents did [6]. A systematic review including 12 studies from countries including the USA, Australia, and Canada showed that outdoor play time for children ranged between 0.7 and 6.2 h per week [7]. A study conducted just before the lockdowns imposed due to the COVID-19 pandemic, found that Australian children spent on average 5.5 h outdoors each week. Children in America were reported to spend as little as 0.46–0.81 h per week (4–7 min a day) outside in unstructured play.

One prominent driver for the trend of decreasing time spent in outdoor play is the rapid rate of urbanisation in many countries around the world [8]. For the first time in 2007, the number of people in the world living in urban areas exceeded the number living in rural areas, and by 2050 it is estimated that twice as many people in the world will be living in urban areas than in rural areas [9]. Australia is one of the most urbanised countries within the Organisation for Economic Co-operation and Development (OECD) [10], with ~86.2% of the Australian population living in urban areas [11], and annual urbanisation rate increases of around 1.5% [12]. This situation is prevalent in areas such as

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Abbreviations: TPO, thermoplastic polyolefin; TPV, thermoplastic vulcanizate; EPDM, ethylene propylene diene polymer; SBR, styrene butadiene rubber.

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metropolitan Sydney, where, in many suburbs, over half the population lives in an apartment [13], and a growing proportion of families with young children living in high-density housing due to an inability to afford a property within a suburban area [14]. In these highly urbanised environments, access to spaces that can be used for outdoor play is severely limited.

Time available for outdoor activities is also decreasing due to the growing percentage of family units where both carers are working outside the family home. A recent survey showed that the percentage of Australian couples with dependents in which both adult members work was 69.9%, of which 81.0% had at least one child <15 years old [15]. In Sydney, economic pressures are primarily responsible for the increasing number of parents returning to full time work before their children start school [16]. The result is a smaller window of opportunity when parents or primary carers can supervise children to engage in outdoor play [6].

1.2. *Environmental risks in playgrounds*

In this context, it has become increasingly important to maximise times when playgrounds can be used safely and comfortably. Playgrounds - generally defined as an area designed for children's play including the site, natural features, built landscape, and any manufactured equipment and surfacing [17] - are associated with an inherent level of risk of injury [18]. Indeed, reducing the risk of serious injury has been the main priority of recent updates in standards for the design and construction of playgrounds [19–21]. Standards relating to playgrounds vary depending on location, with global standards yet to be developed [22]. In Australia, there are four standards applicable to playgrounds (i.e., AS 4685.0:2017, AS 4685.1-6:2021, AS 4685.11:2012 and AS 4422:2016). These focus on floor surfaces and equipment design [18], addressing fall heights, impact attenuation, and eliminating risks related to catching, pinching, crushing and other 'mechanical risks'. However, playground use can also involve 'environmental risks', but these are rarely considered within the context of playground safety [23]. The most prominent environmental risk reported to cause direct and serious harm is the contact of skin with hot surfaces.

1.2.1. *Contact burns*

Human skin burns easily when it comes into contact with a hot surface, with the severity of damage suffered depending largely on the object's initial temperature, thermal conductance, and the duration of contact. Uncoated metal, which is known for its high thermal conductance, will inflict a serious skin burn in just 3 s at 60 °C [24]. There are numerous reports of serious burns sustained from metal swings, slides, and climbing platforms from playgrounds around the world [25,26], including in Australia [27–31].

Less well known is that rubber and plastic surfaces can also become overheated and cause serious contact burns [32] within 3 s at 77 °C [24]. Reports show children have suffered severe skin blistering or burns after touching hot plastic surfaces including slides [33], or rubber flooring [34] (Kidspot, 2016b) in New South Wales and Queensland, Australia [35]. A study by Vanos et al. [36] found that sun-exposed playground materials in Arizona (USA) had surface temperatures well above the thresholds for skin burn injuries [37]. Evidence suggests that skin damage is most likely to occur when equipment is exposed to direct sunlight for an extended period [38,39], which is commonly during the middle of the day and the hottest months of the year. However, surfaces can become overheated when the air temperature is not particularly high. In one report, a child received second-degree burns from a sunlit plastic slide when the ambient air temperature was <24 °C [32]. Children - and especially very young children (under 2 years old) - are particularly at risk of contact burns because their skin is thinner and more delicate than adult skin [40]. This problem is exacerbated by the fact that young children are likely to be in contact with a hot surface for longer because they have not yet developed the protective reflexes to remove themselves from the heat source [32].

1.3. *Engineered playground surfacing*

Changes to playground design standards that are aimed at decreasing risk of serious injury [17] and increasing inclusivity [19], have led to a marked decrease in the use of natural materials such as bark mulch, and a subsequent increase in the use of engineered surfaces such as synthetic (aka artificial) turf and wet pour rubbers. Both surface types are commonly installed over a rubber base layer [41] made from crumbs of styrene butadiene rubber (SBR) - a synthetic copolymer of styrene and butadiene - which, when combined with the polyurethane (PU) binding agent, result in a highly impact-absorbing surface [42]. Synthetic turf has been used on sports fields for over 50 years [43], although its use in playgrounds was limited until the early 2000s, after which its use has increased greatly [41]. Wet pour or 'poured-in-place' (PIP) rubber has a slightly longer history of use, becoming popular for playgrounds in the late 1990s. To date, SBR, ethylene propylene diene monomer (EPDM), thermoplastic polyolefin (TPO) and thermoplastic vulcanised (TPV) plastic granules are glued together with PU binding agents into contiguous coloured playground surfaces. These surfaces are referred to as 'bonded rubber crumb' or BRC. Many playgrounds around the developed world now have some form of rubber floor surfacing. For example, 27 of 28 (96%) playgrounds studied in the City of Boston (MA, USA) were found to have rubber surfacing [44], and in Sydney, 54 out of 61 (89%) playgrounds investigated had areas of rubber floor surfacing [45].

The dominant use of synthetic surfaces has been linked with increased burn risk in playgrounds [46], and numerous anecdotal and common media stories demonstrate the risks are real. But despite the known significant risks to children, there is no published data available for surface temperatures of common synthetic playground surfaces. This is particularly relevant in areas such as Australia where solar radiation loads are very high to extreme during the hotter months of the year. Indeed, the paucity of data on potential maximum surface temperatures for these materials under current or predicted climatic conditions suggests that contact burn risks have been historically ignored but need to be identified as a matter of priority to protect children from potential burn risk.

1.4. *Environmental hazards under climate change*

Extreme heat and the increasing number of hot days each year present serious hazards to public health in Australia [47,48]. The City of Parramatta in the geographic centre of Greater Sydney (NSW, Australia) is one of Australia's fastest growing metropolitan regions [49], and in the summer of 2019, the city experienced 47 days with temperatures over 35 °C [50], making it one of the increasingly hot areas across Greater Sydney. In this study we aimed to determine (i) how hot common playground floor surface materials and playground equipment can get in and around Parramatta; (ii) how material type and colour-tone affect maximum and average surface temperatures; and (iii) how quickly different floor surface materials/colours heat up. Results of this study can be used to inform heat-responsive design of outdoor playgrounds to maximise the time when it is safe and enjoyable for visitors to stay and play, and so improve the future health of children in urban Australia and other countries with hot environments expected under climate change [51]. Here we present a systematic study of surface temperatures associated with a range of common playground materials used across Greater Sydney, testing the hypotheses that:

- sun-exposed playground equipment and floor surfaces can get hot enough to inflict serious skin contact burns,
- surface temperatures of floor materials in the sun depend on material type and colour-tone, with synthetic and darker-coloured materials getting hotter than natural and/or lighter-coloured materials, and

- shading of materials can reduce surface temperatures to substantially reduce or eliminate skin contact burn risk for playground users including children.

2. Materials and methods

This study had two components: (i) field-based, *in-situ* spot measurements of surface temperatures (T_S) for sun-exposed floor surface material types and playground equipment located at 10 playgrounds within the Cumberland and Parramatta local government areas (LGAs) in metropolitan Sydney (NSW, Australia), and (ii) measurement of surface temperatures of 29 common playground floor surface materials in full sun and in shade over the course of a typical summer day at the Outdoor Heatlab at the Kingswood campus of Western Sydney University (Penrith, NSW, Australia).

2.1. In-situ playground measurements

The playgrounds visited within the densely populated Western Sydney (NSW, Australia) suburbs were Auburn Park (Auburn), Bennalong Park (Granville), Colquhoun Park (South Granville), Doyle Ground (North Parramatta), Hannibal Macaruthur Park (Rydalmere), Kootingal Street Park (Greystanges), Memorial Park (Merrylands), Portico Park (Toongabbie), Rydalmere Park (Rydalmere), and Sherwin Park (North Parramatta). For images of the playgrounds see in Supplementary Material Fig. S1. Playgrounds were visited between 11:00 and 17:00 h across five hot to very hot, sunny days in the warmer (mostly summer) months (August–January) of 2019, 2020 and 2021. At each playground, details of the predominant floor surface materials, and their colour-tone were recorded. Simultaneous infrared and red-green-blue (RGB) images of each flooring material were collected (see Fig. 1 for examples) using a radiometric infrared camera (models T540 and T640, Teledyne FLIR, Wilsonville, OR, United States) with an accuracy of 2% of temperature readings and emissivity set to 0.95. Surface temperatures (T_S) were extracted using FLIR Tools software (version 6.4, https://www.flir.com.au/products/flir-tools, accessed 20 March 2022). In each image, five individual random spot measurements of surface temperature were extracted and averaged for each target material, playground and date. A total of 57 images of floor materials were used, giving a total of 285 individual measurements of surface temperature for playground floor materials.

Surface temperatures of a selection of playground equipment were also measured. Equipment was selected if it had a surface area that was facing predominantly upward, would allow for high-quality imaging, and was thought most likely to present a contact burn hazard for users because it would commonly come into contact with the skin for >3 s. Metal slide surfaces were not included because emissivity is markedly different from 0.95 and no post-capture corrections were to be applied to images. The equipment used and methods for extraction of data from images of playground equipment were identical to those described

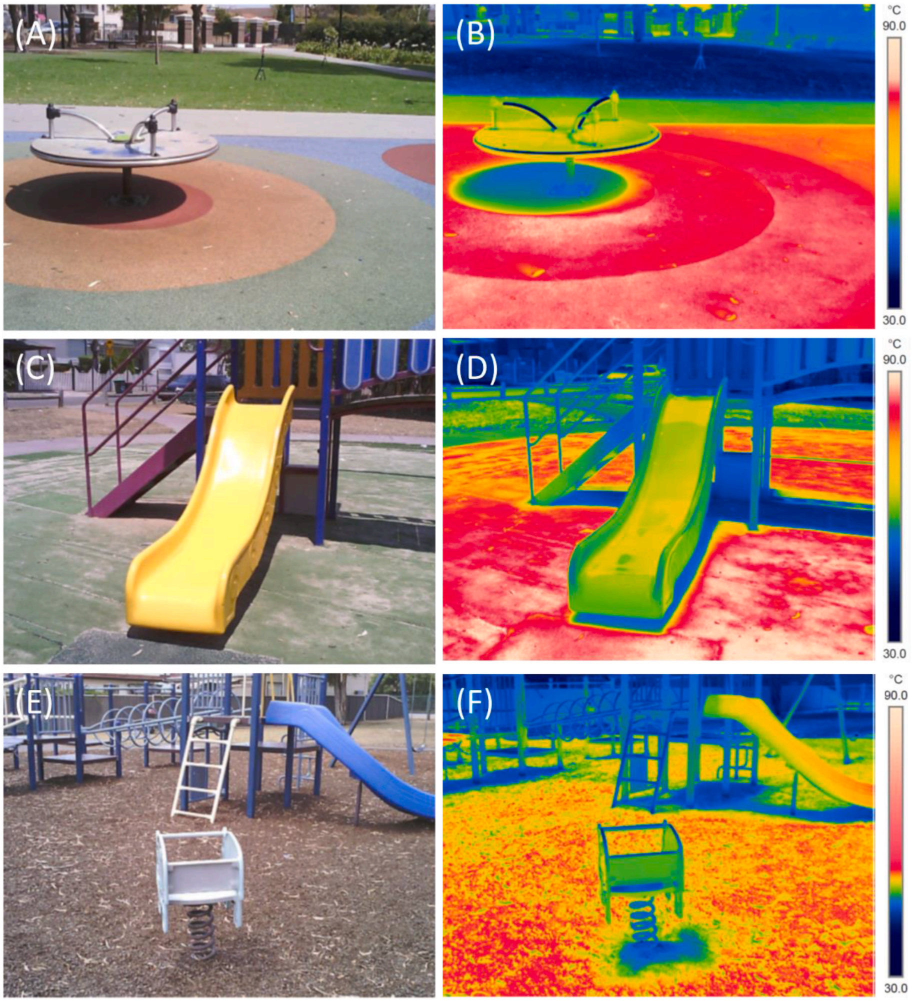

Fig. 1. [2-column fit]. Normal red-green-blue (A, C, E) and infrared (B, D, F) images of *in-situ* playground surface temperatures at 3 of the 10 playgrounds visited within metropolitan Sydney (NSW, Australia). Images were taken at Auburn Park at 15:30 h (A, B), Bennalong Park at 13:30 h (C, D), and Colquhoun Park at 14:20 h (E, F) on 4 January 2020. Colour scales on the right-hand side indicate the range of surface temperatures (°C) measured.

previously for floor surface materials. A total of 50 images of equipment were used, giving a total of 250 individual surface temperature measurements for pieces of playground equipment.

2.2. Systematic assessment - sun and shade experiment

The sun and shade experiment took place at the Outdoor Heat Lab at the Kingswood campus of Western Sydney University (Penrith, NSW, Australia). The first set of measurements was taken on 9 February 2022, which was a typical warm, sunny, summer day with no cloud cover (used for the 'sun' treatment) and predicted maximum temperatures in the low 30s (°C) - a day when children would be very likely to use outdoor playgrounds. The second set of measurements was collected on 10 February 2022, which was also a calm, warm, sunny day with maximum temperature very similar to the day before. On this day, samples were placed under a temporary shade structure (approximately 3 × 3 m, ~1.3 m above the ground) that shaded all samples throughout the measurement time window (constituting the 'shade' treatment). Spectro-radiometric measurements (Stellar-RAD, StellarNet Inc., Tempe, FL, United States) indicated that the shade structure blocked 97% of light between 250 nm and 1100 nm, and 100% of harmful UV-A and UV-B radiation (250–400 nm) (see Supplementary Materials S2 and S3). Sample 'tiles' (each measuring approximately 30 × 30 cm with sides covered by white tape to prevent heat absorption by the black SBR cushioning layer) of 28 common playground floor surface materials were placed on a concrete slab within a fenced compound located in a large, grassed area (Fig. 2). A sample of natural turf was assessed *in situ* just beyond the fenced area.

The experiment included 28 synthetic materials (24 sample 'tiles' made of rubber, and 4 of synthetic turf), and 1 natural turf (living green grass). All rubber samples had a cushioning underlayer (30 mm thick) made of black rubber crumb (or fibres) overlaid with a 'wet pour' upper layer (10–17 mm thick) consisting of one of the variety of materials (i.e., SBR, EPDM, TPO or TPV). Synthetic turf samples were placed on foam pads (15 mm thick) held down with cable ties, and the natural turf was a section of established lawn outside the fenced experimental area. Samples were classified into groups based on material type and colour-tone. Materials were thermoplastic polyolefin (TPO; $n = 6$), thermoplastic vulcanizate (TPV; $n = 9$), ethylene propylene diene polymer (EPDM; $n = 5$), styrene butadiene rubber (SBR; $n = 4$), synthetic turf (ST; $n = 4$), and natural turf ($n = 1$). TPO, TPV, and EPDM materials were solid in colour throughout the whole profile of the surface layer and the crumb, whereas the SBR crumbs (which are derived from recycled black rubber tyres) were black on the inside with a colour coating on the outside only. The colour-tone groups were based on the outside colour of each material, these being considered as dark (D, $n = 13$), intermediate (I, $n = 9$), or light (L, $n = 6$). For images of the experimental set-up and the colours of sample tiles see Supplementary Materials S3 and S4.

High-resolution thermal images of sample tiles were taken every 30 min from 08:00 to 16:00 (10 February 2022) or 16:30 h (9 February 2022, excluding the measurement at 15:00 h due to cloud cover) with a radiometric infrared camera (T540, Teledyne FLIR) that was kept ~1 m above the ground. The 'box measurement tool' (165 × 165 pixels) in the FLIR Tools software was used to extract temperature readings from each image. The box was located at the centre of each tile (omitting 5–7 cm around the edges) and used to extract a mean surface temperature ($T_{\mathrm{s\_mean}}$, °C, based on 27,225 radiometric pixels), absolute minimum surface temperature ($T_{\mathrm{s\_min}}$, °C) and absolute maximum surface temperature ($T_{\mathrm{s\_max}}$, °C) values for each sample and time point. A total of 983 images were taken from which 2949 individual readings (mean, minimum, and maximum values) were extracted over the entire measurement period (i.e., 2 days), and a total of 26,762,175 radiometric pixels were analysed. An emissivity of 0.95 was used for all materials in this study. This level of emissivity is in the narrow range documented for different types of rubber, plastics, concrete, and vegetation.

On each of the sampling days, background ambient air temperature (T_{air}), wind speed (m s^{-1}), and solar radiation (W m^{-2}) and relative humidity (RH, %) were recorded every 15 min using the on-site weather station (WeatherHawk 520, Campbell Scientific, Logan, UT, United States). The station was mounted 2 m above the ground in full sun over natural green turf adjacent to the sampling area. Wet bulb globe temperature (WBGT, °C) was also recorded to capture outdoor human heat stress in response to the combined effect of temperature, humidity, wind speed, direct solar radiation and radiant heat. The WBGT is widely used

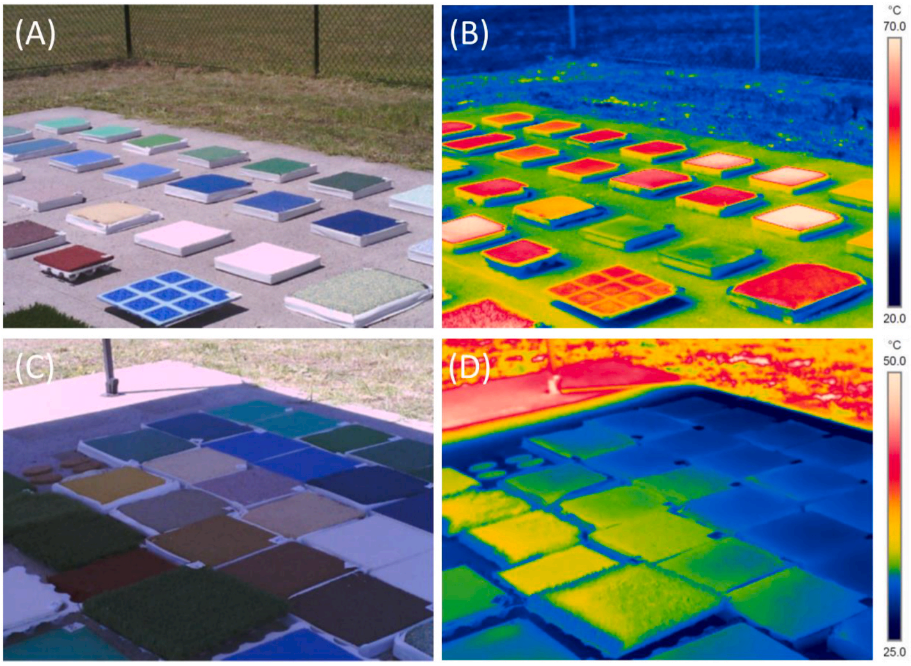

Fig. 2. [2-column fit]. Normal red-green-blue (A, C) and infrared (B, D) images of sample tiles used in the systematic assessment of playground floor materials at the Outdoor Heatlab (Kingswood Campus, Western Sydney University, Penrith, NSW, Australia). The images were taken at 12:00 h under sun-exposed (9 February 2022; A, B) and shaded (10 February 2022; C, D) conditions. Colour scales on the right-hand side indicate the range of surface temperatures (°C) measured.

to determine the heat stress on the human body [52,53], and it closely reflects similar indices like the Universal Thermal Climate Index [54]. WBGT was measured every minute with a Kestrel 5400 Kestrel Heat Stress Tracker near the playground samples, positioned 1 m above the concrete slab in either the sun and shade depending on sampling day.

2.3. *Statistical analyses*

Statistical analyses and data graphing were done using R (version 3.6.0, R Foundation for Statistical Computing, Vienna, Austria). For all analyses, statistical significance was assumed when $p < 0.05$. A *t*-test on overall data between 8:00 and 16:30 h was used (*t.test* from *stats* R package) to test whether the ambient environmental conditions differed significantly between the 2 days at the Outdoor Heatlab. The main focus of analyses was on $T_{\text{s\_max}}$, as the upper threshold of potentially hazardous surface temperatures. We assessed how fast the sample tiles warmed up by inspecting slopes of linear relationships. The $T_{\text{s\_max}}$ were fitted for each material and treatment between 8:00 and 12:00 h, with three exceptions due to the curve shape commencing plateau phase (natural grass at 10:30 h, $\text{ST}_{\text{sht-G}}$ and $\text{TPV}_{\text{I-Bl1}}$ at 11:30 h). To verify material- and colour-tone-specific differences in $T_{\text{s\_max}}$ for the systematic assessment, three-way ANOVA was used (*lm* from the *stats* R package; [55]). For this analysis, the plateau part of the line plot was selected for all materials, using absolute maximum $T_{\text{s\_max}}$ values measured between 12:00 and 14:00 ($n = 5$). Treatments (sun vs shade) with grouped playground floor materials (ST, SBR, EPDM, TPO, and TPV), and colour-tone (L, I, and D) were used as fixed factors. Interactions 'Material type × Treatment' and 'Colour-tone × Treatment' were also included in the analysis. The interaction 'Material type × Colour-tone' was not considered due to multicollinearity from unbalanced colour-tone classification for the materials groups. To address this, the 'Material type' and 'Colour-tone' were combined into a new factor containing ten levels and used in a two-way ANOVA with the Treatment. As natural turf was the only natural surface in this study, it was not used in any ANOVA analysis. When effects for the factors and interactions were significant, differences were tested using Tukey's HSD test (*glht* from *multcomp* R package, [56]). The data was checked for normality by visually inspecting the Q-Q plots.

3. Results

3.1. *In-situ playground measurements*

For playground equipment exposed to full sun, the hottest maximum surface temperature was recorded at Memorial Park on 4 January 2020 - a day of extreme heat with air temperatures above 40 °C across the Cumberland LGA - where a dark blue rubber dolphin had a surface temperature of 88.0 °C (Fig. 3). Other high surface temperatures recorded on this day included a black rubber swing seat at Bennalong Park (76.2 °C), and a blue rubber swing seat at Auburn Park (76.3 °C). On 8 April 2019, the surface temperature of an unshaded black wooden bench seat at Hannibal Macarthur Park reached 76.5 °C at 12:14 h when the ambient air temperature was 31.5 °C. Mean surface temperatures varied with material type and colour-tone (Fig. 1). The rubber dolphin had the highest mean surface temperature (averaged across playgrounds and measurement days) of all playground equipment tested (mean ± 1 standard deviation, 72.5 ± 11.9 °C, $n = 3$), followed by plastic swing seats (59.7 ± 10.0 °C, $n = 9$), wooden benches (58.1 ± 8.9 °C, $n = 12$), plastic slides (56.0 ± 7.5 °C, $n = 13$), and metal platforms (54.5 ± 7.6 °C, $n = 13$) (Fig. 4A).

Maximum and mean surface temperatures of sun-exposed playground floor materials varied widely depending on material type and colour-tone (Fig. 4). The highest maximum surface temperature for playground flooring material was measured on 4 January 2020, when black rubber in full sun at Bennalong Park had a surface temperature of 88.7 °C at 13:30 h (shown in Fig. 1D) and synthetic grass at the same park at that time was 88.1 °C. On the same day, the surface temperature of pine bark mulch reached 81.9 °C at Kootingal Street Park, and 75.9 °C at Memorial Park. Maximum surface temperature of sun-exposed natural green turf was always very similar to ambient air temperature, the highest maximum surface temperature recorded being 43.1 °C at 15:34 h on 19 December 2020 at Colquhoun Park. Of the flooring materials,

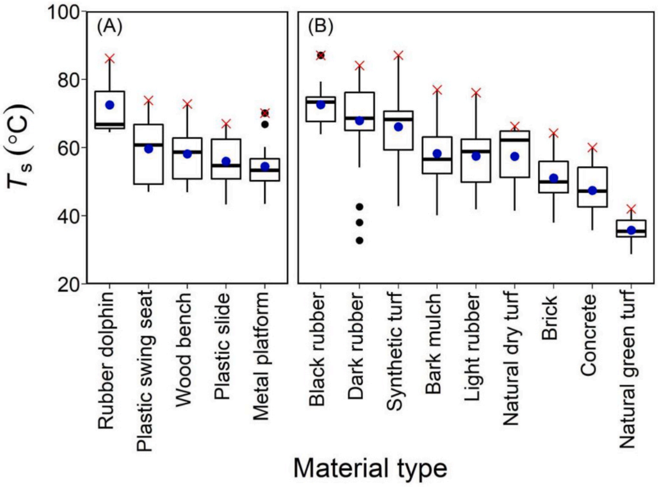

Fig. 4. [2-column fit]. Surface temperature (T_s) of playground equipment (A, $n = 3$–13) and floor materials (B, $n = 7$–32) in the late morning through to the early afternoon on hot, sunny days in the summers of 2019/2020 and 2020/2021 when exposed to full sun at ten playgrounds in Sydney (NSW, Australia). Upper and lower ends of box plots indicate 75th and 25th percentiles respectively, the line inside the box shows the median, and the whiskers indicate minimum and maximum ranges. Blue dots indicate means, and red crosses the absolute maximum values recorded for each surface type.

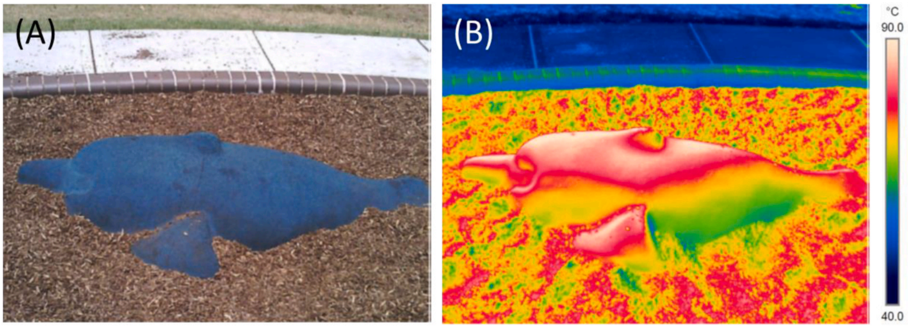

Fig. 3. [2-column fit]. Normal red-green-blue (A) and infrared (B) images of the blue rubber dolphin at Memorial Park playground (Merrylands, NSW) at 13:00 on 4 January 2020. The colour scale on the right-hand side indicates the range of surface temperatures (°C) measured.

black rubber had the highest mean surface temperature of 72.6 °C (±6.9 °C, $n = 11$), followed by dark-coloured (blue, red, orange and green combined) rubber at 67.9 °C (±12.4 °C, $n = 32$), and synthetic turf at 66.1 °C (10.8 °C, $n = 20$) (Fig. 4B). Natural dry turf, bark mulch, and light-coloured rubber had similar surface temperatures (natural dry turf: 57.5 ± 9.9 °C ($n = 7$), bark mulch: 58.3 °C (±10.2 °C, $n = 17$), light-coloured rubber: 57.5 °C (±11.2 °C, $n = 8$) whereas brick and concrete surfaces were cooler, at 51.1 °C (±8.3 °C, $n = 11$) and 47.4 °C (±7.5 °C, $n = 26$) (Fig. 4B). The coolest surface, and also the one with the least variability, was that of natural green turf, which had a mean surface temperature of 35.8 ± 3.5 °C during hot summer days (Fig. 4B).

3.2. Systematic assessment - sun and shade experiment

Mean ambient air temperature (T_{air}, °C), solar radiation, and wind speed at the experiment site were similar on both measurement days (Fig. 5). Differences in ambient air temperature measurements ranged from 1.2 to 2.8 °C during the measurement window. The overall difference in mean T_{air} between the 2 days was insignificant, with 10 February (shade treatment) being only slightly warmer than 9 February (sun treatment). Ambient air temperature increased steadily from around 17–20 °C at the beginning of the measurement window (08:00 h) until reaching a maximum of about 32 °C in the early-to mid-afternoon, after which it decreased at a rate similar to the morning increase. Solar radiation levels followed a steady, rapid increase from zero before sunrise to a maximum around 940 W m^{-2} between midday and 15:00 h. In addition, the 2 days did not differ in the amount of solar radiation received. Wind speed was generally low (<3 m s^{-1}) with small gusts between 1 and 3 m s^{-1} throughout the measurement period, the highest gusts being recorded in the afternoon between 14:00 and 16:00 h. Statistical analyses showed that wind speed between the 2 days was significantly different ($p < 0.01$), but Fig. 5 shows that these differences only occurred during late afternoons. RH decreased with the increase of T_{air} throughout the day, ranging from 67 to 83% (08:00 h) to 24–31% (16:30 h). Although 9 February was slightly more humid than 10 February, the overall difference in RH between the two days was insignificant.

The WBGT increased similarly to T_{air}, reaching a plateau from 12:00 on 9 February (sun treatment) and with a slight delay when shade was used on 10 February (Fig. 5D). WBGT was below 24 °C until around 8:30 on 9 February and 10:00 on 10 February when outdoor play would have been safe for children. From 11:30 on 9 February, the WBGT exceeded 29 °C, which would prevent safe play on an unshaded playground, while the values were generally below 29 °C on 10 February (see Table 1).

When exposed to the sun, the absolute $T_{\text{s max}}$ of most sample tiles closely reflected the changes in solar radiation, increasing rapidly and linearly at the start of the day (between 8:00 and 12:00 h, see Fig. 6). Samples had received a small amount of sun after sunrise before measurements began, which produced slight differences between materials from the initial measurement. Materials reached their maximum surface temperatures between 12:00 and 14:00 h when solar radiation was peaking. $T_{\text{s max}}$ then decreased gradually over the afternoon. Overall, the hottest surface temperature was 84.5 °C for synthetic turf with the longest grass blade lengths (40 mm, $\text{ST}_{\text{lng-GR}}$), followed by dark-blue SBR at 81.1 °C ($\text{SBR}_{\text{D-BL}}$, Table 2). The coolest material was white TPO ($\text{TPO}_{\text{L-W}}$, 48.7 °C; Table 2). The second coolest surface temperature was measured on light beige EPDM ($\text{EPDM}_{\text{L-BE}}$), which was 5.0 °C warmer (Table 2). Most other materials were markedly hotter, with $T_{\text{s max}}$ between 55 and 80 °C (Table 2). Surface temperature of natural green turf responded to direct solar radiation similarly to the coolest engineered material (i.e., $\text{TPO}_{\text{L-W}}$; Fig. 6), and its $T_{\text{s max}}$ was 29 °C cooler than the hottest material in this study ($\text{ST}_{\text{lng-GR}}$, Table 2).

The samples differed in the heating rates during the morning hours (8:00–12:00 h, see Supplementary Material S5), with significant linear fits for all 29 samples ($p < 0.001$, fitted lines not shown). All green synthetic turf materials warmed the fastest when exposed to solar radiation, reaching the highest absolute $T_{\text{s max}}$ earlier than other material types. Among rubber-based materials, $\text{SBR}_{\text{D-BL}}$ and $\text{EPDM}_{\text{D-GR-2}}$ heated most rapidly. By contrast, linear trends for $\text{TPO}_{\text{L-W}}$ and $\text{EPDM}_{\text{L-BE}}$ had the smallest slopes, indicating they had the slowest rate of warming in the sun. Moreover, natural green turf had a comparable heating rate to the light beige EPDM ($\text{EPDM}_{\text{L-BE}}$).

When shaded, $T_{\text{s max}}$ of all materials were similar to ambient T_{air}, increasing gradually and mostly linearly during the day (Fig. 7). Shade significantly reduced $T_{\text{s max}}$ of all material types and colour-tones, the difference being greatest for synthetic turf with the longest grass blades (Table 2). Maximum surface temperatures for synthetic turf were reduced by 43 °C (from 84.5 to 41.7 °C, Table 2). These values were only marginally greater than those for dark blue SBR ($\text{SBR}_{\text{D-BL}}$), for which shade reduced the surface temperature by 40 °C (from 81.1 to 41.3 °C, Table 2). Green synthetic turfs had the highest surface temperature in the shade, the maximum being turf with short (13 mm long) grass blades

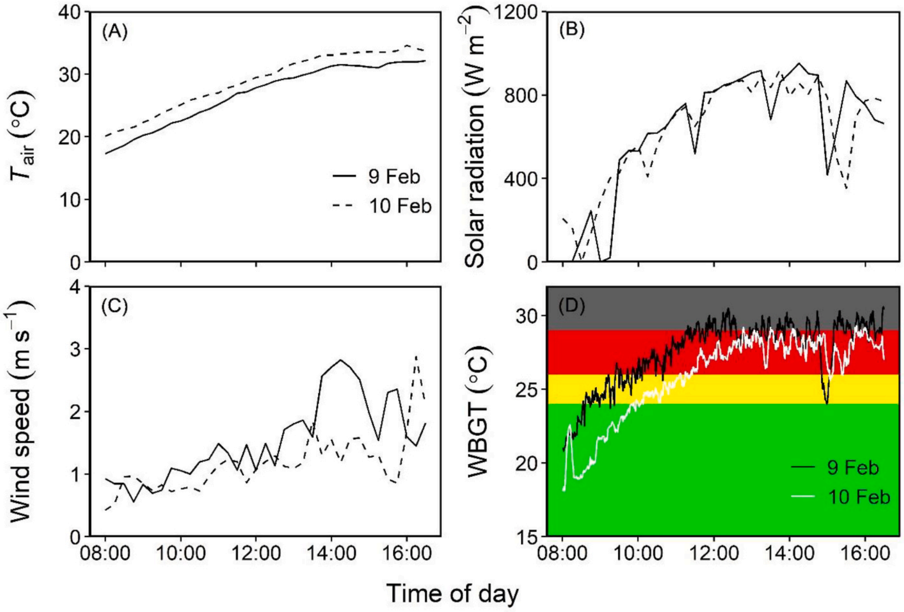

Fig. 5. [2-column fit]. Mean air temperature (T_{air}, A), solar radiation (W m^{-2}, B), and wind speed (m s^{-1}, C) and Wet Bulb Globe Temperature (WBGT, D) measured between 08:00 and 16:30 h at the Outdoor Heatlab (Western Sydney University) on 9 and 10 February 2022 (solid line and dashed line, respectively). A–C: Measurements were recorded every 15 min from a fixed weather station (WeatherHawk 520, Campbell Scientific) located 2 m above the ground. D: WBGT was recorded every 1-min with a Kestrel Heat Tracker positioned 1 m above the concrete slab. The colours in panel D indicate restraint-levels on outdoor activities of exercising children: green (<24.0 °C) = all activities allowed; yellow (24.0–25.9 °C) = longer rest periods in the shade and drinking water every 15 min; red (26.0–29.0 °C) = stop activity of unacclimatized persons and high-risk persons and limit activities of all others; black (>29.0 °C) = cancel all athletic activities. After [98].

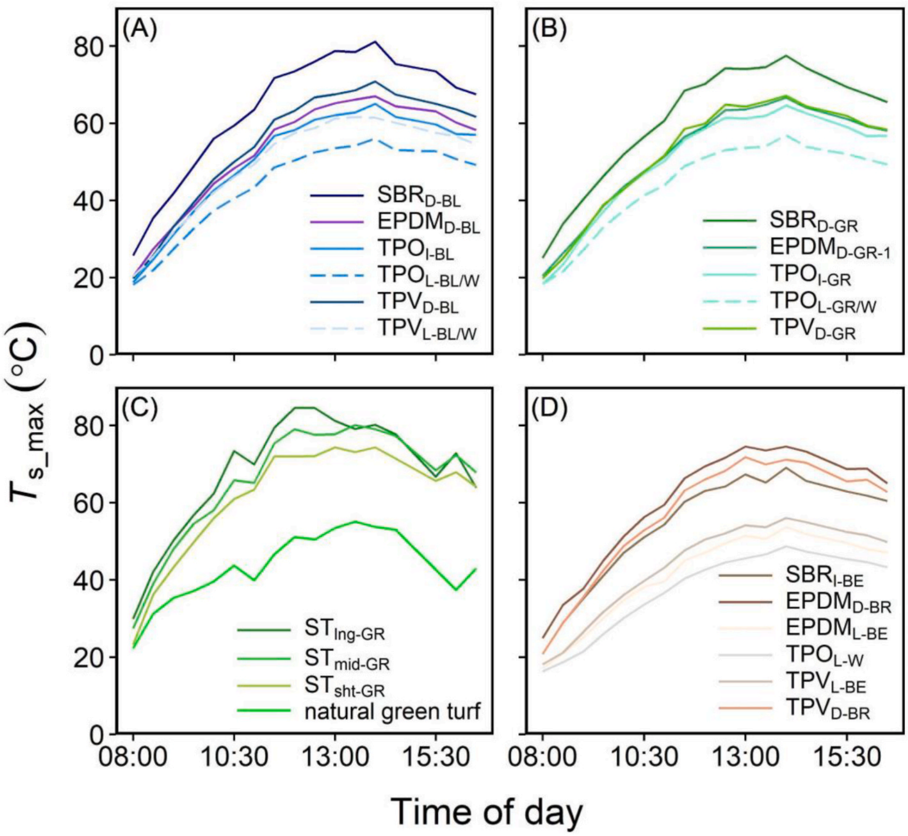

Fig. 6. [2-column fit]. Maximum surface temperatures (T_{s_max}) of a selection of playground materials and colours measured in the sun from 08:00 to 16:30 h on the 9 February 2022. Data are absolute maximum surface temperatures (one value of 27,225 pixels in thermographs taken from each sample and time point) for blue rubber types (A), green rubber types (B), synthetic and natural turf types (C), and earth- and light-coloured rubber types (D). Solid lines indicate plain-coloured materials, and dashed lines mixed-coloured (speckled) materials. For abbreviations see Table 2.

at 42.6 °C, but this was only 9 °C warmer than the coolest surface temperature of natural turf in the shade (34 °C; Table 2).

The type of material had a significant effect on T_{s_max} ($F = 38.59$, $p < 0.001$; Table 3), where synthetic turf was significantly hotter than all other groups of materials (Tukey's test, $p < 0.05$). The largest difference of 14 °C was found between the synthetic turf and TPO across treatments and colour-tones. Also, the T_{s_max} varied significantly depending on colour-tone ($F = 43.67$, $p < 0.001$; Table 3), where dark-coloured tiles were, on average, 10 °C hotter than the light-coloured tiles. Further, significant interaction of 'Treatment × Colour-tone' ($F = 51.13$, $p < 0.001$; Table 3) was found for materials in the sun but not in the shade. When exposed to peak solar radiation, the mean T_{s_max} changed significantly with colour-tone ($p < 0.05$). In the sun, the dark-coloured materials (72.0 °C ± 6.1) were 9 °C and 18 °C hotter than intermediate- (63.1 °C ± 4.5) and light-coloured samples (54.5 °C ± 6.2), respectively, and all colour-tones were significantly hotter than the same colour-tones measured in the shade ($p < 0.05$).

A similar pattern was found for the significant interaction of 'Treatment × Material type' ($F = 4.76$, $p < 0.01$; Table 3), where the influence of material type on the T_{s_max} was strong in the sun but not in the shade. The T_{s_max} varied significantly between most material types in the sun ($p < 0.05$), except for synthetic turf and SBR, which had similar mean T_{s_max} (ST: 77.2 °C ± 3.8; SBR: 71.8 °C ± 5.1) and EPDM and TPV (EPDM: 65.0 °C ± 8.9; TPV: 62.7 °C ± 5.4). The coolest group of materials measured in the sun was TPO, which warmed up to 56.0 °C ± 6.2, regardless of the colour-tone. Furthermore, the combination of 'Material type with Colour-tone' also had a significant effect on the T_{s_max} ($F = 65.95$, $p < 0.001$; Table 3). Dark ST was hotter than dark EPDM, dark SBR, all colour-tones of TPO and TPV. Similarly, intermediate colour-tone SBR were significantly hotter than light and intermediate TPO materials.

The T_{s_max} changed significantly with an interaction of 'Material type with Colour-tone' × 'Treatment' ($F = 30.69$, $p < 0.001$; Table 3). Overall, most sample tiles had comparable mean T_{s_max} in the shade with a few exceptions. The shaded synthetic turfs were significantly warmer than dark-coloured EPDM, light- and intermediate-coloured TPO and intermediate- and dark-coloured TPV ($p < 0.05$) of the same treatment. By contrast, solar radiation significantly influenced the T_{s_max} of most sample tiles depending on the material and colour-tone ($p < 0.05$). Exceptions were once again the equally hot synthetic turf and dark-coloured SBR, as well as the equally warm dark-coloured EPDM, intermediate-coloured SBR and dark-coloured TPV materials. Mean T_{s_max} of intermediate-coloured TPO were not significantly different from light- and intermediate-coloured TPV, dark-coloured TPV had comparable mean T_{s_max} to intermediate-coloured SBR, and light-coloured TPO were similar to light coloured EPDM.

4. Discussion

4.1. *Hazardously hot surface temperatures in public playgrounds*

Surface temperatures of sun-exposed playground equipment and floor materials measured *in situ* on warm and hot to very hot summer days in Sydney were frequently well above contact burn thresholds for skin [24], even with very short contact times of just a few seconds. The measured surface temperatures would be capable of inflicting serious skin burns to children, as demonstrated by numerous popular media reports about burns from playground equipment in areas in hot climates around the world [39,57–59]. In this study we focussed on maximum measured surface temperatures because they represent the 'worst case scenario' for a child who may touch a particular surface within a playground setting. Surface temperature and duration of contact with the skin affect the severity of skin burns, and this time-temperature relationship varies with material type according to its heat transfer properties. A burn injury occurs when the basal layer of the skin epidermis reaches 44 °C, and that damage caused in superficial burns increases

Table 1

Burn threshold temperatures (°C, as per ISO 13732-1:2006) and exceedances (grey shading) for different playground equipment and floor surface materials with three contact times at maximum and mean surface temperatures (T_s) measured *in situ*.

Contact time	Maximum T_s (°C)	Threshold temperature (°C)			Mean T_s (°C)	Threshold temperature (°C)		
		3 s	5 s	1 min		3 s	5 s	1 min
Equipment								
Rubber dolphin	86.2 ± 1.5	77	74	60	72.5 ± 11.9	77	74	60
Plastic slide	67.0 ± 1.5	77	74	60	56.0 ± 7.5	77	74	60
Plastic swing seat	73.8 ± 2.7	77	74	60	59.7 ± 10.0	77	74	60
Metal platform	70.1 ± 1.9	60	57	51	54.5 ± 7.6	60	57	51
Wood bench	72.8 ± 3.3	99	93	60	58.1 ± 8.9	99	93	60
Floor surfaces								
Black rubber	87.1 ± 1.5	77	74	60	72.6 ± 6.9	77	74	60
Dark-coloured rubber	84.1 ± 0.6	77	74	60	67.9 ± 12.4	77	74	60
Light-coloured rubber	76.1 ± 1.1	77	74	60	57.5 ± 11.2	77	74	60
Synthetic turf	87.1 ± 0.7	77	74	60	66.1 ± 10.8	77	74	60
Bark mulch	76.9 ± 3.1	99	93	60	58.3 ± 10.2	99	93	60
Natural dry turf[a]	66.3 ± 0.9	99	93	60	57.5 ± 9.9	99	93	60
Brick	64.3 ± 0.6	73	60	56	51.1 ± 8.3	73	60	56
Concrete	60.0 ± 0.6	73	60	56	47.4 ± 7.5	73	60	56
Natural green turf[a]	42.0 ± 0.7	99	93	60	35.8 ± 3.5	99	93	60

[a] Burn thresholds for natural turf are unknown, so values for the most similar material (wood) were used.

logarithmically with a linear rise in surface temperature [60]. According to ISO 13732-1:2006, contact burns from hot plastic will occur within 3 s at 77 °C, within 5 s at 74 °C, and within 1 min at 60 °C. Uncoated metal surfaces will produce burns within 3 s at 60 °C, within 5 s at 57 °C, and within 1 min at 51 °C. Using these values, many of the maximum temperatures we measured (as well as the average temperature for the rubber dolphin) would be sufficient to cause skin contact burns.

Time-temperature relationships for contact burns are complex [61–63]. However, they are dependent on the type of surface material under consideration as well as the sensitivity of the skin that comes into contact with it. Materials with higher thermal conductivity inflict burns over a shorter contact time and/or at a lower temperature. The commonly applied time-temperature relationships for contact burns as specified in ISO 13732-1:2006 were initially established for adults using data from scald burns (i.e., from hot water), and despite claims the values are "applicable to … healthy adults, children, elderly people", accurate time-temperature relationships have not been established for children [60]. Thus, applying the values given in the standard to a setting involving a child's skin should be done with extreme caution [60]. It is ubiquitously accepted that a child's skin will likely burn more quickly and to a greater depth than that of an adult [64,65], but data on children's skin burn injuries from hot surfaces is limited [66], and likely varies both from those of an adult and between children of different ages. Although contact burns (thermal burns from hot surfaces) and scalds (thermal burns from hot liquids) have differing pathophysiologies [67], data from scalds of children suggests it is probable that time-temperature thresholds for contact burns are significantly lower than those reported in the ISO standard [24].

Our real-world measurements of maximum surface temperatures for playground equipment and floor materials were higher than those reported for sun-exposed playgrounds in Arizona [36], Texas [68], and Budapest [69]. The two studies in the USA were conducted in areas that have hot summer climates similar to those in Sydney, so differences in surface temperatures are likely to be the result of higher levels of solar irradiance in our study, as is the case across much of Australia compared to many areas around the world [70].

In our *in-situ* study, natural green turf was the only floor surface that did not heat up to surface temperatures capable of inflicting burns when exposed to full sun, with maximum and average surface temperatures of 42.0 and 36.1 °C respectively. Similar results have been demonstrated elsewhere. For example, the maximum apparent surface temperature of turf grass in full sun during summer in Perth (Western Australia) was ~46 °C [71], and the average surface temperature of irrigated grass in the sun in Florence (Italy) reached 42 °C [72]. Similarly, on a sunny summer day in Hong Kong, China, natural turf had average and maximum surface temperatures of 36.6 and 41.0 °C respectively [73]. Other work shows that natural green turf is consistently cooler than other surface materials tested [74,75]. Importantly, grass can provide a significant surface cooling effect, reducing the boundary air temperature above the grass by consuming solar heat through evapotranspiration [76], especially when it is well irrigated [77]. Natural green turf is not commonly used under playground equipment because it does not have the impact-absorbing capacity needed to satisfy current standards and safely protect children from fall injuries, but it can be used around the 'fall zone' to help mitigate radiant heat from synthetic surfaces and provide a cooler surface for children and visitors to retreat to when they need to cool down.

4.2. *Systematic assessment of surface temperature*

The systematic assessment of common playground floor materials that we conducted over the course of two sunny days showed that maximum surface temperatures differed between material types in both the sun and shade conditions, but colour-tone was significant only when materials were exposed to direct sunlight. Synthetic turf and SBR heated up fastest and got the hottest, followed by EPDM and TPV. Each of these materials have different physical and chemical properties, and available data are generally derived from their use in applications other than playgrounds. Synthetic turf is commonly used in athletic and urban settings where it reaches very high surface temperatures (e.g., 72.4 °C [73], 75.0 °C [71], 73.0 °C [78]) when exposed to direct sunlight. Maximum surface temperature values for synthetic turf in our systematic assessment (74.3–84.5 °C) are higher than those reported elsewhere including in our *in-situ* measurements, possibly due to higher levels of solar radiation in our experiment, different heat transfer capacities from specific fibre material, length, variations in colour-tone, or installation methods. We note that some differences are expected because our samples were insulated from the ground rather than installed *in situ* as in work by Jim [73], they lacked infill material so are more akin to 'household' versions of synthetic turf than modern high-performance versions used in sporting [79], and sample tile sizes and preparation were different from those in work by Loveday et al. [71] and Doulos et al. [78]. However, the majority of reports agree that synthetic turf often reaches surface temperatures well above accepted contact burn thresholds.

Surface temperatures of EPDM have been investigated in just two studies where it was used as a roofing membrane. In New York, average and maximum summer surface temperatures of white EPDM roofing reached 39.7 and 53.1 °C compared with 63.3 and 76.5 °C for the black EPDM roof [80], and white EPDM and TPO roof membranes reached ~57 and 40 °C respectively [81]. Black and white TPO roof membranes in Queens (NY, USA) had average and maximum surface temperatures in the first summer after application were 51.0 and 64.0 °C (black), and

Table 2

Mean ($T_{\text{s mean}}$), absolute minimum ($T_{\text{s min}}$) and maximum ($T_{\text{s max}}$) surface temperatures of various playground materials and colour-tones measured in the sun (9 February 2022) and shade (10 February 2022) at the Outdoor Heatlab (Western Sydney University). The extracted mean values (27,225 radiometric pixels) were averaged (± standard deviation) for each sample tile across the 14 (shaded natural turf) or 17 time points (n = 381,150 - 462,825). The absolute minimum and maximum values were extracted (regardless of time) from data between 08:00 and 16:30 h. Note: ΔT refers to a difference between treatments (i.e., shade minus sun), where negative values indicate a cooling effect.

Material type	Tone	Colour	Abbreviation	$T_{\text{s mean}}$ (°C)		$\Delta T_{\text{s mean}}$ (°C)	$T_{\text{s min}}$ (°C)		$\Delta T_{\text{s min}}$ (°C)	$T_{\text{s max}}$ (°C)		$\Delta T_{\text{s max}}$ (°C)
				Sun	Shade		Sun	Shade		Sun	Shade	
ST (30 mm)	D	Green	$\text{ST}_{\text{mid-GR}}$	57.5 ± 14.4	32.2 ± 7.7	−25	20.2	15.5	−5	80.1	42.1	−38
ST (40 mm)	D	Green	$\text{ST}_{\text{lng-GR}}$	56.6 ± 13.6	32.5 ± 7.5	−24	20.3	15.4	−5	84.5	41.7	−43
ST (13 mm)[a]	D	Red	$\text{ST}_{\text{sht-R}}$	58.2 ± 14.5	31.9 ± 7.7	−26	21.0	16.0	−5	77.7	41.6	−36
ST (13 mm)	D	Green	$\text{ST}_{\text{sht-GR}}$	56.6 ± 14.3	32.6 ± 7.3	−24	18.0	14.9	−3	74.3	42.6	−32
EPDM	D	Green	$\text{EPDM}_{\text{D-GR-1}}$	49.0 ± 13.9	27.4 ± 7.3	−22	18.0	15.0	−3	66.6	37.7	−29
EPDM	D	Blue	$\text{EPDM}_{\text{D-BL}}$	50.1 ± 14.0	28.0 ± 7.6	−22	18.7	15.4	−3	67.0	38.2	−29
EPDM	L	Beige	$\text{EPDM}_{\text{L-BE}}$	38.6 ± 11.0	27.7 ± 6.8	−11	16.0	14.4	−2	53.7	35.8	−18
EPDM	D	Brown	$\text{EPDM}_{\text{D-BR}}$	57.0 ± 15.6	30.3 ± 8.7	−27	18.7	16.0	−3	74.5	41.1	−33
EPDM[a]	D	Green	$\text{EPDM}_{\text{D-GR-2}}$	57.1 ± 15.6	28.3 ± 7.9	−29	19.9	16.1	−4	77.8	39.6	−38
Natural turf	I	Green	Natural turf	33.2 ± 5.6	26.1 ± 4.4	−7	18.7	17.1	−2	55.1	34.0	−21
SBR	D	Green	$\text{SBR}_{\text{D-GR}}$	56.4 ± 15.4	28.6 ± 7.9	−28	18.6	14.7	−4	77.5	40.3	−37
SBR	D	Blue	$\text{SBR}_{\text{D-BL}}$	59.1 ± 16.2	29.2 ± 8.5	−30	19.0	14.0	−5	81.1	41.3	−40
SBR	I	Beige	$\text{SBR}_{\text{I-BE}}$	51.1 ± 13.8	29.8 ± 7.6	−21	18.6	14.7	−4	69.0	38.5	−31
SBR[a]	I	Orange	$\text{SBR}_{\text{I-O}}$	54.4 ± 14.3	31.2 ± 8.2	−23	18.8	15.1	−4	71.9	40.2	−32
TPO	I	Blue	$\text{TPO}_{\text{I-BL}}$	48.3 ± 13.6	28.1 ± 7.0	−20	17.8	15.2	−3	65.0	37.2	−28
TPO	L	White	$\text{TPO}_{\text{L-W}}$	35.9 ± 10.3	27.0 ± 7.4	−9	15.7	14.0	−2	48.7	35.7	−13
TPO[a]	I	Blue-green	$\text{TPO}_{\text{I-BL/GR}}$	47.1 ± 13.1	26.7 ± 7.3	−20	17.9	15.1	−3	63.2	37.4	−26
TPO	L	Green-white	$\text{TPO}_{\text{L-GR/W}}$	41.6 ± 11.7	26.0 ± 7.2	−16	16.6	14.5	−2	56.9	36.3	−21
TPO	L	Blue-white	$\text{TPO}_{\text{L-BL/W}}$	41.2 ± 11.5	26.2 ± 7.5	−15	16.4	14.3	−2	56.0	36.6	−19
TPO	I	Green	$\text{TPO}_{\text{I-GR}}$	47.7 ± 13.7	28.6 ± 6.9	−19	17.5	15.4	−2	64.6	40.5	−24
TPV	D	Green	$\text{TPV}_{\text{D-GR}}$	48.8 ± 14.3	27.7 ± 7.1	−21	17.0	14.6	−2	67.1	38.1	−29
TPV	D	Blue	$\text{TPV}_{\text{D-BL}}$	52.0 ± 15.3	28.4 ± 7.9	−24	18.2	14.7	−4	70.8	38.9	−32
TPV[a]	I	Blue	$\text{TPV}_{\text{I-BL-1}}$	50.3 ± 14.0	28.8 ± 6.8	−21	16.9	15.3	−2	66.7	39.1	−28
TPV[a]	I	Blue	$\text{TPV}_{\text{I-BL-2}}$	50.9 ± 14.9	29.6 ± 7.1	−21	17.8	15.4	−2	68.3	39.1	−29
TPV	L	Beige	$\text{TPV}_{\text{L-BE}}$	41.7 ± 12.0	28.2 ± 7.8	−14	16.4	14.3	−2	56.0	37.2	−19
TPV	L	Blue-white	$\text{TPV}_{\text{L-BL/W}}$	46.7 ± 13.0	28.0 ± 8.4	−19	17.4	14.6	−3	61.6	39.1	−23
TPV	D	Brown	$\text{TPV}_{\text{D-BR}}$	54.0 ± 15.2	30.2 ± 8.4	−24	18.9	15.2	−4	71.8	39.7	−32
TPV[a]	L	Grey	$\text{TPV}_{\text{L-GY}}$	50.3 ± 14.0	30.5 ± 7.5	−20	18.3	15.3	−3	67.1	38.7	−28
TPV[a]	I	Yellow	$\text{TPV}_{\text{I-Y}}$	43.6 ± 12.2	29.7 ± 6.9	−14	16.6	14.9	−2	58.6	36.9	−22

[a] Material not shown in Figs. 6 and 7 because surface temperature values were very similar to those of another sample shown.

39.4 and 53.1 °C (white). These results, although limited, agree with our finding that TPO has lower surface temperatures than EPDM, and that dark colour-tones are hotter than light ones. Vanos et al. [36] reported that sun-exposed dark rubber 'soft ground surface' in Arizona had a surface temperature of 87.2 °C during September, and Ford [46] reported various coloured 'rubber' surfaces having surface temperatures between 27 and 46 °C (80 and 116 °F), although these measurements were taken in the 'fall', so are unlikely to be representative of maximum surface temperatures that could be reached. Both these sources lack details of the exact material type used so cannot be used reliably for comparisons with our data. Extensive online searches revealed no reports of surface temperatures of sun-exposed SBR or TPV, so the results from our study are the first to show that these materials are hotter than EPDM and TPO (and almost as hot as synthetic turf), and certainly above current contact burn thresholds.

Results from a systematic assessment are not directly comparable with *in-situ* measurements for a number of reasons including that assessment samples are insulated from the ground, which alters the heat exchange process that would normally occur when materials are properly and fully installed. In our experiment, the use of tape around each sample tile prevented solar radiation from reaching the sides or heating the black rubber layer underneath the surface layer. Further, foam under the synthetic turf stopped samples from absorbing heat from the concrete underneath, although they may have normally been able to stay cooler by transferring heat to the ground, so measurements may be higher than they would have been *in situ*. Loveday et al. [71] investigated the effect of sample size and level of 'coupling' to the ground using 14 different materials in summer in Perth (WA, Australia), and found that investigations should use samples as large as possible and be positioned or installed as closely as possible to their real-world application. Maximum surface temperatures of synthetic turf surfaces from the systematic assessment ranged between 74.3 and 84.5 °C. These values are comparable to *in-situ* values reported elsewhere [71,73,78], suggesting that the sample tiles behaved in a similar way to fully installed synthetic turf in a real-word setting.

4.3. *The importance of shade*

Shade has long been recognised as a desirable feature in public parks [82], providing many benefits to park visitors. Trials investigating the use of artificial shade structures in public parks in Melbourne, Australia and Denver, USA, demonstrated that members of the public will use the shade where it is provided for sun protection, suggesting there is a practical application of an investment in improving shade infrastructure [83]. Overhead shading by sun sails and/or trees has been shown to effectively reduce physiological equivalent temperature (PET, a measure that expresses the effects of several micro-meteorological variables including mean radiant temperate (T_{mrt})) and improve thermal comfort in temperate climates [84]. For playgrounds, shade is essential in preventing overheating of floor materials and play equipment in a sunny environment [38,85].

Playgrounds in Sydney [45,86] and elsewhere in the world (e.g., New Zealand [87,88], United States [23]) lack adequate shading. Shade has been shown to lower surface temperatures of floor materials in school yards [89,90], and other urban environments [72,91,92], as well as in modelling studies [93,94]. Trees and other natural vegetation can form an integral part of a shade provision strategy [82], and will provide the additional benefit of further cooling of ambient air temperature through evapotranspiration. However, the quantity and quality of shade likely to result from different types of vegetation can vary markedly. Not all trees provide adequate protection from UV radiation [95,96], and many will not provide uniform cover within a play area. Alternatively,

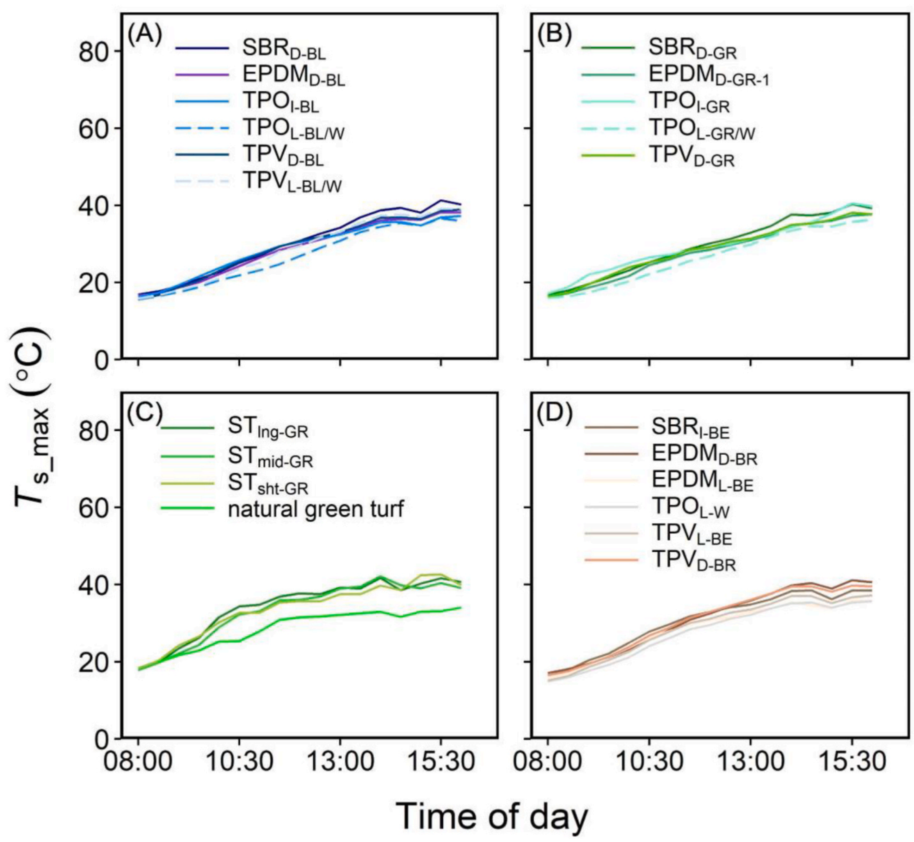

Fig. 7. [2-column fit]. Maximum surface temperatures (T_{s_max}) of a selection of playground materials and colours measured in the shade from 08:00 to 16:00 h on the 10 February 2022. Data are absolute maximum surface temperatures (one value of 27,225 pixels in thermographs taken from each sample tile and time point) for blue rubber types (A), green rubber types (B), synthetic and natural turf types (C), and earth- and light-coloured rubber types (D). Solid lines indicate plain-coloured materials, and dashed lines mixed-coloured (speckled) materials. For abbreviations see Table 2.

Table 3
Results of two- and three-way ANOVAs of treatment, material type and colour-tone and interactions for absolute maximum surface temperatures (T_{s_max}) of 28 common playground floor types. The analysis used five absolute maximum values ($n = 5$) for each sample tile at the plateau phase (12:00–14:00 h) when surface temperatures were not changing greatly. Abbreviations: df, degrees of freedom; SSq, sum of squares.

Source of Variation (three-way ANOVA)	df	SSq	F-test	*p*-value
Treatment	1	67332	5139.34	<0.001
Material type	4	2022	38.59	<0.001
Colour-tone	2	1144	43.67	<0.001
Treatment × Material type	4	250	4.76	<0.01
Treatment × Colour-tone	2	1340	51.13	<0.001
Source of variation (Two-way ANOVA)				
Treatment	1	67332	5776.34	<0.001
Material type with Colour-tone	9	6919	65.95	<0.001
Treatment × Material type with Colour-tone	9	3219	30.69	<0.001

shade can be provided by structures such as shade sails or canopies. Built shade structures have the benefits of providing immediate protection, being customisable for location, size, appearance, and materials, giving rise to the potential to engineer highly adaptable solutions for different settings and purposes. In Australia, however, many shade structures fail to provide effective protection against UV radiation across the entire play area, and the design and construction of shade sail or similar structures for playgrounds is noted as requiring 'considerable technical expertise' [97]. General guidance for the provision of shade in relation to UV protection exists in most states in Australia, but information regarding the quality or quantity of shade regarding its ability to reduce surface temperatures in public parks and playgrounds is non-existent.

4.4. *Bioclimatic design implications*

The combination of real-world *in-situ* measurements and surface temperature analyses from the systematic assessment at the Outdoor Heatlab provides designers and managers of playgrounds with a novel resource to help make informed decisions that can lead to more heat-responsive, safer play spaces for children. The high WBGT data recorded during a regular sunny summer day, indicated that based on the recommendations for the American Academy of Pediatrics [98], outdoor play in the sun was only safe until around 10:00 h in the morning. From thereon, high physical activity of children should be limited and, in the afternoon, stopped completely. These data underline the importance of improving microclimatic conditions in playgrounds to widen the time window when active play is safe in a warmer future and must be seen in the context of climate-change related increases of summer heat in Australia [99–101] as well as in other hot climates around the world. The importance is magnified when considering the increased vulnerability of children to the health effects of climate change [102].

To maximise the time available for families to take children to outdoor playgrounds and to minimise the environmental risks during outdoor play under climate change conditions, planning authorities and others responsible for the construction and maintenance of public playgrounds should take their duty of care very seriously. In the Australian early childhood education and care sector too arise serious risks for owners of playgrounds. Failure to protect children from environmental hazards such as those presented by overheated playground equipment or surfaces can lead to enforcement actions from regulatory authorities [103,104]. Although such consequences are not currently applicable in public settings, local governments and councils should give due respect to their duty of care in recognising their role in providing appropriate urban planning, which plays an essential role in the health of communities [105].

4.5. Recommendations and application

From the work completed here, two important recommendations for industry and government organisations are put forward. According to their importance these are:

1. Provide shade over the entire play area with consideration given to changes in daily and seasonal sun angles to ensure adequate cover when needed. Carefully planned and appropriate shade will reduce surface temperatures and associated risk for contact burns. Shade will also have the additional benefit of reducing the risk of overexposure to harmful UV radiation. Immediate shade can be provided by engineered shade structures. Shade provided by trees should be the preference for a long-term cooling strategy where dense, wide canopies provide additional evapotranspirative air cooling. A combination of short- and long-term strategies should be adopted where shade is currently absent. Consideration should also be given to providing shade over areas near the playground area from where parents and caretakers observe safe play.
2. Choose floor surface materials to minimise heat absorption and radiation to reduce surface temperatures. When shade is provided, surface temperatures vary only marginally between material types and colour-tones. However, if no shade is provided and materials are exposed to sunlight, light-coloured surfaces are better than dark-coloured ones for reducing surface temperatures. Materials for areas where an impact-absorbing surface is needed (i.e., under a 'fall zone') should be given preference in the general order: TPO > TPV/EPDM > SBR. Based on our data from Sydney, we deduct that unshaded synthetic turf is not a safe material to use in playgrounds in hot climates.

The concepts described above have been implemented in the creation of Australia's first 'UV-Smart Cool Playground', where introduction of a high-quality shade structure and light-coloured TPO floor surfaces resulted in surface cooling effects of more than 45 °C [106]. In a similar study in Wuhan (China), a playground renovation that included addition of shading shelters and vegetation to decrease heat stress attracted 80% more occupants in summer months, where visitors stayed longer and reported lower levels of thermal discomfort [107].

5. Conclusions

Children have the need [108] and right [109] to play outside to experience healthy physical and emotional development but playing at outdoor playgrounds can result in serious skin burns if equipment and floor materials get too hot. Surface temperatures of common playground equipment and floor materials in the sun in Sydney were often hot enough to result in skin burns upon contact on days when the ambient air temperature was not extremely hot, and they would likely have been encouraged to get outside and play. Shading floor materials largely eliminated the difference between different material types and colour-tones of the man-made materials tested and reduced maximum surface temperatures below the burn threshold. These findings can be used by anyone responsible for designing, constructing, or maintaining playgrounds as they show the importance of shading in reducing environmental risks from contact burn hazards while at the same time reduce the risk of overexposure to harmful UV radiation. Application of this simple design principle could protect children from serious skin burns and allow them to maximise the time available for safe play outside in urban environments.

CRediT authorship contribution statement

Sebastian Pfautsch: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Agnieszka Wujeska-Klause:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Judi Walters:** Writing – review & editing, Writing – original draft.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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