Advancing Methods to Monitor and Assess Personal Ultraviolet Radiation Exposure During Physical Activity

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved July 2021 by the
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ARIZONA STATE UNIVERSITY

December 2021

ABSTRACT

Ultraviolet (UV) radiation is the most well-known cause of skin cancer, and skin cancer is the most common type of cancer in the United States. People are exposed to UV rays when they engage in outdoor activities, particularly exercise, which is an important health behavior. Thus, researchers and the general public have shown increasing interest in measuring UV exposures during outdoor physical activity using wearable sensors. However, minimal research exists at the intersection of UV sensors, personal exposure, adaptive behavior due to exposures, and risk of skin damage. Three studies are presented in this dissertation: (1) a state-of-the-art review that synthesizes the current academic and grey literature surrounding personal UV sensing technologies; (2) the first study to investigate the effects of specific physical activity types, skin type, and solar angle on personal exposure in different outdoor environmental contexts; and (3) a study that develops recommendations for future UV-sensing wearables based on follow-up interviews with participants from the second study, who used a wrist-worn UV sensor while exercising outdoors. The first study provides recommendations for 13 commercially available sensors that are most suitable for various types of research or personal use. The review findings will help guide researchers in future studies assessing UV exposure with wearables during physical activity. The second study outlines the development of predictive models for individual-level UV exposure, which are also provided. These models recommend the inclusion of sky view factor, solar angle, activity type, urban environment type, and the directions traveled during physical activity. Finally, based on user feedback, the third study recommends that future UV-sensing wearables should be multi-functional watches where users can toggle between showing their UV exposure results in cumulative and countdown formats, which is intuitive and aesthetically pleasing to users.

ACKNOWLEDGMENTS

I would like to thank my two co-advisors, my dissertation committee, and my family for their support and advising. I would also like to thank Dr. Ariane Middel for advising and assisting on sky view factor research methodologies and providing a sky view factor map of the ASU Tempe campus so I could choose an urban canyon-like location for my research. Additionally, I would like to thank the following co-authors of the papers that serve as dissertation chapters:

Ch.1: Dr. Jennifer Vanos and Dr. Nathan Downs
Ch.2: Dr. Jennifer Vanos, Dr. Nathan Downs, and Catherine Hudson

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CHAPTER 1
INTRODUCTION

The research projects that are presented in this dissertation focus on measuring personal ultraviolet (UV) radiation exposure with wearable dosimeters, with Chapters 2 and 3 focused on adult research volunteers exercising outdoors in different urban environments. The purpose of these research projects was to provide insight on the magnitude of UV exposure while performing common outdoor activities in the areas that we live and work in. Excessive UV exposure has been linked to skin cancer; thus, measuring UV exposure during outdoor activities over a specific amount of time in designated urban environments provides the research community and the public with information concerning acceptable levels of UV exposure for people of different skin types.

Those who will benefit from this research include skin cancer survivors, who need to track their personal UV exposure for critical health reasons with guidance from their doctors; urban planners, who will benefit from understanding how natural and artificial shade sources can be used to reduce excessive UV exposure; wearable device developers, who may be interested in including UV measurement in future devices; and the general public, who may like to have resources about what an advisable level of UV exposure would be during their outdoor activities and about how to avoid excessive UV exposure.

Prior studies placed UV sensors on manikins, asked human subjects to do specified activities under direct sunlight, and used mathematical and computational models to estimate personal UV exposure. The studies within this dissertation are the first to measure personal UV exposure in areas with different levels of shade and with different shade sources, such as leafy trees and tall buildings.

This dissertation is comprised of three studies. The first study (Chapter 2) is a state-of-the-art review of commercially available UV sensors and their potential usefulness for personal and behavioral or clinical research use. For the second study (Chapter 3), 14 subjects volunteered to wear a wrist UV dosimeter and a global positioning system (GPS) sport watch for measuring their personal UV exposure in urban areas with different levels of shade, such as an unshaded bike path and a neighborhood with trees. The goal of the third study (Chapter 4) was to determine how adults would like to see personal UV exposure information displayed on a small wearable or mobile phone screen. It employed qualitative methods, such as interviews and thematic analysis, to follow up with 12 of the 14 subjects from Chapter 3 regarding how they would prefer to see their personalized UV exposure data depicted in different types of graphs and about whether knowing information about their UV exposure might help them adjust their outdoor exercise behaviors to reduce their exposure. Finally, a conclusion is provided to tie these chapters findings and implications together.

CHAPTER 2
WEARABLE ULTRAVIOLET RADIATION SENSORS FOR RESEARCH AND PERSONAL USE

2.1 INTRODUCTION

2.1.1 Sun Exposure and Health

Skin cancers are the most common type of cancer in the United States (Centers for Disease Control and Prevention, 2019) (American Cancer Society, 2021), with ultraviolet radiation (UVR) the leading and most preventable risk factor (U.S. Department of Health and Human Services, 2014). In 2020, approximately 100,350 cases of melanoma will be diagnosed; 6,850 of those people will die (National Cancer Institute, 2020). From 2007–2011, approximately five million people in the United States received treatments at a total cost of eight billion dollars (Guy et al., 2015). Additionally, melanoma—the most serious type of skin cancer—is the sixth most diagnosed cancer in the United States, ranked fifth for men and sixth for women in 2018 (U.S. Department of Health and Human Services, 2018).

Outdoor physical activity (PA) increases the risk of sunburn, melanoma, and non-melanoma skin cancers (Lee et al., 2012; Physical Activity Guidelines Advisory Committee, 2008). For example, a meta-analysis of 1.4 million adults from the U.S. and Europe showed that leisure-time PA is associated with a 27% increased risk of malignant melanoma (Moore et al., 2016). To help prevent overexposure to UV radiation, it is recommended that people wear wide-brimmed hats, wear long sleeves or pants, stay in the shade or indoors at midday (~10am–2pm), and wear sunscreen. However, remaining indoors or covering up too often can lead to vitamin D deficiency (Webb & Engelsen, 2006). For example, although the southwest region of the United States has primarily clear skies with sparse tree cover, residents lack vitamin D synthesis because they tend to stay inside to protect themselves from the desert heat (Jacobs et al., 2008). Vitamin D deficiency has also been observed in Australia even though the country is generally known for its sunny climate. Finally, over- or underexposure to UVR differs by person, as the thresholds for skin damage depend on skin type and genetics; thus, blanket recommendations cannot be made (D'Orazio et al., 2013).

Due to concerns about personal UV exposure and skin cancer, wearable UV sensors are being developed for sun-conscious consumers wanting to monitor their exposure and/or strike a balance between "too much" or "too little" sun. Some of these wearable sensors are part of the same industry that has emerged for smartwatches, fitness trackers, and running watches that work in tandem with smartphones, tablets, and computers (Henriksen et al., 2018; Rawassizadeh et al., 2015). These devices have become commonly used in research in addition to consumer use.

2.1.2 UVR Wearables: Past and Present Use

Interest in monitoring personal UV exposure originated in the 1970s with concerns about the thinning ozone layer and how this phenomenon would affect the amount of UVR reaching the Earth's surface (Challoner et al., 1976; Diffey, 2020). Wearable polysulfone films were the first methods used to monitor personal UV dose (hence "dosimeter"). Polysulfone darkens when exposed to UV radiation and is responsive to 254–335 nm wavelengths (Davis et al., 1976; Diffey, 2020). Polysulfone film dosimeters are still commonly used today. Other polymers suitable for film dosimetry have also been employed to monitor personal UV exposure and include phenothiazine (Diffey & Davis 1978), polyphenylene oxide (Schouten et al. 2010), and polyvinyl chloride (Amar & Parisi 2013). Studies that employ polymer dosimeters mount small sections of film to metal and cardboard holders to be worn like lapel pins on tops and jackets. These small, wearable pins made the measurement of whole-body UV doses easier compared to the previous method of placing larger devices on the subject's torso that used photographic film (Diffey, 2020).

VioSpor, a *B. subtilis* biofilm-based sensor made of polyester sheets with bacterial spores (Moehrle et al., 2000), is another early UV wearable technology that uses UV-induced DNA alterations in *B. subtilis* spores to determine personal UV dosage (Quintern et al., 1996). For example, *VioSpor* was first tested at the top of an observatory in Osaka, Japan in the 1990s and used in subsequent field studies of personal UV exposure (Quintern et al., 1996). It was also tested on human subjects during a day trip at a beach in Denmark and over two-week holidays (Thieden et al., 2000). Numerous other studies have used *VioSpor* films since (Andersen et al., 2013; Giménez et al., 2015; Gurrea Ysasi et al., 2014; Moehrle, 2001; Serrano et al., 2010, 2011). These film-based dosimeters, while still used, are unable to report personal UV exposure without using laboratory equipment. They are therefore not user-friendly for the general public or suitable for use outside of research studies.

The health-technology-sensor revolution and need to reliably measure personal UV exposure has resulted in the gradual replacement of polysulfone and spore films by a wide variety of new sensing technologies with diverse form factors, including temporary tattoos, paper-based photochromic indicators, and electronic dosimeters (e.g., wrist-worn). This movement is filling a need for novel, reliable, and accurate sensing technologies for addressing research gaps that align UV exposure with behavior (e.g., such as PA and sun-protective behaviors) and to allow researchers to confirm associations between PA and skin cancer risk fully. Further, recent years have also seen an influx of new consumer-based UV sensing technologies with wide-ranging form factors and purposes. However, to measure the UV exposure accurately, sensors must be designed to be responsive to wavelengths that affect skin (erythema) health within the erythema spectrum (which is weighted from 280nm to 400nm, or UVB to UVA).

The overall goal of this state-of-the-art review is to synthesize the current academic and grey literature surrounding personal UV sensing technologies, specifically concerning the availability, uses, and potential of UV-sensing wearables. We systematically compare the technical specifications of various commercial- and research-based UV sensors relating to their stated applications and provide recommendations for appropriate personal use and research contexts. The synthesis of available information provides an overview of current wearables, helps researchers choose the best sensors for their specific research studies, and delineates between research-grade and consumer-grade wearables. Thus, this work may help researchers involved in personal UV exposure studies choose sensors appropriate for the given application and sampling needs. Finally, we highlight particular aspects of currently available personal UV sensors that may influence and motivate future sensor development and research studies, such as data display for behavioral change, Bluetooth connectivity, programming of sensors, and specific application. These considerations may lead to advanced user applications for safe behavior in the sun and skin cancer prevention.

2.2 METHODS

As a state-of-the-art review, this paper narrows its focus on UV sensing wearables that are available for purchase as of March 2021. A state-of-the-art review addresses current matters and approaches and offers new perspectives and applications on issues for further research (Grant and Booth, 2009). This review describes the form factors and sensing technologies that UV wearables are currently using, discusses how these design choices influence their UV sensing functions, and finally recommends which wearables are optimal for use in different types of research studies.

To identify commercial and research UV sensors from both academic and grey literature, online searches were conducted on search engines and within academic databases (e.g., PubMed, Google Scholar, Science Direct, and Web of Science). The following search terms were used: portable, mobile, or wearable UV exposure sensor; wearable UV exposure monitoring; and wearable UV dosimeter. Because many of the available sensors' information is not available from peer-reviewed literature, further informational sources were included in this review to obtain sensor-specific information (e.g., technical specifications, use, cost). These additional sources include commercial websites and gray literature such as government reports, technical reports, working papers, white papers, theses, and dissertations. The literature search was ended in Spring 2021.

Results were narrowed to include only available wearables that track UV exposure on a person (i.e., mobile) over time—electronic dosimeters and photochromic dosimeters such as clips, stickers, bands, and jewelry. Handheld devices (e.g., general UVI readers) and non-wearable devices (stationary UVI instruments) in general were not included. Wearable UV sensors that are no longer produced are included in the discussion section but are not included in the sensor comparison tables.

Commercial sensor websites were analyzed by investigating the product page and other relevant pages that discussed how the sensor works and—if needed—how its mobile smartphone application compliments the sensor. Sensors that rely on a companion smartphone app were distinguished from those that do not. If the company also provided a white paper or peer-reviewed publication about its wearable UV sensor product, these publications were also included.

2.3 RESULTS

2.3.1 Overview

Thirteen wearable UV sensors are available for personal use and/or research applications. Figure 1.1 displays photos of the selected sensors. Attributes, form factors, cost, and further characteristics are listed in Tables 2.1–2.2, while classifications for appropriate use/targeted audiences are provided in Figure 2.2. Overall, four sensors report personal UV doses electronically without the need for laboratory analysis, five give a photochromic output, and three have outputs that must be analyzed in a laboratory. The cost per wearable ranges from $1 to $4 for color-changing (photochromic) disposable sensors and from $59.99 to $499.00 for electronic (Table 2.1). The electronic wearables that do not require laboratory analysis include two clips (*My Skin Track UV* and *QSun Wearable Sun Tracker* (“*QSun*” herein)) and two wristbands (*Eclipse Rx* and *Shade*). The color-changing wearables include two wristbands and three stickers that interact with UV rays and sunscreen to notify the wearer when they need to reapply sunscreen or step out of the sun (LogicInk, 2021; SmartSun, 2021b, 2021a; Sunburn Alert, 2021; Suncayr, 2021). The *Scienterra* electronic dosimeter (Version 2), polysulfone dosimeters, and *VioSpor B. subtilis* spore-based sensors require specific software, hardware, and/or spectrophotometry equipment to interpret their UV outputs, and thus are more suitable for research purposes rather than consumer use.

Finally, many of the sensors importantly account for user skin type in their outputs, which is an essential factor in determining how skin (erythema) may be damaged. There are six different skin types ranging from Type I (i.e., people who generally have red hair, pale skin, freckles, and sunburn easily) to Type VI—those who have very dark skin and do not sunburn (Fitzpatrick, 1988). Skin cancer is most prevalent in skin types I and II (Fitzpatrick, 1988); hence, the photochromic wearables (Section 3.3) use lower sunburn thresholds to protect those most at risk. Current factors and approaches affecting wearable use across electronic, photochromic, and polymer-based UV wearables, and their common uses, are provided in detail below.

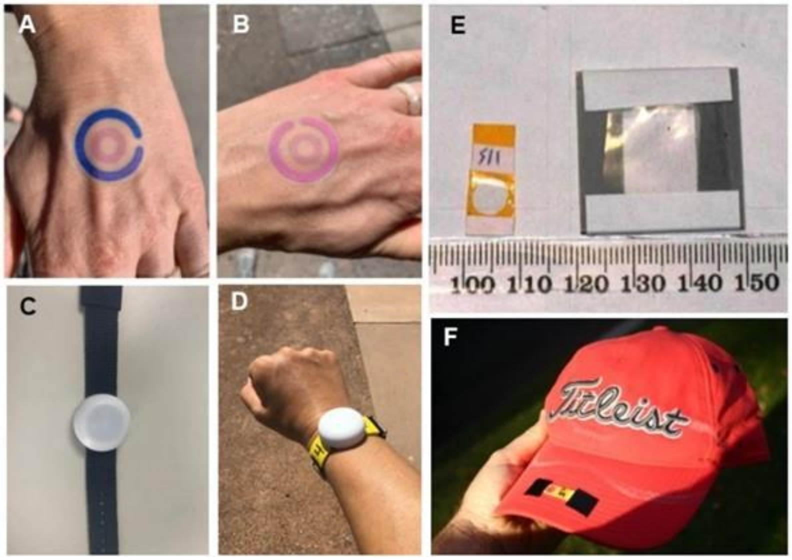


Figure 2.1: Images of UV-sensing wearables. (A, B) *LogicInk*; (C, D) *Scienterra* dosimeter; (E, F) polysulfone badges. Images are from research use by the authorship team.

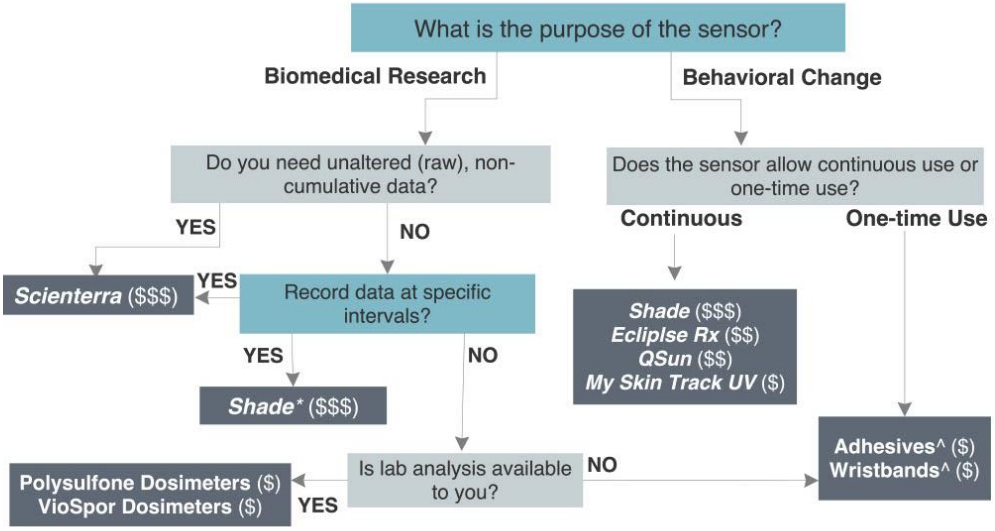


Figure 2.2: Flowchart for determining which wearables to use for physical or behavioral research studies or for personal use. ($) low, ($$) medium, or ($$$) high cost (see Table 2.1). ^ often waterproof or water resistant. * = Shade requires the use of its research-focused application, *Shade Meter*, to see the data.

2.3.2 Electronic UV Wearables

Electronic wearables—often called “dosimeters”—consist of a photodiode detector, which generates a digital signal to represent an irradiance (Nagelhout et al., 2020). Dosimeters vary considerably in how they communicate personal UV exposure to the user. These dosimeters generally detect UVA (~320–400nm) or UVB (~280–320nm) radiation, which is often translated into the UV index (UVI). The UVI represents an internationally recognized weighted erythemal UV irradiance (UV_{Ery}) of UVA and UVB. Electronic dosimeters with real-time outputs on the sensor screen itself or an integrated phone app (all but the *Scienterra* dosimeter)—see section 3.1.1—may display personal UV dose in terms of percentage of total or daily exposure, or they indicate how much time is left until a sunburn might occur (Table 2.1). These outputs provided by the general consumer-based products listed in Tables 2.1 & 2.2 also do not allow for user programming. However, the *Scienterra* dosimeter, a research-focused sensor, measures UV radiation at user-programmed intervals (from 1 sec–18 hr). These sensors have various uses—for example, validating personal UV diaries (Køster et al., 2015, 2016) or monitoring child sun exposure during play (Vanos et al., 2017). The Shade sensor informs the user about the six Fitzpatrick skin types after the user signs up. The user can then adjust their desired daily UV threshold limit at any time (Dumont & Kaplan, 2021; Scienterra Ltd, 2015; Shade, 2021b).

Three other electronic wearables—*Eclipse Rx*, *My Skin Track UV*, and *QSun*—emphasize skin care in addition to UV exposure. To calculate personalized UV exposure and link to skin care, these wearables require a user survey that is presumably based on Fitzpatrick skin types (Fitzpatrick, 1988). Additionally, *Eclipse Rx* and *QSun* ask about the type of sunscreen that the user is wearing, if any, and *QSun* probes the user about the clothing they are wearing, which is used to calculate how much sunscreen is needed. *My Skin Track UV*, which is sold by the La Roche Posay skincare company through the Apple Store, does not calculate sunscreen reapplication time, but it uses UVI, pollen, and humidity data to recommend its sunscreen products and other skincare products to the user (Apple, 2021b).

Instead of reporting an exact dose estimate, all but one of the electronic wearables (the *Scienterra* dosimeter) use proprietary algorithms that calculate a sunburn threshold based on the user-provided and environmental inputs. Only the *Scienterra* dosimeter reports an exact dose via ADC counts that can be converted to a UV irradiance in absolute units (e.g., Wm^{-2}); the rest of the electronic dosimeters report UV exposure in arbitrary units. For example, *Eclipse Rx* reports total daily exposure, and *Shade*—based on user input for how much UV they want to receive—recommends a personalized daily exposure in "UV units". The user is presented with questions that determine their skin type and information about UV exposures for different skin types; then the user can choose to stay within the recommended maximum UV dose or change the dose level (Dumont & Kaplan, 2021).

Table 2.1: UV Exposure output and sunscreen tracking capabilities of UV wearables. Derivation of categories for electronic, consumer/public, and research & education are shown in Figure 2.2.

Wearable	**UV Exposure Output & Alerts**	**Precision**	**UV Measured**	**Measurement Interval**	**Calibration**	**Accounts for Sunscreen**	**Cost ($US)**	**Main Source**
Electronic Consumer-based for Public Use								
Eclipse Rx	% Total Exposure, Real-Time UVI; LED & vibration alerts	0.1 UVI	UVA, UVB, UVI	User-Initiated	NA#	Yes	$299	User manual & website (Eclipse Rx, 2021)
My Skin Track UV	% Sunstock	1 UVI	UVA, UVB	User-Initiated	NA#	No	$59.99	Apple Store product page (Apple, 2021b)
QSun	Time to Sunburn, Local Estimated UVI, LED &vibration alerts	1 UVI	UVA, UVB, UVI	User Initiated	NA#	Yes	$222.99*	User manual & website (QSun, 2021)
Electronic: Physical or Clinical Research & Education Use								

Scienterra Dosimeter V2	Voltage converted to ADC	12-bit	UVA, UVB, or UV_{Ery}	Programmable; 1sec–18 hr	Send to company for calibration equations	No	$300^	User manual & website (Scienterra Ltd, 2015)
Consumer-based plus Physical or Clinical Research & Education Use								
Shade	UV Units, % Daily Limit, Real-Time UVI	0.001 "UVI Units"	UV_{Ery}	User-Initiated	NA# Output can be "calibrated" by predefined user survey	No	$499	Website (Shade, 2021b)
Color-based Non-Electronic Consumer-based for Public Use & Behavioral Research								
LogicInk Sun Signals	Dye-Based Color	NA	Unknown	Activity Duration	NA	Yes	$4	Website (LogicInk, 2021)
SPOTMYUV	Dye-Based Color	NA	UVA, UVB	12 hours or 6 sunscreen applications		Yes	$1	Website (Suncayr, 2021)
Smartsun UV Stickers	Dye-Based Color	NA	UVA, UVB	Activity Duration		Yes	Unknown	Website (SmartSun, 2021a)
Smartsun UV Wristbands	Dye-Based Color	NA	UVA, UVB	Activity Duration		Yes	Unknown	Website (SmartSun, 2021b)
Sunburn Alert UV Stickers	Dye-Based Color	NA	UVA, UVB	Activity Duration		Yes	$0.80	Website (Sunburn Alert, 2021)

Sunburn Alert UV Wristbands	Dye-Based Color	NA	UVA, UVB	Activity Duration		Yes	$0.64	Website (Sunburn Alert, 2021)
				Film-Based for Physical or Clinical Research				
Polysulfone Dosimeters	Polymer-Based	Instrument-based	UVB	Activity Duration	Calibration curve	No	$0.5	(Davis et al., 1976; Diffey, 2020; N. Downs, 2021; Thieden et al., 2000)
VioSpor Dosimeters	Polymer-Based	Instrument-based	UVA, UVB, UVC	Activity Duration	Send to company for processing, calibration curve	No	$48	Website (BioSense, 2021)

**Cost includes one wearable and the professional version of its phone application. ADC = analog to digital converter. ^ Requires purchase of one docking cradle ($300) for data transfer and sensor programming; UV*$_{Ery}$*: Erythemal weighted UV (280–400nm).* [#]*These sensors would be calibrated beforehand by the company, yet there is no information provided as the needs or ability to obtain ongoing calibrations. However, many of these electronic sensors ask for skin-type related information to do a 'personal calibration' for time to skin damage.*

Table 2.2: Additional uses and phone application dependency of UV wearables.

Wearable	**Additional Outputs**	**Skin Type Included**	**Waterproof or Resistant**	**Form Factor**	**Power Source(s)**	**Smartphone Application & Connectivity**	**Application Dependency**
Electronic Consumer-based for Public Use							
Eclipse Rx	Sunscreen reminder, step count	Yes	Resistant	Wristband	Solar; Wired Charger	iOS; BLE	Yes
My Skin Track UV	Pollen level, humidity, air quality, skincare recommendations	Yes	Waterproof	Clip	Battery-Free	iOS, Android; NFC	Yes
QSun	Vitamin D (pro), physical activity (pro), sunscreen reminder, sunscreen quantity, skin analyzer, weather	Yes	Resistant	Clip	Coin-Cell Battery	iOS, Android*; BLE	No
Electronic: Physical or Clinical Research & Education Use							
Scienterra Dosimeter V2	None	No	No	Wristband	Coin-Cell Battery	NA	NA
Consumer-based plus Physical or Clinical Research & Education Use							
Shade	None	Yes	Waterproof	Wristband	Wireless Charger	iOS, Android*	Yes
Color-based Non-Electronic Consumer-based for Public Use & Behavioral Research							

LogicInk Sun Signals	Sunscreen indicator	No	Waterproof	Adhesive	NA	NA	NA
SPOTMYUV	Sunscreen indicator	No	Waterproof	Adhesive	NA	NA	NA
Smartsun UV Stickers	Sunscreen indicator	No	Resistant	Adhesive	NA	NA	NA
Smartsun UV Wristbands	Sunscreen indicator	No	Resistant	Wristband	NA	NA	NA
Sunburn Alert UV Stickers	Sunscreen indicator	No	Waterproof	Adhesive	NA	NA	NA
Sunburn Alert UV Wristbands	Sunscreen indicator	No	Waterproof	Wristband	NA	NA	NA
Film-Based for Physical or Clinical Research							
Polysulfone Dosimeters	NA	No	No	Clip	NA	NA	NA
VioSpor Dosimeters	NA	No	No	Wristband	NA	NA	NA

**Sensor works with more than one phone application; BLE: Bluetooth Low-Energy; NFC: Near-field Communication*

My Skin Track UV reports the percentage of “max sunstock”, which is the maximum amount of UV rays the skin can be exposed to—accounting for skin type—before potentially sunburning (QSun, 2021). *QSun* outputs the time that the user has left before they sunburn, which contrasts with how the other electronic wearables report cumulative UV exposure (QSun, 2021).

According to user manuals, product websites, and mobile phone application descriptions, the precision and range of outputs of the electronic wearables vary, and the wearables often report the user’s UV exposure based on the location of the sensor (e.g., wrist) and the local UV index (UVI). Importantly, such outputs to users can cause confusion, as the UVI is based on the amount of horizontal erythemally-weighted UV, yet sensors can have various orientations and may not weight the wavelengths (McKinlay & Diffey, 1987). Only the Scienterra and Shade electronic sensors measure erythemally-weighted UV (UV_{Ery}), yet both would not always be oriented horizontally depending on the body location. These outputs range from 0.001–60 “UVI Units” for the *Shade* sensor and 0–11 UVI for *My Skin Track UV* and *QSun* (accuracy ±0.5 UVI). Because the percentage outputs, such as daily % exposure or % Sunstock, use proprietary algorithms, their exact accuracy and precision are unknown. The *Scienterra* dosimeter has a higher 12-bit resolution (1 in 4095) and ≤5% accuracy (Scienterra Ltd, 2015). A previous study discussed the importance of clear, understandable UV exposure feedback to users, where units such as UVI can be difficult to interpret because UVI indicates the potential for harmful exposure, but it does not directly state the amount of UV exposure that a subject has received, especially if the subject’s skin type is also accounted for (Schmalwieser et al., 2021). Using skin type, the *QSun*, *Eclipse Rx*, *Shade*, and *My Skin Track UV* sensors output UVI as well as another type of personal exposure output, such as % exposure or % Sunstock.

The *Scienterra* dosimeter indicates through its user manual and product webpage that it requires calibration (Scienceterra Ltd 2015), which it offers with product purchases as well as for a fee in subsequent years. There is minimal to no information for the remaining electronic UV sensors regarding the accuracy and precision of the UV measurements. The *Shade* sensor asks its user to self-input maximum daily UV exposure limits, and the *Shade, QSun*, and *Eclipse Rx* sensors give the user quizzes to determine their skin type, but these sensors do not describe a calibration process in their documentation to the same extent as *Scienterra*.

Non-electronic sensors can also be calibrated. Polysulfone badges are calibrated by creating a calibration curve and measuring the change in absorbance at 330 nm (Challoner et al., 1976; Davis et al., 1976). *VioSpor* dosimeters are calibrated by the company, which also creates calibration curves. Post-exposure, the films are grown in a *B. subtilus* growth medium and stained to quantify the number of *B. subtilus* spores (BioSense, 2021).

2.3.3 Smartphone Applications & Real-time Data Display for Electronic UV Sensors

The Shade sensor, *Eclipse Rx*, *QSun*, and *My Skin Track UV* require the user to download a smartphone application to receive any real-time information and to help interpret their results (Table 2.2). *My Skin Track UV* is also dependent on the user's phone to function via near-field communication (NFC) and is entirely dependent on its smartphone app to gather and display to the user, and data are not continuously tracked or stored. The *My Skin Track UV* NFC and wireless dosimetry technology are described in a previous study (Heo et al., 2018). The others function independently (with additional features outlined below) and connect with the phone via Bluetooth (BLE). However, only the *Scienterra* and *Shade* dosimeters provide continuous data and a way for users to download said data.

Select electronic dosimeters offer real-time measurement and alerting capabilities (*Eclipse Rx, Shade,* and *QSun*), while others require data download afterward (*Scienterra*). For example, *Eclipse Rx* shows real-time percentage of total recommended UV exposure on the companion smartphone app alerting the user of 25, 50, 75, and 100% of their "Daily Exposure Reached" on the app screen and also with vibration and LED warning lights. Similarly, the *QSun* has five LED lights and vibration to indicate the UVI to the wearer, with 1 LED indicating a low level from 0–2 UVI and 5 LEDs indicating an extreme level of 11+ (QSun, 2021), with real-time UVI viewing also provided on the companion App. The light indicators alert the user when they have reached the point of potential sunburn; the vibrations and flashing continue every minute for up to five minutes after the threshold is reached (QSun, 2021).

Finally, the *Shade* sensor also requires a companion smartphone application to view the real-time "UVI Units." The Shade sensor has three phone applications on Android or iOS: *Shade, Shade Meter,* and *Shade Orbit*. The first ("*Shade*") is intended for personal/public use, and two are for clinical research studies. The primary *Shade* application (“*Shade*”) is intended for personal use and tells the user their personal UV exposure data in UV Units. After downloading the application, the user will see an explanation of the Fitzpatrick skin type scale and will be shown daily recommended UV dose thresholds for each skin type. The user can then choose a UV threshold and adjust it up or down as desired (Dumont & Kaplan, 2021). If multiple devices are used for multiple human subjects in a research study, the devices can all be seen on a web-based dashboard because the *Shade* phone applications collect real-time data. (Dumont & Kaplan, 2021). For research purposes, “*Shade Meter*” is a phone application that displays real-time UVI, UVA, and UVB readings, yet it does not save and record the data. *Shade Meter* can also be used to program the sensor to collect data at specific time intervals. The user is shown UV data in 1 hr intervals and in daily exposure histories, and researchers can break down the data further into intervals as small as 10 seconds (Dumont & Kaplan, 2021). “*Shade Orbit*” is the second application meant for researchers, where *Shade* users are not shown their UV exposure data. *Shade Orbit* is therefore intended for clinical studies.

QSun and *Eclipse Rx* are the only electronic wearables designed for personal use that do not depend on a phone application to communicate UV overexposure (yet the apps display other real-time outputs; see Table 2.2). Both wearables use an LED display; *QSun* indicates the local UVI with five levels of vibrations and flashing white lights to tell the user that they are at risk of becoming sunburned (QSun, 2021). *Eclipse Rx* also uses LEDs and vibrations, but the LEDs are red, and there are four stages of LED and vibration alerts from 25% to 100% of recommended daily UV exposure (Eclipse Rx, 2021). The *QSun* application is also available in free and premium versions, with the premium version offering vitamin D tracking, activity tracking, and UVI and precipitation maps in addition to UV exposure information.

2.3.4 Color-Changing UV Wearables for Photochromic Monitoring

Color-changing UV wearables (or photochromic) are the least expensive and use dye-based color outputs to inform the user about real-time and cumulative UV exposure levels and sunscreen reapplication needs (Tables 2.1–2.2). Each employs adhesives or wristbands to provide a unique set of colors to communicate sunscreen and UV exposure information. For example, *LogicInk* (Figure 2.1) has two rings; the inner ring turns from white to pink to indicate the real-time environmental UVI level, and the outer ring changes from purple to pink to show cumulative UV exposure. Conversely, “” stickers turn blue when the user needs to reapply sunscreen, and their wristbands turn red. *SmartSun* stickers and wristbands first turn from beige to orange, which indicates that the user needs to reapply sunscreen. Once the sticker or wristband turns pink, the user is advised to head indoors because they are potentially close to receiving a sunburn (Hacker et al., 2019; Horsham, Antrobus, et al., 2020; LogicInk, 2021; SmartSun, 2021a; Sunburn Alert, 2021; Suncayr, 2021). *SPOTMYUV* begins as purple, which then turns clear after applying sunscreen; after exposing the sticker to sunlight (with or without sunscreen), it will slowly return to a purple color, indicating that sunscreen should be reapplied (Hacker et al., 2019; Horsham, Antrobus, et al., 2020; Suncayr, 2021).

The quantity of photochromic dyes in these adhesives is unknown, and only one adhesive, *LogicInk*, states a color change threshold. The *LogickInk* adhesive assumes that the user has a sunburn threshold that corresponds with Type I skin, the most UV-sensitive skin type (LogicInk, 2021). In contrast, *SmartSun*, *Sunburn Alert,* and *SPOTMYUV* do not state an assumed sunburn threshold for their adhesives and wristbands. Their websites state that they are designed to be dye-based sunscreen reapplication indicators that start as one color and then gradually change to a second color as the user's sunscreen degrades. Therefore, the photochromic adhesives can work either with or without sunscreen; adding sunscreen makes the color change more gradually and also indicates to the user that using sunscreen blocks harmful UV rays (Hacker et al., 2019; Horsham, Antrobus, et al., 2020; Suncayr, 2021). *SmartSun*, *Sunburn Alert*, and *SPOTMYUV* do not claim to estimate the user's exact UV exposure because the color change is based on the state of the sunscreen layer on the user's skin if sunscreen was applied (SmartSun, 2021b, 2021a; Sunburn Alert, 2021; Suncayr, 2021).

SmartSun stickers, wristbands, and their packaging are both waterproof and recyclable. The wristbands and stickers are shelf-stable for two years if they are stored away from sunlight (SmartSun, 2021b, 2021a). *SPOTMYUV*, *Sunburn Alert*, and *LogicInk* adhesives are waterproof, but their websites do not state whether they are recyclable (LogicInk, 2021; Sunburn Alert, 2021; Suncayr, 2021).

2.3.5 Polymer-Based UV Wearables & Use

Unlike the electronic wearables, the polysulfone and *VioSpor* film dosimeters must be analyzed in a research laboratory to obtain precise UV exposure results and are thus most appropriate for physical and clinical-based research studies. Polysulfone film dosimeters respond to short UVA and UVB wavelengths from 254–335 nm by degrading and experiencing a color change when exposed to UV light (Challoner et al., 1976; Davis et al., 1976; Diffey, 2020). The absorbance of an exposed polysulfone film dosimeter experiences its peak change at 330 nm. Hence, the UV dose of any individual dosimeter is determined by measuring the physical change in dosimeter absorbance at 330 nm and comparing this change to an appropriate field calibration curve to determine the UV exposure. Field calibrations are obtained by exposing sets of polysulfone dosimeters in an open environment and removing dosimeters of the calibration set after known periods of UV exposure, which is measured simultaneously by a field radiometer. Previous studies used polysulfone film dosimeters as lapel badges to study UV exposure at a British aircraft company (Leach et al., 1978); for geriatric patients, gardeners, and laboratory workers at an undisclosed location (Challoner et al., 1976); during different sporting activities (Herlihy et al. 1994) and more recently, for teachers and students in Queensland, Australia and for triathletes competing in Australia and New Zealand (N. J. Downs et al., 2019; N. J. Downs, Axelsen, Parisi, et al., 2020; N. J. Downs & Parisi, 2009). In older studies from the 1970s, the polysulfone films were 40 µm thick and placed in single-aperture square transparency mounts, which were attached to 50 mm metal black square holders with a safety pin on the back (Challoner et al., 1976; Diffey, 2020). These metal holders were later replaced with smaller 30 mm cardboard ones (Diffey, 2020). The more recent studies used polysulfone films that were mounted on flexible polymer frames and placed on the human subjects with strips of medical tape on helmets, hats, and exposed areas of the skin on the face, neck, arm, hand, or leg (N. J. Downs et al., 2019; N. J. Downs, Axelsen, Parisi, et al., 2020; N. J. Downs & Parisi, 2009)

VioSpor B. subtilis dosimeters utilize spores from a DNA repair-deficient bacteria strain to relate DNA damage to the action spectrum for human skin erythema (Davis et al., 1976; Diffey, 2020; Quintern et al., 1996). These sensors are made from desiccated bacteria spores immobilized on polyester sheets that are then contained in a plastic or aluminum casing (Moehrle et al., 2000). After exposure, the films are incubated in a bacterial growth medium and any proteins that the spores produced during the incubation period are stained and quantified. After using a photometer to conduct optical density measurements and to create a calibration curve, this curve is used to relate the number of proteins to the UV dose, where fewer active *B. subtilis* spores correspond with higher UV doses (BioSense, 2021; Moehrle et al., 2000; Quintern et al., 1996). A previous study used *VioSpor* sensors to measure occupational exposure for lifeguards, alpinists, and ski instructors, where the sensors were mounted as clips horizontally to caps and shoulders and vertically to sunglasses frames (Moehrle et al., 2000). Another study used *VioSpor* film badges to measure UV exposure at the top of the Okinawa Meteorological Observatory and personal UV exposure for European subjects of Fitzpatrick skin type II (Quintern et al., 1996). Additional studies have investigated the personal UV exposure of cyclists, golfers, construction workers, and adolescent girls and elderly women (Andersen et al., 2013; Giménez et al., 2015; Gurrea Ysasi et al., 2014; Moehrle, 2001; Serrano et al., 2010, 2011). Although *VioSpor* film dosimeters are mostly as badges in research studies, the manufacturer also sells wrist straps (BioSense, 2021).

2.4 DISCUSSION

There is a wide variety of commercially available wearable UV detection technologies, form factors, and price points. Hence, it is important to determine which sensor is best for one’s needs based on specific, situational considerations. Many of the reviewed wearables can be used for both research and personal applications, depending on user requirements and the type of research study (Figure 2.2). The *Scienterra* and *Shade* sensors (Scienterra Ltd, 2015; Shade, 2021b) are the most highly recommended electronic sensors for human research studies, and they have already been used in numerous research studies outlined above. The wearables that require laboratory analysis or special hardware to generate an output—*Scienterra*, polysulfone, and *VioSpor* dosimeters—are recommended for research only.

Limitations of this review include only using wearables used that are available as of Spring 2021 and at times a scarce lack of research, thus the need to use product websites and manuals available online. When important information was not accessible, the research team contacted companies or researchers who used the UV sensors to obtain more information about the sensors and phone applications.

2.4.1 Choosing Wearables for Specific Purposes

Select wearables provide real-time UV exposure information while others give "point-in-time" information upon request. Further, some sensors can display or collect raw data at desired time points, but others only show cumulative data. The type and amount of data needed and the time intervals in which the data is required will affect which wearables are best for a research study. Tables 2.1 and 2.2 can be used to compare metrics such as precision, measured UV wavelengths, and cost for UV-measuring research projects. Information like phone application comparisons and additional features (e.g., sunscreen reminders) is also helpful in comparing sensors for personal use. Figure 1.2 can be used to guide decisions on which wearable(s) might be best suited for a research project or personal use.

As shown in Figure 2.2, the research-only sensors—*Scienterra, Shade, VioSpor,* and polysulfone badges—require additional analysis in a laboratory or additional software, hardware, and/or calibration services. These extra steps to obtain data make these sensors ideal for biomedical and clinical research studies because researchers have laboratory space and equipment for working safely and efficiently with these sensors. However, these sensors may be too complex to measure personal UV exposure for non-researchers, especially since other electronic sensors are available that can provide similar data without these additional analysis steps. The simpler UV exposure output data as cumulative or countdown for *Eclipse Rx* and *QSun*, respectively, are suitable for measuring personal UV exposure and for behavioral research, such as during outdoor exercise or while attending an outdoor event like a concert or sports match (Horsham, Antrobus, et al., 2020; Horsham, Ford, et al., 2020). Still, they lack the precision required for biomedical and clinical research studies. Because *Eclipse Rx* and *QSun* show the user their UV exposure in terms of exposure percentage (*Eclipse Rx*) or time until sunburn (*QSun*), their outputs are more accessible for users to act upon than that of *My Skin Track UV*. The proprietary percentage of Max Sunstock units and percent UVA/UVB used by *My Skin Track UV* units are not immediately understood by the user (Apple, 2021b). These limitations may make *My Skin Track UV* suitable for personal use and less desirable for research studies.

Select wearables have additional features that might be very useful for both behavioral research and personal use (Table 2.2). All the photochromic adhesive wearables and wristbands are sunscreen indicators and are also disposable, which might be very useful for research with a large group of human subjects or for traveling or attending an event. For example, a recent study used photochromic wristbands to encourage sun-protective practices at an outdoor festival (Horsham, Antrobus, et al., 2020). *QSun* and *My Skin Track UV* also provide additional outputs; *QSun*'s pro version of its application estimates vitamin D synthesis, and both sensors provide information about the user's skin health. The *QSun* and *My Skin Track UV* phone applications use the phone camera to notify users of blemishes such as acne lesions and moles, which might be useful for those who want to track their facial skin health (Apple, 2021b; QSun, 2021). Vitamin D deficiency is a significant issue in high latitude regions in the winter, as well as in hot climates where people tend to stay indoors to protect themselves from the heat (Andersen et al., 2013; Gill et al., 2014; Jacobs et al., 2008). Finally, the use of an electronic wearable precursor to *My Skin Track UV* was used to help skin cancer survivors avoid sunburns and track their skin health (Robinson et al., 2020).

The polysulfone and *VioSpor* film dosimeters provide cumulative UV exposure data from different areas of the body. Notably, multiple film badges can be placed on a human subject, which is crucial for understanding how other areas of the body such as the face and top of the head are affected by posture and time spent in the sun (Andersen et al., 2013; Giménez et al., 2015; Gurrea Ysasi et al., 2014; Moehrle, 2001; Moehrle et al., 2000; Rettberg & Cockell, 2004; Serrano et al., 2010, 2011; Thieden et al., 2000). Polysulfone is also waterproof and has been used to measure the UV exposure of swimmers and reef snorkelers (Parisi et al. 2000; Downs et al. 2010). These film-based sensors are recommended for research studies where UV exposure estimates are needed for different areas of the body using a tiny, ubiquitous, and inexpensive sensor. Although the photochromic adhesives and wristband sensors can also be placed on different areas of the body, they do not provide personal UV exposure—they merely change color when sunscreen needs to be reapplied or, in the case of the *LogicInk* adhesive, if the sunburn threshold for a fair-skinned person has been reached (LogicInk, 2021).

2.4.2 Use in Clinical Research

Two wearables—the Shade electronic sensor and the *SPOTMYUV* dye-based stickers—conducted clinical trials and research studies to determine the wearables' effectiveness in preventing sunburns and pre-cancerous lesions. The purpose of the *SPOTMYUV* research study and clinical trials was to test the stickers' adhesive and color-changing properties (Hacker et al., 2019; Horsham, Antrobus, et al., 2020; Horsham, Ford, et al., 2020). The research study that involved *SPOTMYUV* prototype stickers included 550 participants in a two-day rugby event with players aged 14 – 18 years; only sunscreen was provided on the first day, and photochromic stickers were also handed out on the second day. Giving the participants a photochromic sticker resulted in higher sunscreen use, with 81% of the event's total sunscreen use occurring on the second day (Horsham, Ford, et al., 2020).

The clinical trial for *SPOTMYUV* prototype stickers involved offering participants either sunscreen or sunscreen and one photochromic sticker while spectating a cricket match (Hacker et al., 2019). The trial with wristbands at an outdoor music festival that tested the purple photochromic effect offered participants sunscreen, but all festival attendees received a wristband required to be worn throughout the festival (Horsham, Antrobus, et al., 2020). The 428 people who completed the clinical trial with the sticker prototypes reported more sunburns in the intervention group that received the stickers, but participants in the intervention group also reapplied sunscreen significantly more than those in the control group (Hacker et al., 2019). This shows that wearables such as the *SPOTMYUV* have potential merit in preventing sunburn. The 188 participants who completed the wristband clinical trial and its follow-up survey reported increased use of some sun protection items such as sunscreen and sunglasses. However, the overall degree of sun protection—which the study measured as a sun habits index of all behaviors, including seeking shade, wearing a hat, wearing sunglasses, wearing long-sleeved shirts, and wearing sunscreen—remained the same regardless of intervention because festivalgoers wore fewer long-sleeve shirts and hats than usual (Horsham, Antrobus, et al., 2020).

The participants in the *Shade* trial had past histories of developing actinic keratoses (pre-cancerous skin lesions), and kidney transplant patients were included because they are 65 times more likely to develop squamous cell carcinomas (ClinicalTrials.gov, 2017). The purpose of the clinical trial was to determine whether using *Shade* to monitor personal UV exposure could reduce the number of new actinic keratosis lesions and new non-melanoma skin cancers that the participants developed after 6 months—including summer months—versus those in a control group who received clinical counseling by their dermatologist. The results were that, at 6 months, using the *Shade* sensor significantly reduced the number of new non-melanoma skin cancers in the treatment group compared to the control group, but not the number of new actinic keratoses (ClinicalTrials.gov, 2017).

2.4.3 UV Wearable Regulation and Cost

All electronic wearables sold in the United States that make use of radio-frequency electromagnetic energy are regulated by the Federal Communications Commission (FCC) (Federal Communications Commission, 2021). Telecommunications devices are governed under Title 47 of the Code of Regulations, and Part 15 specifically addresses devices that emit radio frequencies (Federal Communications Commission, 2021; U.S. Government Publishing Office, 2021). The electronic UV-sensing wearables generally seek Class B classification, which includes digital devices commonly used in the home that emit radio frequencies, e.g. computers and calculators (Federal Communications Commission, 2021; U.S. Government Publishing Office, 2021). *Eclipse Rx, QSun*, and *Shade* are listed as Class B devices on their websites, whereas the *My Skin Track UV* website just has a link to Part 15. Although these wearables aim to inform the user about their UV exposure, none of them made health claims and sought classification as medical devices.

Wearables sold in the U.S. that claim to have features that provide health information are regulated by the Food and Drug Administration (FDA). The electronic UV-sensing wearables in this review do not claim that their UV exposure and sunscreen reapplication data will give results of similar accuracy to medical devices or scientific measurement instruments (Eclipse Rx, 2021; QSun, 2021; Shade, 2021a), as stated in their manuals and terms of service. The *Shade* sensor provides some medical information in its terms of service (i.e., it is unsafe for users with pacemakers because the device contains strong magnets (Shade, 2021a)). Therefore, none of these are classified as medical devices. The former *My Skin Track UV* product website only contained a link to information about FCC part 15, yet did not make any references to medical devices. Notably, the *My Skin Track UV* page does not exist anymore on the La Roche-Posay website, and the only documentation for the device is currently the product page on the Apple website (La Roche-Posay, 2021). Hence, health insurance cannot be used to pay for the wearables because they cannot diagnose potential medical issues or be considered as providing medical treatment. Some *Shade* UV sensor users have used Health Spending

Accounts to pay for their device, but the device is not covered by health insurance (Dumont & Kaplan, 2021).

The UV wearables' compliance with FCC Part 15 rule but not having features that are FDA cleared or approved mirrors the regulatory pathway for other fitness wearables such as most running and multi-sport watches with heart rate monitors and most fitness wearables that track sleep and steps. For example, the *Apple Watch* electrocardiogram (ECG) and fall detection applications on watch models 4 through 6 have been granted FDA clearances. This watch is considered a Class II medical device (US Food and Drug Administration, 2018). Similarly, the *Fitbit* ECG application has also been granted FDA clearance (Fitbit, 2021b), but no *Fitbit* devices are currently considered Class II medical devices (Fitbit, 2021c). The *WHOOP* strap, a fitness wearable that tracks recovery, sleep, and strain with resting heart rate, heart rate variability, sleep, and respiration metrics, does not have any FDA cleared or approved features (WHOOP, 2021).

The single-use color-changing wearables are also not regulated as medical devices. Only *SPOTMYUV* adhesives discuss safety testing in their FAQ section. None of the product information pages for *LogicInk* or *SmartSun* stickers or wristbands make references to safety testing or medical claims (or the lack thereof). Also, neither the *VioSpor* nor polysulfone wearables have sought FDA clearance or approval for any of their features, which means that they can be considered as fitness and wellness devices, but not as medical devices.

Regarding the cost of producing and purchasing UV-sensing wearables, many of the UV sensors in this review started as university research projects, which are subject to the “technology valley of death.” This phenomenon describes how promising new technologies funded by government research grants struggle to become profitable once they are produced industrially (Murphy & Edwards, 2003). Some of the sensors in this review, such as *Shade* and *My Skin Track UV,* had previous commercially-available versions that were sold as a *Shade* clip and as a photochromic sticker and as an electronic wearable adhered to the fingernail (Banerjee et al., 2018; Heo et al., 2018; Robinson et al., 2020). Previous studies have asked human subjects for their thoughts about using the *Shade* sensor and photochromic adhesives and wristbands, but none of these studies informed the subjects of the cost of the wearable (Alshurafa et al., 2019; Hacker et al., 2019; Horsham, Antrobus, et al., 2020; Horsham, Ford, et al., 2020; Nagelhout et al., 2020; Stump et al., 2018).

2.5 CONCLUSIONS

The current state-of-the-art review compared technical specifications of commercially available UV wearables with their stated applications. The review also guides researchers involved in personal UV exposure studies to determine which wearables are best for their purposes. Thirteen commercially available UV-sensing wearables exist for use in different research studies, and ten are also suitable for personal use. These sensors vary from electronic to photochromic, with large differences in price point, outputs provided, accuracy, and precision. The three limited to research use are suitable for physical or clinical studies that require raw, real-time data (*Scienterra*) or cumulative data from different areas of the body (polysulfone and *VioSpor* film badges).

Numerous areas of future research and applications exist in the UV wearable space across populations and user types. For example, ensuring accurate outputs during physical activity relevant to personal attributes (e.g., skin type, previous skin cancer) is vital for behavioral change. Moreover, these sensors have immense potential to fill gaps in the measurement of co-occurring activities, UV exposures (and skin damage), and behaviors (such as sun-protective behaviors) — relationships that we are unable to fully confirm. There is also potential to provide estimates of Vitamin D synthesis and light exposure related to sleep patterns. One wearable, *QSun*, already reports vitamin D estimates (QSun, 2021), which can be calculated with UV exposure and skin types as inputs (P. Gill & Kalia, 2015). Color-changing stickers and wristbands might also consider including information on vitamin D synthesis, which is which is an important health factor during periods with minimal sunlight, yet difficult to quantify (WHO, 2008; Schrempf et al. 2017).

The cost of wearables and their effect on personal or research use should be studied in future research. Recommendations are provided for which sensors are most suitable for various types of research or for general public use. These findings importantly will help guide researchers in future studies assessing UV exposure during physical activity.

CHAPTER 3

MEASURING AND MODELING ULTRAVIOLET RADIATION EXPOSURE WITH WEARABLE DOSIMETERS DURING PHYSICAL ACTIVITY

3.1 INTRODUCTION

Skin cancers are the most common type of cancer in the United States, and approximately 8,000 people die of melanoma annually (U.S. Cancer Statistics Working Group, 2021). One well-known cause of skin cancer is ultraviolet (UV) radiation. Outdoor physical activity is linked to increased skin cancer risk, but little is known about how outdoor environmental contexts affect individual-level UV exposure.

Initial attempts at measuring UV exposure without recruiting human subjects involved placing dosimeters on manikins or using weather and geographical measurements from the environment (N. Downs & Parisi, 2012; Vernez et al., 2011, 2015; Vuilleumier et al., 2013). For example, one study used polysulfone film dosimeters (Davis et al., 1976) attached to areas of the body, such as the face, neck, forearm, hand, and leg to measure UV exposure in those areas and then proposed a measurement called the Mean Exposure Fraction to describe UV exposures of body areas in relation to that of the entire body (N. Downs & Parisi, 2012). From these manikin studies, additional studies placed a triangle mesh over 3D models of manikins in different poses to estimate UV exposure for different body areas and to create a numeric *in silico* model, *SimUVEx* (Vernez et al., 2011, 2015; Vuilleumier et al., 2013).

When human subjects were recruited in early UV exposure studies, they were asked to record their outdoor activities in diaries (Cargill et al., 2013) and/or wear UV sensors on different areas of their body while being in a stationary posture or walking along a mapped route (Weihs et al., 2013). For example, Cargill et al. (2013), asked a sample of 47 Australian adults to keep diaries of the time they spent outdoors from February to July 2011, and they were then asked to wear wrist dosimeters (Scienterra Ltd., New Zealand—the same dosimeters used in this study) for 7 days (Cargill et al., 2013). The authors found that the time spent outside, as recorded in the diaries and as measured by the UV dosimeters, were strongly correlated (Cargill et al., 2013). However, this study did not compare actual UV doses. Another study by Weihs et al. (2013) placed optoelectronic sensors on specially made suits and on the forehead; subjects were asked to sit, lie down, and then walk along a mapped route (Weihs et al., 2013).

More recent studies have combined both areas of these previous research studies and measured personal UV exposure with dosimeters and mathematical modeling. Pope and Godar (2010) created cylindrical models that represent UV exposure for the human body in different positions, such as horizontal and vertical orientations (Pope & Godar, 2010). Further studies have used the Pope and Godar cylindrical models to estimate personal UV exposure in different contexts, such as for gold medal-winning athletes at the 2020 Olympic Games in Tokyo (now 2021), depending on their sport, their primary posture during the sport, and the type of clothing worn during competition (N. J. Downs, Axelsen, Schouten, et al., 2020). Studies estimating UV doses for athletes were continued with a combination of polysulfone badges and cylindrical modeling for triathletes (N. J. Downs, Axelsen, Parisi, et al., 2020). An additional study utilized film dosimeters on the top of the head and on the wrist and determined that, over an average of 14 days, the wrist UV measurements were consistently 50% of the UV exposure measured on the head, despite factors such as wrist movement and less direct sun exposure to the side of the body, and concluded that wrist sensors could thus be reliably and conveniently used to measure personal UV exposure (Thieden et al., 2000).

The current study fills numerous gaps in the above research by monitoring UV exposures on the wrist during different outdoor activities and in variable outdoor environments. We present a study of 14 adults engaged in walking, jogging, and cycling in three distinct urban environments while wearing a research-grade UV detection device (dosimeter) on the wrist. The goal of this study is to measure personal UV exposure when working or exercising outside and to use that data to create predictive models of UV exposure. This study is the first to investigate the effects of specific physical activity type and skin type on personal exposure in different outdoor environmental contexts—urban canyon, residential area, and an open urban environment. Three types of analyses are presented: exposure ratio by activity and environment, mapped spatially; a statistical predictive model of UV exposure by activity type; and a statistical comparison of measured UV values with common exposure models in the literature for different body parts.

3.2 METHODS

Personal UV exposure and thermal comfort were investigated among 14 ASU students while they walked, ran, and cycled in representative urban environments—urban canyon, residential neighborhood, and open sky. Subjects could participate for up to three days for a total of three ten-minute sessions of walking, jogging, and cycling per day in the three different environments. In total, 103 unique trials occurred. To determine the participants' skin type, they completed a pre-study survey on hair color, eye color, family history of skin cancer, and how often they burn, tan, or develop freckles, among other demographic questions (see Supplementary Data).

3.2.1 Location and Time of Day and Season

All testing occurred in June of 2019 on clear days during times that had air temperatures < 95°F. Subjects generally performed the prescribed activities between 11AM – 2PM, when the sun was highest in the sky. On days where there was an excessive heat warning, the activities took place from 10AM – 12PM to not put participants at risk. The urban canyon (Fig 3.1i, 3.2i) consisted of tall campus buildings near Arizona State University's Noble Library and met the requirements of an urban canyon as described by a previous study (Middel et al., 2019) and sky view factor (see below). The residential neighborhood (Fig 3.1ii, 3.2ii) was slightly south of the ASU campus and contained 1–2 story housing with front yards, trees, and moderately wide streets. The open environment (Fig 3.1iii, 3.2iii) was along a bike path along the Salt River at Tempe Beach Park with very minimal shading from any objects. A map of all three locations is in Appendix A.

Fig. 3.1: Participants exercising in three urban environments—(i) urban canyon, (ii) residential, and (iii) open sky. Each outdoor activity lasted 10 minutes. A full session lasted for 30 minutes and took place between 10AM – 2PM in June 2019**.**

Fig. 3.2: Sky view factors of urban environments. The openness of the environment is quantified by the sky view factor (SVF) (value from 0–100% or a fraction from 0.0–1.0), which is calculated from 170º field-of-view photos. A high SVF is found in environments with minimal shading from buildings and trees, while low SVF is found in dense urban areas.

3.2.2 Field Data Collection: Equipment & Calculations

During testing, the subjects wore two sensors to gather data on UV exposure and improve a technical model of personal UV exposure during these everyday activities. The first sensor was a GPS running watch (Polar, model M200) measuring speed and GPS location at 1-s intervals. The second sensor was a wrist UV dosimeter (Fig 3i; Scienterra Ltd., New Zealand) that reported personal UV exposure at 10-s intervals. The Scienterra dosimeter reports UV exposure as voltages that correspond to UV irradiance and converts these voltages into numbers between 0–1,023 that the user converts using field calibrations into radiation units or W m^{-2}. Conversion is done via a quadratic equation with the intercept forced to zero; the coefficients are provided by an individual Scienterra calibration data for each dosimeter (Vanos et al., 2017).

Additionally, a control UV sensor (Fig 3.3ii, SKYE, model SKU 440) was placed on a roof of the ASU Design North Building to determine the UV index and UV irradiance at 10-s intervals across the testing period. (Refer to Appendix A.) Data were recorded via a datalogger (Campbell Scientific, model CR1000X), and UV index values were converted to radiation units.

Fig. 3.3: Equipment for measuring UV exposure ratios of personal exposure and ambient UV radiation. (i) wearable dosimeter.[5] (ii) ambient sensor on rooftop for measuring UV in the environment.

The UV wrist sensor data, roof UV, and watch data were aligned to 10-s intervals. An exposure ratio (ER) of wrist-to-ambient was calculated using the roof ambient sensor as follows:

$$\mathbf{ER} = \frac{\mathbf{UV_{DOS}}}{\mathbf{UV_{AMB}}} \qquad (1)$$

where UV_{DOS} is the UV radiation measurements from the Scienterra dosimeter, and UV_{AMB} = radiation measurements from the ambient sensor, both in J/m^2 (Vanos et al., 2017; Weihs et al., 2013).

GPS data from the Polar running watches was downloaded as GPX files from the Polar Coach website. The GPS data were then time-matched to dosimeter readings at 10-s intervals.

To calculate the sky view factor (SVF), videos were first taken on clear days using a fish-eye camera (EXILIM) along each activity route for each environment. These videos were used determine the SVF at each 1-second interval along each route, which were processed via MATLAB to do so, creating one picture per second. Finally, each SVF was matched to the closest GPS data point from each subject. The SVF for each picture was determined by multiple algorithms to differentiate sky vs. non-sky areas and edges between these areas (Middel et al., 2018). Finally, the GPS data were time-matched to each photo, thus, each location along each route was associated with a specific SVF (Middel et al., 2017). The converted UV dosimeter data was matched with the GPS data at 10-s intervals.

3.2.3 UV Exposure Mapping and Directions

Maps of subjects’ GPS locations and UV exposure ratios were made in ArcGIS Pro software, version 2.8.3. Subjects’ latitude and longitude coordinates and UV exposure ratios were mapped at 10-second intervals. Outliers in GPS location were removed from the data. The GPS data was provided by running watches (Polar, model M200).

ArcGIS Pro was also used to determine the direction (North, South, East, and West) the subject was headed between each coordinate. The directions were labeled as the subject traveling to the next point in their route. The starting point was assigned the same direction as the first direction the subject traveled towards.

3.2.4 Exposure Modeling Comparisons

Geometric conversion factors (Pope & Godar, 2010) were used to convert wrist dosimeter readings to average UV doses on horizontal and vertical human body surfaces. Vertical body surfaces, such as the side of the body, were modeled with the upright cylinder model (Eqn. 2), and horizontal body surfaces, such as the shoulders were modeled with the horizontal cylinder model (Eqn. 3) (Table 3.1). The model equations are as follows:

$$\text{Upright Cylinder: } \boldsymbol{C}\left[\frac{\mathbf{0.0001218}\boldsymbol{A}^{\mathbf{2}}-\mathbf{10.99}\boldsymbol{A}+\mathbf{1685}}{\boldsymbol{A}^{\mathbf{2}}-\mathbf{166.5}\boldsymbol{A}+\mathbf{8250}}\right] \tag{2}$$

$$\text{Prone Cylinder: } \boldsymbol{C}\left[\frac{\mathbf{0.3751}\boldsymbol{A}^{\mathbf{2}}-\mathbf{58.60}\boldsymbol{A}+\mathbf{2610}}{\boldsymbol{A}^{\mathbf{2}}-\mathbf{154.4}\boldsymbol{A}+\mathbf{6514}}\right] \tag{3}$$

where A = solar zenith angle and C = sky view factor correction, as follows in Eqn 4.

$$\boldsymbol{C} = \frac{\boldsymbol{SVF_E}}{\boldsymbol{SVF_O}} \tag{4}$$

where E = environment (either urban canyon or residential) and O = open environment. The SVF values used in the cylinder model equations were averages of the SVFs for each route (Table 3.2).

Table 3.1: Cylinder models and assumptions by activity type (N. J. Downs, Axelsen, Schouten, et al., 2020; Pope & Godar, 2010)

Activity	**Model Used**	**Assumption Made**
Walking	Vertical Cylinder	Wrist dosimeter parallel to side of body
Jogging	Vertical Cylinder	Wrist dosimeter parallel to side of body
Cycling	Prone Cylinder	Wrist dosimeter in horizontal position

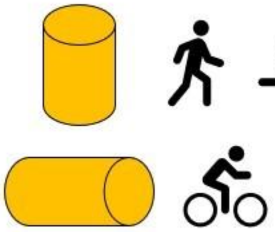


Fig. 3.4: Schematic of cylinder models of the three outdoor activities. SVF_E = mean SVF for the chosen urban environment. SVF_O = open sky. SZA = mean solar zenith angle.

The direction that the wrist dosimeter was facing during each activity determined the equation used to estimate UV doses to exposed body surfaces. For example, during walking and running, the dosimeter generally faces to the side (vertical), while during biking, the dosimeter faces upwards (horizontal) (Figure 3.4). The models in Eqns. 2 and 3 convert planar UV irradiances to cylindrical irradiances and help predict the personal

UV exposure received during the three outdoor activities on three body parts: face, shoulders, side of body.

Table 3.2: Average sky view factor (SVF) values used in model calculations. Values were calculated from 170º field-of-view photos taken along the activity route in each environment.

Parameter	Value
Mean SVF, Urban Canyon	0.49
Mean SVF, Residential	0.70
Mean SVF, Open Sky	0.89

The UV dose for the face was estimated with mean exposure fractions (MEF) provided by a previous study for the forearm, hand, and face (N. Downs & Parisi, 2012). The MEF for the wrist (MEF_W) was calculated by averaging the MEF for the forearm (MEF_F = 0.16) and hand (MEF_H = 0.47) as follows:

$$MEF_W = \frac{\boldsymbol{MEF_F + MEF_H}}{\boldsymbol{2}} = 0.315 \qquad (5)$$

The MEF for the face for walking and jogging (MEF_{FA}) is 0.29 (N. Downs & Parisi, 2012). The MEF for the face for cycling is 0.27/0.47 (or 0.57) because (1) the MEF for the hand area is 0.47 (N. Downs & Parisi, 2012), and, in another study involving a 3D *in silico* manikin model, the manikin was in a kneeling posture similar to the cycling posture, where the face was estimated to be 27% of the body’s total ER (Vernez et al., 2015). Therefore, the MEF for the face for the cycling activity is 0.57.

To account for the fact that UV exposure data were collected with a wrist dosimeter, the facial UV exposure (F) was calculated with exposure ratios (ER) from walking, jogging, and cycling as follows:

$$F = \boldsymbol{ER}\left(\frac{\boldsymbol{MEF_{FA}}}{\boldsymbol{MEF_{W}}}\right) \qquad (6)$$

The measured and modeled radiation values were compared to solar erythema thresholds according to the skin type of study participants (Table 3.3).

Table 3.3: Solar erythema (i.e. skin damage) thresholds by Fitzpatrick skin types, including the number of subjects by skin type in the given study (P. Gill & Kalia, 2015).

Fitzpatrick Skin Type	**SED Threshold Level**	**Number of Subjects**
I	2.0	1
II	2.5	4
III	3.0	2
IV	4.5	5
V	6.0	2
VI	10.0	0

SED = standard erythemal dose.

3.2.5 Statistical Analyses and Predictive Modeling

SPSS software (IBM) was used to calculate descriptive statistics, analysis of variance (ANOVA), and weighted least squares multiple linear regression (WLS regression) for the entire dataset and for each activity. The full dataset consisted of N = 5,792 datapoints of UV exposure ratio data for walking, running, and cycling combined at 10-second intervals.

To determine if there was a difference in ER between activities or environment, ANOVA was conducted using a multi-step process. First, Levene's test was used to determine whether variances of UV ERs were equal or not. Upon finding that variances were unequal among the environments and activities, the Games-Howell test, which is utilized when variances are unequal, was used during the ANOVA procedure to determine whether differences between the environment and activity groups were significant.

Because of the variability inherent in how well human subjects perform outdoor physical activity and in the shadiness of urban environments, the UV exposure data also did not follow a normal distribution. There were 320 zeroes out of 6,170 total ER readings at 10 sec. intervals (5.2% of the data) collected in the study across all subjects and activities, which indicate no exposure to UVB wavelengths based on the location of the wrist (e.g., subjects may have been in direct shade and facing away from sun, thus sunlight was prevented from reaching the dosimeter). These zeroes, as well as the differing number of subjects who participated in each environment and activity (e.g., walking and running, but not cycling) create a non-normal dataset. However, due to the Central Limit Theorem, which states that the probability distribution of a sample approximates a normal distribution as the sample size increases, and due to the sample sizes of the datasets in this study, the results of a multiple linear regression analysis are still valid.

Multiple linear regression has been used to create predictive models of UV exposure by including multiple factors, such as UV measurements from ambient control sensors compared to measurement sensors, solar zenith angle, and sky view factor (Cheng et al., 2020; Vernez et al., 2011, 2015). The assumptions of multiple linear regression include a linear relationship between the dependent variable (UV exposure ratio) and the independent variables (e.g., SVF); multicollinearity; homoskedasticity; that the residuals are normally distributed; and that the variance of the residuals is constant. Multicollinearity refers to when independent variables are correlated with each other as well as with the dependent variable, and heteroskedasticity is when the variance of regression errors is not constant (Hayes & Cai, 2007). When these assumptions were tested, it was found that the data exhibits heteroskedastic behavior.

Weighted least squares regression (WLS regression) is the process of carrying out multiple linear regression with a calculated weight for each data entry; the data is divided by a "weight" term that minimizes squared residuals and thus accounts for heteroskedasticity (Hayes & Cai, 2007; NIST Sematech, 2021). Therefore, WLS regression was used to create predictive models of UV exposure.

This study also differs from previous ones in that there are three types of categorical variables that must be considered—environment type, activity type, and direction (north, south, east, or west). Categorical variables take on fixed category values, such as environment type (Open, Residential, and Urban Canyon). To represent categorical variables in a regression equation, a special type of variable called a "dummy variable" must be used. Dummy variables assign a series of zeroes and ones to categorical variables such that a 1 value can be entered into the regression equation when that variable applies (e.g., inserting a 1 for "Open" when UV exposure for an activity in the Open environment is being calculated) (*Creating Dummy Variables in SPSS Statistics*, 2021; UCLA Statistical Consulting, 2021). For example, in SPSS, the Activity categorical variables are described as follows in dummy variable form:

- Open: 1, 0, 0
- Residential: 0, 1, 0
- Urban Canyon: 0, 0, 1

Additionally, when the WLS regression procedure is carried out, one dummy variable in each category is always excluded. Excluding one variable accounts for how, due to the ones and zeroes, one variable ends up cancelling out of the equation; therefore, regression equations include n -1 dummy variables for each type of categorical variable (*Creating Dummy Variables in SPSS Statistics*, 2021; UCLA Statistical Consulting, 2021).

The data was sectioned by activity for activity-based WLS regression analysis. This decision was made because potential future use of this research is more likely to have activity wearables prompt users to choose their activity, not their environment (which can vary); hence, WLS regression equations within-activity yet across environments is more applicable to real-world future use-cases. There were n = 2,054 entries for walking, n = 1,936 entries for running, and n = 1,802 entries for cycling.

$$\text{ER} = \frac{\boldsymbol{1}}{\boldsymbol{P^2}}(\boldsymbol{\beta_0} + \boldsymbol{\beta_1 X_1} + \boldsymbol{\beta_2 X_2} + \boldsymbol{\beta_3 X_{3\ldots}}) \qquad (7)$$

where ER is the UV radiation exposure ratio, $\boldsymbol{\beta_0}$ is the constant in the model, $\boldsymbol{\beta_1 X_1} \ldots \boldsymbol{\beta_n X_n}$ represents independent predictor variables and their constant, such as SVF or solar zenith angle, and P is the unstandardized predicted values.

The unstandardized predicted values are obtained in three steps: (1) conducting multiple linear regression analysis on the entire dataset, (2) calculating the absolute value of each residual from the regression analysis, and then (3) running a second regression analysis with the absolute values of the residuals as the independent variable. The weights are then added to the regression procedure in SPSS.

3.3 RESULTS

This study is the first to present UV exposure results for human subjects who performed outdoor physical activities in multiple types of urban environments. Wrist-worn dosimeters were used to measure UV exposure to some areas of the body, and cylindrical models representing the human body were used to estimate UV exposure for body areas that could not have UV exposure measured directly (Downs, Axelsen, Schouten, et al., 2020; Pope & Godar, 2010). The UV exposure ratio was measured for each activity in the open, residential, and urban canyon environments. Data measured with UV dosimeters was compared with estimates from the vertical and prone cylinder models, using parameters to account for SVF differences between the environments.

Table 3.4: Summary statistics for measured UV exposure ratio by urban environment and activity. Estimated values are based on models listed in Table 3.1 (i.e., vertical or horizontal cylindrical model using equations (1) and (2), respectively)

Environment	**Activity**	**Exposure Ratio (Mean ± SD)**
Open (n = 1,793) (SVF = 0.89 ± 0.08)	Walk[ac]	0.290 ± 0.174
	Run[ab]	0.312 ± 0.208
	Bike[bc]	0.542 ± 0.240
	All	0.374 ± 0.234
Residential (n = 2,000) (SVF = 0.70 ± 0.12)	Walk[a]	0.175 ± 0.162
	Run[b]	0.177 ± 0.171
	Bike[ab]	0.485 ± 0.244
	All	0.279 ± 0.244
Urban Canyon (n = 1,999) (SVF = 0.49 ± 0.19)	Walk	0.134 ± 0.143
	Run	0.128 ± 0.156
	Bike*	0.358 ± 0.237
	All	0.200 ± 0.208

Note: Two activities with the same letter are significantly different at the p < 0.05 level.

**The sensor orientation for cycling represents horizontal surfaces like the shoulders and back. The vertical orientation for walking and running represents the side.*

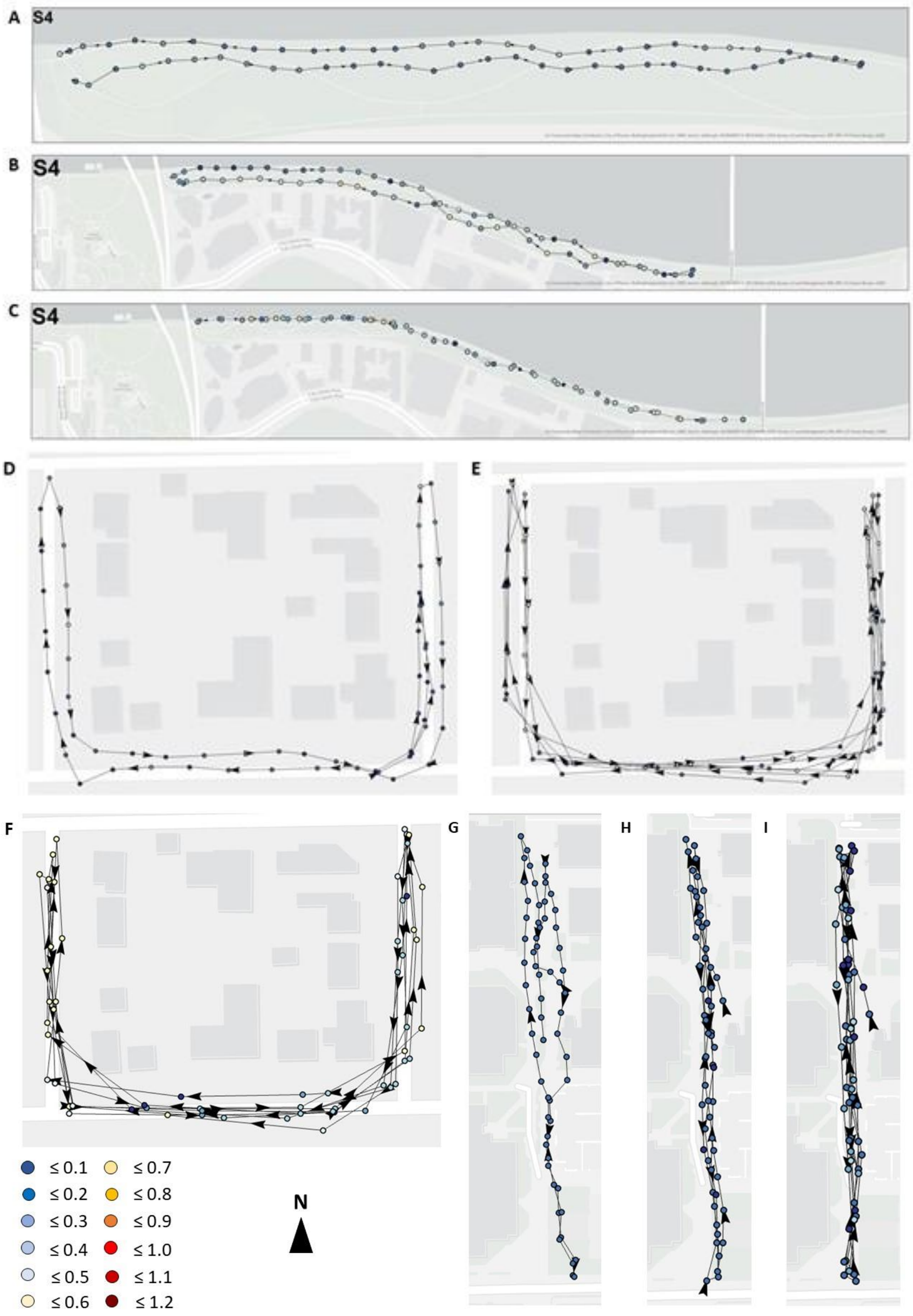


Fig 3.5: Subject 4 exposure ratio activity maps in the Open (A-C), Residential (D-F), and Urban Canyon (G – I) environments. Activities = walking (A, D, G), running (B, E, H), and cycling (C, F, I). Arrows show direction; colors show exposure ratio. North = up.

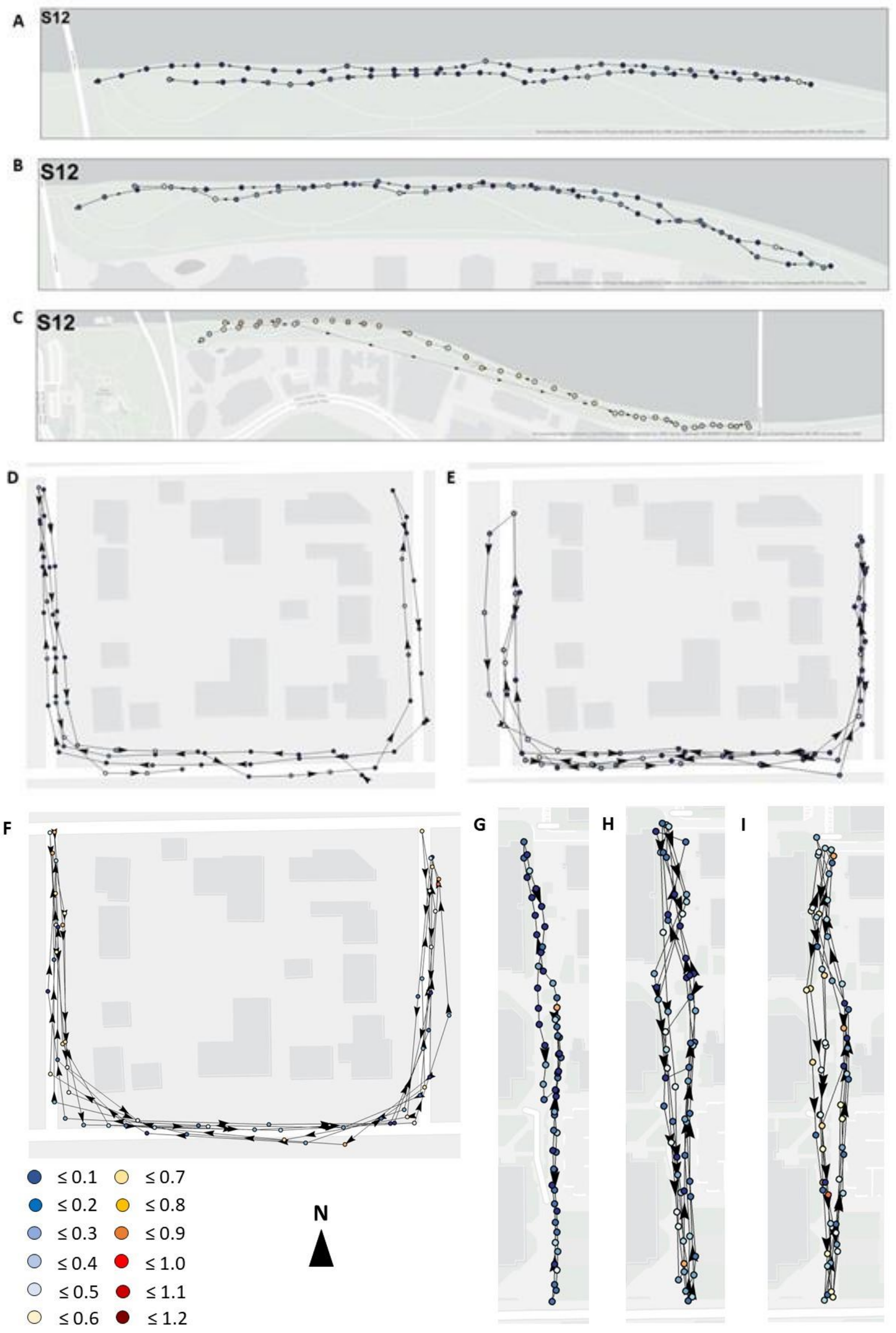


Fig. 3.6: Subject 12 exposure ratio activity maps in the Open (A-C), Residential (D-F), and Urban Canyon (G – I) environments. Activities = walking (A, D, G), running (B, E, H), and cycling (C, F, I). Arrows show direction; colors show exposure ratio. North = up.

Above (Fig. 3.5 and Fig. 3.6) are ArcGIS maps of Subj. 4 (skin type III) and Subj. 12 (skin type V). The spatial reference that was used was NAD 1983 HARN StatePlane Arizona Central FIPS 0202. The maps in Fig. 3.5 and 3.6 demonstrate how different human subjects can have varying levels of UV exposure for the same activities in the same urban environments. For example, Subject 12 (Figure 3.6) seemed to seek shade more than Subject 4 even though subjects were told to follow a specific path; this is why maps for Subject 12 show more instances of low UV exposure (blue dots) than Subject 4. The arrows on the map show the directions that the subjects were heading towards at each 10-second timestamp; hence, the maps also demonstrate the influence of direction of activity and wrist orientation on ER values. The Open environment shows higher UV exposure compared to the Residential and Urban Canyon environments, and the cycling activity showed more instances of ‘high’ UV exposure than the walking and running activities due to the wrist orientation, which is why the horizontal and cylindrical models for different body parts are critical to apply.

3.3.1 Development of UV Exposure Model with Environmental and Directional Factors

Weighted least squares regression (WLS regression) was used along with dummy variables for categorical factors (environment, activity, and direction) to create predictive models of individual-level UV radiation exposure. Results for WLS regression for all data together and by activity type are shown in Tables 3.5–3.8.

Table 3.5: WLS regression terms and their standard error and significance for all activities

Term	**Estimate**	**Standard Error**	**Significance**
Constant	0.063	0.015	0.00
Sky View Factor (X_1)	0.063	0.016	0.00
Solar Zenith Angle (X_2)	0.005	0.000	0.00
Direction 2 (East) (X_3)	0.040	0.010	0.00
Direction 3 (South) (X_4)	0.032	0.060	0.00
Direction 4 (West) (X_5)	-0.053	0.090	0.00
Open Environment (X_6)	0.084	0.008	0.00
Urban Canyon Environment (X_7)	-0.051	0.007	0.00
Activity 2 (Running) (X_8)	0.005	0.005	0.332
Activity 3 (Cycling) (X_9)	0.260	0.006	0.00

N = 5,792 of 6,170 total data points. Excluded data was when subjects went out of bounds in the environments they were exercising in. R = 0.580. R^2 = 0.336

The weighted least squares regression equation can be obtained from the above table, as follows:

$$\text{ER} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1 X_1} + \boldsymbol{\beta_2 X_2} + \boldsymbol{\beta_3 X_3} + \boldsymbol{\beta_4 X_4} + \boldsymbol{\beta_5 X_5} + \boldsymbol{\beta_6 X_6} + \boldsymbol{\beta_7 X_7} + \boldsymbol{\beta_8 X_8} + \boldsymbol{\beta_9 X_9} \quad (8)$$

$\boldsymbol{\beta_0}$ = constant

$\boldsymbol{\beta_1 X_1}$ = sky view factor

$\boldsymbol{\beta_2 X_2}$ = solar zenith angle

$\boldsymbol{\beta_3 X_3}$ = environment type 1 of 3 (categorical dummy variable)

$\boldsymbol{\beta_4 X_4}$ = environment type 2 of 3 (categorical dummy variable)

$\boldsymbol{\beta_5 X_5}$ = direction type 1 of 4 (categorical dummy variable)

$\boldsymbol{\beta_6 X_6}$ = direction type 2 of 4 (categorical dummy variable)

$\boldsymbol{\beta_7 X_7}$ = direction type 3 of 4 (categorical dummy variable)

$\boldsymbol{\beta_8 X_8}$ = activity type 1 of 3 (categorical dummy variable)

$\boldsymbol{\beta_9 X_9}$ = activity type 2 of 3 (categorical dummy variable)

To test this WLS regression model sample values were inserted from human subjects' physical activities. From Subject 1 cycling in the open environment at the 2 min time point:

SVF = 0.940
SZA = 15.01 degrees

And zeroes and ones were entered for the dummy variables. Because the subject was traveling east and west in the open environment, values of 1 were inputted for those activity, direction, and environment dummy variables, and zeros were assigned elsewhere.

ER = $\boldsymbol{0.063 + 0.063(0.940) + 0.005(15.01) + 0.040(1) + 0.032(0) - 0.053(1) + 0.084(1) - 0.051(0) + 0.005(0) + 0.260(1)}$

ER = 0.528, or 52.8%

This predicted value is close to the measured ER value, 0.576.

Another example at the 5 min. timepoint of the same activity is as follows:

SVF = 0.927

SZA = 14.5 degrees

ER = $\mathbf{0.063 + 0.063(0.927) + \ 0.005(14.5) + 0.040(1) + 0.032(0) -}$

$\mathbf{0.053(1) \ + 0.084(1) - 0.051(0) + 0.005(0) + \ 0.260(1)}$

ER = 0.517, or 51.7%

This predicted ER value is much greater than the measured ER value, 0.316. The R^2 value for the WLS equation indicates that the equation only explains 33% of the variance in individual-level UV exposure across all activities and urban environments. Although the R^2 value is low, this does not mean that the WLS regression model is not applicable, especially since all but one of the terms were deemed statistically significant. Human behavior is highly variable and not very predictable, and the different environments also had different amounts of shade, so high variance in the data and low R^2 values are expected (Abelson, 1985).

Table 3.6: WLS regression terms and their standard error and significance for walking

Term	**Estimate**	**Standard Error**	**Significance**
Constant	-0.011	0.021	0.615
Sky View Factor (X_1)	0.082	0.023	0.00
Solar Zenith Angle (X_2)	0.004	0.001	0.00
Open Environment (X_3)	0.087	0.011	0.00
Urban Canyon Environment (X_4)	-0.025	0.011	0.025
Direction 1 (North) (X_5)	0.058	0.012	0.00
Direction 2 (East) (X_6)	0.099	0.010	0.00
Direction 3 (South) (X_7)	0.078	0.013	0.00

n = 2,054. R = 0.437. R^2 = 0.189

The weighted least squares regression equation from the table above for activity 1 (walking) is in the following format:

$$\text{ER} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1 X_1} + \boldsymbol{\beta_2 X_2} + \boldsymbol{\beta_3 X_3} + \boldsymbol{\beta_4 X_4} + \boldsymbol{\beta_5 X_5} + \boldsymbol{\beta_6 X_6} + \boldsymbol{\beta_7 X_7} \qquad (9)$$

Where the terms are the same as described above for the full regression equation, without the activity terms $\boldsymbol{\beta_8 X_8}$ and $\boldsymbol{\beta_9 X_9}$.

For the sample values of 0.508 for SVF, 16.3 degrees for SZA, and zeroes and ones for the dummy variables (e.g., Subject 5, at 5:00 minutes in their walking activity in the urban canyon),

$$\text{ER} = \boldsymbol{-0.011 + 0.082(0.508) + 0.004(16.3) + 0.087(0) - 0.025(1) + 0.058(1) + 0.099(0) + 0.078(1)}$$

ER = 0.207, or 20.7%

This value is much smaller than the measured value, 0.705. Similar to the model described in Table 3.5 for the entire dataset, the WLS regression equation for walking has a low R^2 value despite all factors being significant in explaining individual-level UV exposure.

Table 3.7: WLS regression terms and their standard error and significance for running

Term	**Estimate**	**Standard Error**	**Significance**
Constant	0.083	0.024	0.001
Sky View Factor (X_1)	0.039	0.027	0.155
Solar Zenith Angle (X_2)	0.004	0.001	0.000
Open Environment (X_3)	0.103	0.014	0.00
Urban Canyon Environment (X_4)	-0.047	0.012	0.00
Direction 2 (East) (X_5)	0.052	0.016	0.001
Direction 3 (South) (X_6)	0.037	0.010	0.000
Direction 4 (West) (X_7)	-0.029	0.014	0.041

n = 1,936. R = 0.423. R^2 = 0.179

The weighted least squares regression equation from the table above for activity 2 (running) is the same as Equation 9**.**

An example calculation using this model to determine ER is given below for the sample values of: SVF = 0.728, SZA = 13.4°, and zeroes and ones for the dummy variables (e.g., Subject 12, at 5:10 minutes during their running activity in the Residential environment),

$$ER = \mathbf{0.083 + 0.039(0.728) + 0.004(13.4) + 0.103(0) - 0.047(0) + 0.052(1) + 0.037(1) - 0.029(1)}$$

ER = 0.225, or 22.5%

This value is close to the measured value, 0.233, but as with previous WLS regression examples, the P-values are low and the R^2 value is low, indicating high scatter in the UV exposure data.

Table 3.8: WLS regression terms and their standard error and significance for cycling

Term	**Estimate**	**Standard Error**	**Significance**
Constant	0.310	0.034	0.000
Sky View Factor (X_1)	0.097	0.041	0.019
Solar Zenith Angle (X_2)	0.008	0.001	0.000
Open Environment (X_3)	0.035	0.020	0.081
Urban Canyon Environment (X_4)	-0.139	0.017	0.000
Direction 2 (East) (X_5)	0.008	0.021	0.705
Direction 3 (South) (X_6)	0.048	0.015	0.002
Direction 4 (West) (X_7)	-0.092	0.021	0.000

n = 1,802. R = 0.392. R^2 = 0.153

The weighted least squares regression equation from the table above for activity 3 (cycling) is the same as Equation 9**.**

For the values of 0.921 for SVF, 27.9 degrees for SZA, and zeroes and ones for the dummy variables (e.g., Subject 10, at 5:00 minutes in their cycling activity in the Open environment),

$$\text{ER} = \mathbf{0.310 + 0.097(0.921) + 0.008(27.9) + 0.035(1) - 0.139(0) + 0.008(1) + 0.048(0) - 0.092(1)}$$

ER = 0.574

This value is smaller than the measured value, 0.767.

2.3.2 Measuring UV Exposure by Body Area

In addition to calculating UV exposure for the body overall, UV exposure for key areas of the body were estimated with Pope and Godar cylindrical models for horizontal and vertical surfaces (Eqns. 2 and 3) and with MEF listed for the face, forearm, and hand (N. Downs & Parisi, 2012; Pope & Godar, 2010). These MEFs were then averaged across all subjects by activity within each urban environment (Fig. 3.7) to determine whether the type of urban environment and the type of physical activity affect UV exposure.

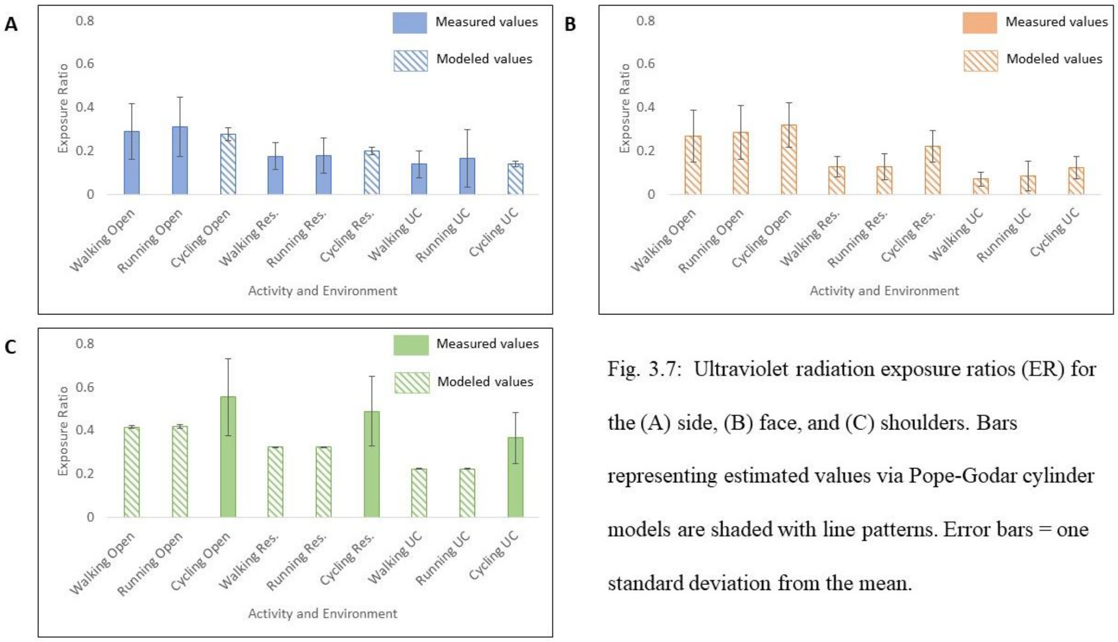


Fig. 3.7: Ultraviolet radiation exposure ratios (ER) for the (A) side, (B) face, and (C) shoulders. Bars representing estimated values via Pope-Godar cylinder models are shaded with line patterns. Error bars = one standard deviation from the mean.

Overall, the Open environment caused higher levels of UV exposure due to its lack of shade compared to the Residential environment, which had occasional trees and low buildings, and compared to the Urban Canyon environment, which had tall buildings that blocked sunlight. The Open environment also had the most reliable UV radiation measurements from the wearable dosimeters due to clear skies and lack of obstruction from shade sources (Table 3.9). The effect of shade is also reflected in the average SVF reported for each environment (Table 3.4; Fig. 3.2). The average ER levels by activity were approximately twice as high for the Open environment. Additionally, the shoulders (Fig. 3.7 C) received the highest UV exposure because of the (generally) horizontal body surface's higher exposure to sunlight compared to the face and to the side of the body. There is low percent error between measured and modeled UV exposure in the Open environment, and the percent error is higher in the Residential and Urban Canyon environments (Table 2.9). The cylinder model in Eqn. 2 was used to estimate the UV exposure for the side during the cycling activity, and the cylinder model in Eqn. 3 was used to estimate the UV exposure for the shoulders for walking and running. The UV exposure for the side during walking and running and the UV exposure for the shoulders during cycling were direct measurements. The cylindrical models from Pope and Godar underestimated the cycling exposure, so there is larger percent error between measured and modeled values for cycling than for walking and running (N. J. Downs, Axelsen, Schouten, et al., 2020; Pope & Godar, 2010).

Table 3.9: Pope-Godar cylinder models and how they compare to measured results

Environment	Activity	Model Used	Percent Error (%)
Open (n = 1,793)	Walk	Vertical	5.76
	Run	Vertical	5.91
	Bike	Horizontal	25.07
Residential (n = 2,000)	Walk	Vertical	16.28
	Run	Vertical	15.00
	Bike	Horizontal	33.58
Urban Canyon (n = 1,999)	Walk	Vertical	0.38
	Run	Vertical	16.57
	Bike	Horizontal	38.79

3.3.3 Estimated Time to Sunburn Based on Skin Type

After the exposure ratios were calculated for each area of the body, they were converted to erythemal doses and compared to Fitzpatrick skin type thresholds for receiving a sunburn, or skin erythema (Table 3.3). Subjects with lighter skin types (I – III) have much lower erythema thresholds than subjects with darker skin types (IV – VI). Figure 3.8 shows the progress towards sunburn on the face, side of body, and shoulders for two sample subjects of skin types III and V. Remaining subject results are provided in the Supplemental Material (Appendix D).

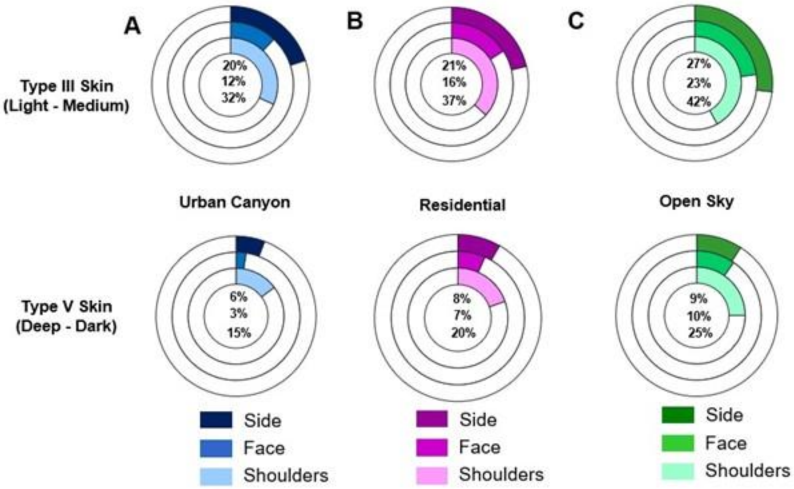


Fig. 3.8: Progress towards sunburn (assuming no sunscreen) for all the outdoor activities for one subject with Type III skin and a subject with Type V skin. (A) Urban canyon, (B) residential, and (C) open sky. The ring graphs reflect how, in post-study interviews, the subjects preferred their results to be shown on a future UV wearable. See Appendix D for remaining subjects.

3.4 DISCUSSION

Dosimetry, mathematical modeling, solar zenith angle measurements, and sky view factor measurements were used to calculate and predict personal UV radiation exposure during human subjects' physical activities in multiple urban environments. Direct measurements from wrist-worn UV dosimeters were compared to estimates derived from cylindrical models that represent the human body's full exposure. Due to the variation in the amount of shade present in the urban environments and in subjects' routes while completing their physical activities, the measured and modeled UV exposure values matched more closely in the Open environment compared to the Residential and Urban Canyon environments. Additionally, the wrist dosimeters measured higher levels of UV exposure during the cycling activity compared to the walking and running activities in all environments.

3.4.1 Significant Factors in Modeling UV Exposure

According to the WLS regression models, sky view factor, solar zenith angle, the type of urban environment, and the direction in which a subject traveled in were all significant factors in predicting personal UV exposure. The data from all 14 subjects for all activities and locations were separated by activity because sport watches and smart watches that are commercially available ask their users to input the type of activity they will be performing (e.g., walking or running outdoors or indoors). Data is then outputted in terms of how close the watch user is to completing a fitness goal, such as how *Apple Watches* encourage users to "close [their] rings for calories burned, minutes of exercise, and how often they stand up during the day to reduce sitting in the same posture for over one hour at a time (Apple, 2021a).

The SVF quantitative variables and environment categorical variables were included in the regression equations because SVF can vary by environment, but each environment has a different mean SVF that describes how much shade each environment provides, either through tall buildings or trees (Table 3.4). Some variables are significant in some equations but not in others, such as how SVF is significant in the WLS regression equation for the overall dataset, but not for the running activity. This variability in which terms are significant is a reflection of how much personal UV exposure varies by environment and by activity.

Additionally, the directions that subjects traveled in were determined by environment, so analyzing the data in terms of both the environment and the activity performed (e.g., Urban Canyon and walking) would have generated the most accurate WLS regression models. The data was not analyzed as such to reflect how a sport watch or smart watch would just ask the user for information about the activity that they are performing.

The R^2 values for the WLS regression equations were low, ranging from 0.153 for cycling and 0.336 for the entire dataset (Tables 3.5 – 3.8). Low R^2 values are expected in the social sciences, where human behavior is difficult to predict (Abelson, 1985). The regression equations consisted of terms that were highly significant in describing the UV exposure data (low P-values), which indicates that SVF, solar zenith angle, environment, and direction are all significant predictors despite the low regression model fit to the data.

3.4.2 Wrist Sensor Position Affects UV Measurements

The *Scienterra* wrist dosimeter measures UV radiation that comes into contact with the top of the circular and flat sensor device (Shade, 2021b). Therefore, the position of the sensor and which side of the body it is on in relation to the sun's position affects the sensor's readings. There were minor differences between subjects completing the same activities within the same environment at the same time, which is caused by the wrist dosimeters being angled differently while the subjects exercised, or perhaps some dosimeters might have been more loosely tightened than others. The higher UV radiation measurements for the Open environment and for the cycling activity reflect the findings of previous studies that used wearable dosimeters (Cheng et al., 2020; Thieden et al., 2000).

When human subjects were asked to wear *VioSpor* film dosimeters on their heads, arms, chests, and wrists whenever they were outside during clear summer days for 8 – 26 days (mean number of days = 14), the wrist-measured UV exposure was consistently measured to be 50% of the UV exposure measured at the top of the head (Thieden et al., 2000). The authors concluded that, although the dosimeters placed on top of the head gave the clearest UV exposure results, the wrist was an appropriate site to measure UV exposure because wrist measurements were reliably 50% of the head measurements, regardless of how the human subjects' UV exposures varied. Additionally, the wrist was deemed to be a reliable location to place UV dosimeters because hats were not commonly worn when and where the study was carried out (Thieden et al., 2000). Also, the UV radiation readings from the head were approximately twice as large as the readings from the wrist sensors (Thieden et al., 2000).

Cheng et al. (2020) used wearable UV-sensing clips attached to a box and facing in six directions (up, down, north, south, east, and west) and a reference sensor placed in a flat position on a building roof. The study used equations from Vernez et al. (2015), where a 3D human computer model was positioned in different common postures (e.g., kneeling and standing) to estimate UV exposure to different areas of the body. Similar to the results in this study, Cheng et al. (2020) found that the shoulder area had the highest estimated UV exposure, and the top of the head—another horizontal body surface, which maximizes sun exposure in comparison to more vertical surfaces such as the side of the body—had the second-highest estimated exposure. The results of Thieden et al. (2000) and Cheng et al. (2020), along with this study, are therefore in agreement with the fact that sensor orientation impacts UV radiation readings.

Table 3.9 also shows that there is low percent error between measured UV exposure in an unshaded environment and estimated UV exposure based on cylindrical models, but the percent error increases for shaded areas. Shade from trees and tall buildings in the Residential and Urban Canyon environments caused UV exposure measurements to vary significantly from predicted values generated from cylindrical models that had been formulated without accounting for shade (Table 3.9).

3.4.3 Measured and Modeled UV Exposure Results are Comparable to Previous Studies

This study utilized the same horizontal and vertical cylindrical Pope and Godar (2010)-inspired models as a previous study that estimated UV exposure to Olympic gold medal-winning athletes in the 2016 Summer Games (Downs, Axelsen, Schouten, et al., 2020; Pope & Godar, 2010). Mean Exposure Fraction estimates for the wrist, forearm, and face were also used from a previous study (Downs & Parisi, 2012). Using these models and suggestions for estimating UV exposure to different body areas, this study confirmed that UV exposure to horizontal body areas that receive the most possible UV radiation from the sun show the highest readings on wearable dosimeters, and approximately double that received to the side of the body. Thieden et al. (2000) showed similar results in that dosimeters placed on top of the head reported UV exposure that was twice the amount reported on the wrist.

This study's results are also comparable to those of Vanos et al. (2017), which showed that UV exposure as measured by wrist sensors only accounted for 18% of the UV measured by a stationary dosimeter placed on the roof of a building as a control (Vanos et al., 2017). The same study also found that shade reduced UV exposure readings by 55%, which is comparable to how the Open environment produced significantly higher UV readings than the Residential and Urban Canyon environments.

3.4.4 Implications for Urban Development

Significant differences in UV exposure between the Open, Residential, and Urban Canyon environments are relevant to protecting residents in urban environment from UV and heat overexposure. The significantly lower exposures in the shadier environments compared to the unshaded Open environment show the positive impact of urban planning initiatives such as creating urban forests to provide more shade to residents (City of Phoenix, 2021). Thermal comfort in urban spaces is significantly improved by shade, and routes can be recommended based on how comfortable it feels to venture outdoors along those routes (Middel et al., 2017).

3.5 CONCLUSIONS

This study is the first to analyze UV exposure data for human subjects that performed multiple types of physical activities completed in three types of urban environments. Quantifying UV exposure for different areas of the human body during outdoor physical activity is useful for people who venture outdoors for recreation, outdoor workers, skin cancer survivors, and wearable devices developers who may want to include UV measurement in future devices. Being able to estimate one's personal UV exposure when spending significant time outside will help people avoid overexposure to UV radiation and reduce their risk of skin cancer or of their skin cancer returning.

Previous studies investigated personal UV exposure in an open, non-shaded environment because open environments with clear skies provide the most easily interpretable exposure data. This study demonstrated that sky view factor, the type of activity, the type of environment, and the direction that the subject was traveling in relation to the sun in are all significant factors in predicting UV exposure. Also, the wrist UV dosimeters displayed high exposure values for cycling compared to running and walking because sunlight hit the face of the dosimeter at a higher angle for longer periods of time due to dosimeter orientation. Additionally, this study demonstrated that exercising or working outdoors in residential and urban canyon environments results in less UV exposure due to shade from trees and from tall buildings, and horizontal body surfaces such as the shoulders are more prone to becoming sunburned.

For further research on personal, individual-level UV exposure measurement, a larger sample size that includes all Fitzpatrick skin type subjects should be used to improve the accuracy of UV exposure prediction models. This study only included 14 subjects with skin types I – V. The unique data collected, and various types of models developed and tested, help advance our understanding of personal exposure to UV radiation during exercise in urban environments. The data and methods are valuable to the wearable industry for supporting health behaviors (Chapter 3) around physical activity and sun exposure, as well as for urban planning for recreational activity in hot, sunny places. Ultimately, this innovative research will contribute to new efforts to improve cancer-related health behaviors with innovative methods and technologies, which have the potential to decrease the risk for skin cancer incidence and mortality.

CHAPTER 4

PERCEPTIONS OF PERSONAL ULTRAVIOLET RADIATION EXPOSURE RESULTS FROM WEARABLE SENSORS AND RECOMMENDATIONS FOR FUTURE WEARABLES

4.1 INTRODUCTION

Skin cancer is the most commonly diagnosed cancer in the United States, with 5 million cases causing $8 billion in treatment costs every year (U.S. Department of Health and Human Services, 2014). Ultraviolet (UV) radiation is a known cause of skin cancer (U.S. Department of Health and Human Services, 2014). There is a lack of grant-funded research studies that examine associations between different urban environmental contexts, human behaviors in these environments affecting UV exposure, and how policies and planning can be used to aid behavioral intervention efforts and reduce skin cancer risk (Perna et al., 2017). A conceptual model called the Skin Cancer Intervention Across the Cancer Control Continuum (SCI-C3) includes human behavioral interventions as an important method for reducing sunburns, and thus skin cancer risk (Perna et al., 2017). Behavioral interventions that can reduce the risk of contracting skin cancer are called sun-protective practices (SPP), such as applying sunscreen, wearing a hat, wearing sunglasses, and seeking shade.

Physical activity is a significant predictor of sun exposure and skin cancer risk (Schneider et al., 2014), but few studies have investigated both activity level and SPP together. Adults who engage in physical activity for at least 150 minutes per week were shown to have more sun exposure than adults who exercise less than 60 minutes per week, but both groups had similar SPP levels (Schneider et al., 2014). Previous studies have also examined SPP of collegiate student-athletes who experience long periods of sun exposure during games and practices—on average, 1,000 hours annually (Ally et al., 2018; Wysong et al., 2012). Surveys of collegiate student-athletes at Duke and Stanford Universities have shown that lack of sunscreen use is associated with a desire to be tan (Ally et al., 2018; Wysong et al., 2012), lack of perceived risk to skin cancer (Schneider et al., 2014; Wysong et al., 2012), and greasiness and discomfort when sunscreen affects how the body sweats (Aburto-Corona & Aragón-Vargas, 2016; Schneider et al., 2014).

This chapter aims to address knowledge gaps concerning how people of different Fitzpatrick skin types (Fitzpatrick, 1988), outdoor activity levels, and prior engagement with personal health monitoring use SPPs to reduce skin cancer risk, potentially with assistance from wearable technology. Chapter 2 used wearable UV dosimeters and GPS sport watches to measure the personal UV exposure of 14 subjects completing activities in three urban environments and compared these measurements to models from the literature. To build upon the results discussed in Chapter 2, 12 of the 14 subjects were interviewed 12 months after their outdoor testing to discuss their results and perceptions of wearable UV sensors. Most importantly, the subjects were asked about their preferred data display format for their personalized results and their opinions on whether they would potentially adjust their outdoor exercise behaviors and/or use UV-sensing wearables in the future.

Although 1 in 5 Americans wear a smartwatch or fitness tracker due to interest in measuring personal health metrics (Pew Research Center, 2020), wearables are not as ubiquitous as smartphones, which are used by 85% of Americans (Pew Research Center: Internet and Technology, 2021). The use of emerging technology is influenced by income, education, personal values, and interests. For example, 1 in 3 Americans who live in households that have an annual income of at least $75,000 report using a wearable fitness tracker, but only 12% of Americans who live in households earning $30,000 or less report using one (Pew Research Center, 2020). An example of how values and interests influence the adoption of emerging technology is how Amish communities have a code of conduct that can be adjusted via group discussions to include technologies that are deemed beneficial, and that will also not adversely affect the community's social identity and way of life (Wetmore, 2007). Additionally, new technology adoption is also affected by whether individuals perceive the technology to be threatening to themselves or to their livelihoods.

For example, when the automobile was first developed in the early 1900s, town residents and farmers reacted negatively because the loud cars startled and sometimes killed livestock and blocked roads for those who needed to drive their horse-drawn buggies (Kline & Pinch, 1996). Although rural residents were initially wary of automobiles, they adapted them with support from the Ford Motor Company to be useful on farms as a power source for farm equipment like shellers and grinders and household equipment such as washing machines. (Kline & Pinch, 1996). Adjustments made to automobile design due to rural residents' feedback and creativity are examples of how emerging technologies are shaped by society and how they are gradually used and adapted, even if they might have been initially feared and hated.

Understanding how and why people use technology and how technologies are shaped by society is a concept called responsible innovation. Responsible innovation is often framed as the regulation of emerging technologies and the anticipation of potential safety and security issues (Stilgoe et al., 2013). There are currently four UV-sensing electronic wearables available to purchase (Apple, 2021b; Eclipse Rx, 2021; QSun, 2021; Shade, 2021b), and all electronic wearables sold in the United States that use radio-frequency electromagnetic energy are regulated by the Federal Communications Commission (FCC) (Federal Communications Commission, 2021). Only wearables that make health claims seek classification as medical devices from the Food and Drug Administration (FDA) (US Food and Drug Administration, 2018). None of the UV-sensing wearables have sought FDA clearance or approval.

Another side of responsible innovation—as seen in the automobile adaptation example—is use-inspired design. Obtaining user feedback to design better technological solutions and asking for public input on safety and security through opportunities like focus groups and public forums (Goodin & Dryzek, 2006) is an emerging trend of inclusion in responsible innovation (Stilgoe et al., 2013). Therefore, both regulation and user input are important factors in designing well-made and accurate wearables.

This study was motivated by the need to provide user-specific and use-inspired information to the research community surrounding the design and use of wearable UV sensors, thus better serving the needs of downstream users. An inductive approach was used to analyze semi-structured interviews with 12 subjects with experience performing physical activity with wearables in three environments on hot sunny days. The interviews set out to explore (1) how individuals understand and perceive their individual-level UV data, (2) what interviewees identified as preferred visual formats on a wearable or phone screen, (3) whether any factors (e.g., Fitzpatrick skin type, prior interest in health monitoring) were associated with adapting outdoor exercise behaviors and sun-protective practices after viewing individual-level data, and (4) how insights from these interviews can be used to design a user-centered UV-sensing wearable that is truly helpful to the user. Additionally, the interviews examined whether subjects view themselves using UV-sensing wearables in the future and inquired about the activities that the subjects might participate in with these wearables.

4.2 METHODS

4.2.1 Pre-Study Survey and Post-Study Semi-Structured Interviews

Personal UV exposure was investigated among 14 ASU graduate students in June 2019 while they walked, ran, and cycled in in three locations that represent three kinds of urban environments—urban canyon, residential neighborhood, and open sky (Figure 4.1). The subjects wore a GPS watch on the left wrist and a UV dosimeter (Scienterra Ltd., New Zealand) on the right wrist. Subjects could participate for up to three days for a total of three ten-minute sessions of walking, jogging, and cycling in the three different environments. The participants started their first session with a pre-study survey (Appendix B) that asked about their skin type—how often they burn, tan, or develop freckles—and about their SPP and family history of skin cancer.

Figure 4.1: Participants exercising in three urban environments and the UV wrist sensor they wore. (A) urban canyon, (B) residential neighborhood, (C) open sky, (D) *Scienterra* UV dosimeter.

Semi-structured interviews were conducted virtually on the Zoom platform in Summer 2020 as a follow-up study with 12 of the subjects. Instead of a more quantitative approach like post-study surveys, semi-structured interviews were used to obtain more in-depth information about subjects' perceptions regarding using wearable technology to potentially guide their SPP. During the interview, each subject was shown their personal,

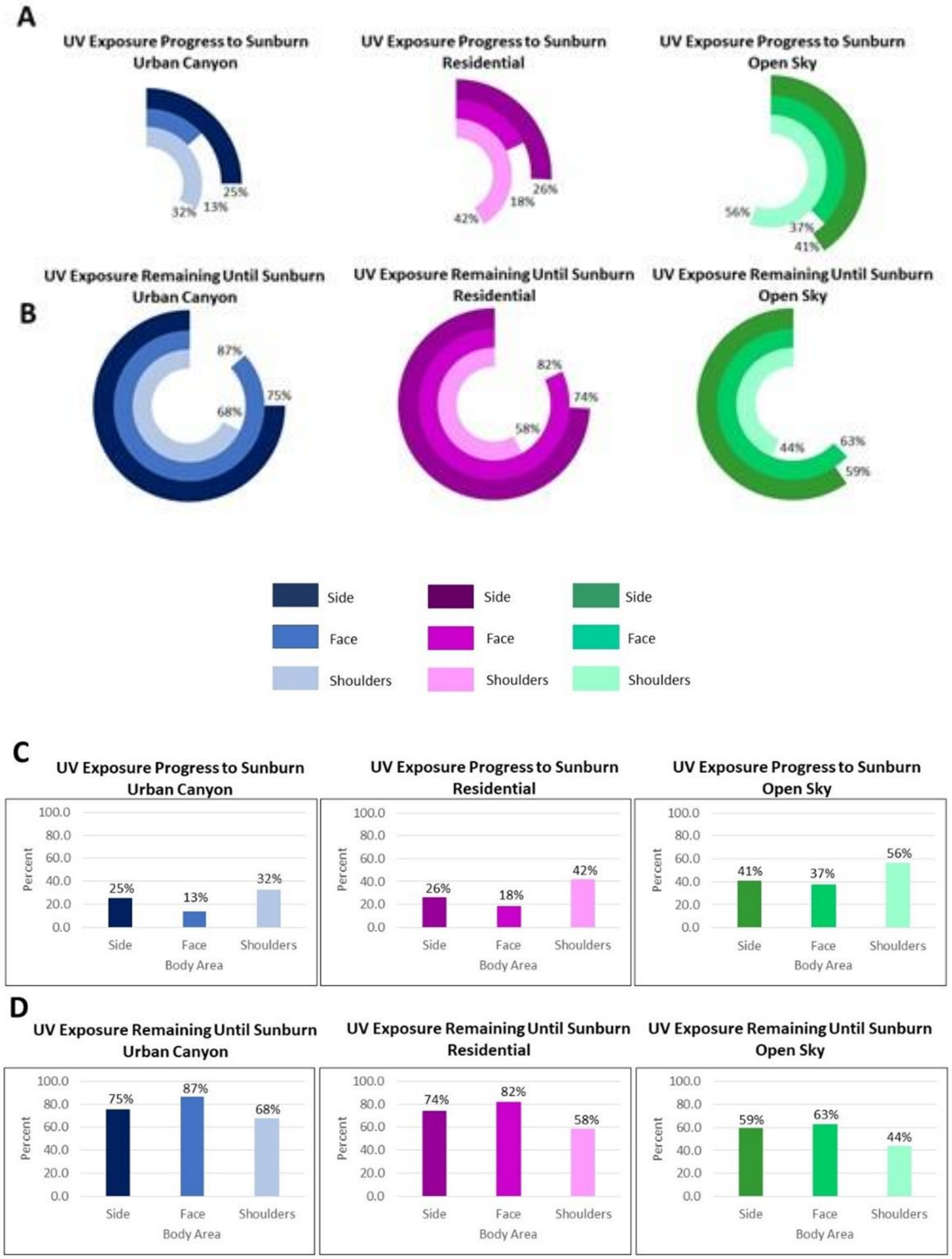


Figure 4.2: Sample ring and bar graphs for a subject of Fitzpatrick skin type II. Figures were adapted from PowerPoint slides used in the actual interviews. (A) cumulative ring graph, (B) = countdown ring graph, (C) = cumulative bar graph, and (D) = countdown bar graph.

individual-level UV data in a custom format as part of their interview. These images were used in certain questions around data display. The portrayal of the data was based on examples of what a user may see on a wearable e.g., cumulative or remaining exposure via ring and bar graphs (Figure 4.2). The interviews allowed the subjects to express their feelings in an open-ended way, including how easy or challenging personalized UV exposure results were to understand and why they might consider (or not consider) adapting their outdoor exercise behaviors or using a UV-sensing wearable in the future to guide their SPP.

Thematic analysis was used to discover emerging themes and patterns in the interviews (Braun et al., 2018; Clarke & Braun, 2017). The usability analysis framework was used to investigate subjects' past use of wearables, how subjects liked their UV exposure data to be shown on a wearable or phone application, whether they might consider changing their exercise behaviors and SPPs according to their UV exposure results, and whether they envisioned themselves using UV-sensing wearables in the future. The study was approved under ASU IRB protocol 00009996 (Appendix E).

4.2.2 Usability Analysis Framework

To determine whether the subjects used their UV exposure results to reconsider SPPs and whether they would potentially wear a UV-sensing wearable in the future, a usability analysis framework was employed to create interview questions (Appendix C). Usability analysis is an investigation of user experiences while testing products, which can include intangible products, like websites, and physical products, such as wearables (Usability.gov, 2020). This framework has been used in studies on how people interact with computers (or devices that connect to the internet) through websites, applications, and various types of interfaces (Cappel & Zhenyu, 2007).

Some of the interview questions asked the subjects to view their personal UV exposure results in four formats—cumulative ring graphs, countdown ring graphs, cumulative bar graphs, and countdown bar graphs (Figure 4.2). The ring graphs were inspired by how the *Apple Watch* encourages users to "close [their] rings" by burning calories, being active for a target duration, and standing and moving for 12 different hours during the day (Apple, 2021a). *Fitbit* devices also use ring graphs as well as bar graphs (Fitbit, 2021a).

4.2.3 Thematic Analysis

The interview questions that were coded and analyzed were those that asked subjects for more detail about their preferences and behaviors; other questions that were able to be quantified (e.g., number of days per week that a subject applied sunscreen) were described in tables. MAXQDA software was used to apply the codes to the interview data.

Approximately half of the interview questions were open-ended. Inductive thematic analysis**,** where patterns and themes in the interviews are extracted by coding the data according to the research questions**,** was used to discover emerging themes and patterns in the interviews (Clarke & Braun, 2017). To avoid making assumptions about why a subject might have made a certain statement, manifest coding—whereby codes are used for comments that were stated directly (Bernard & Ryan, 2016; Clarke & Braun, 2017)—was used. Latent codes, which allow for underlying meanings and assumptions, were not used. Grounded theory was also not used because it requires comparative analysis, or a second round of data collection (interviews or other types of data), to provide further insight on themes that emerged from the first round of data collection (Chun Tie et al., 2019).

4.3 RESULTS

Responses to interview questions such as how many outdoor exercise sessions the subject did per week and the exercise time and location were recorded in tables. For analyzing questions that required a thoughtful response from the subject, 21 codes were created (1 standalone code, 4 parent codes, and 16 subcodes). The codes about aesthetics, assumptions that the results would eventually be displayed on a circular smartwatch-like future wearable, and the intuitiveness of results are *in vivo* codes that were taken directly from subjects' responses (Braun et al., 2018). These codes (Table 4.1) describe how subjects reacted visually and sometimes emotionally when looking at potential ways that their UV exposure data could be graphed and shown on an electronic wearable or phone application. The codes also describe how subjects engaged or did not engage in personal health monitoring; whether subjects valued aesthetics or commented on "trendiness" when discussing the various results formats (Figure 4.2), and how the subjects envisioned themselves potentially using a UV-sensing wearable in the future, such as attending outdoor events or exploring new areas.

Table 4.1: Codes for analyzing prior health monitoring with wearables or phone applications, perceptions and interpretations of UV exposure results, and future use of UV-sensing wearables

Code	**Frequency (Number of Subjects)**
Lack of Agency	3
(Prior Health Monitoring) Uses Wearable	2
(Prior Health Monitoring) Step Tracking Application	1
(Prior Health Monitoring) Distance and Duration Only	2
(Prior Health Monitoring) Dislikes or Cannot Wear	2
(Prior Health Monitoring) Wearable Makes Claims	1
(Prior Health Monitoring) No Wearable or Phone App	5
(Perception About Visuals) Aesthetics	7
(Perception About Visuals) Circular Watch Assumption	2
(Interpretation) Psychological	2
(Interpretation) Intuitive	12
(Interpretation) Nonintuitive	5
(Interpretation) Positive Feeling	3
(Future Use) Explore an Area	1
(Future Use) Daily Life	3
(Future Use) Outdoor Events	1
(Future Use) No Interest in Future Health Monitoring	3

Parent codes are in parentheses, and subcodes are not.

4.3.1 Exploratory Behavior Profiles

As inspired by a previous study (Abbas et al., 2014), the 12 subjects were categorized into behavior profiles. Among the 12 subjects, 4 behavior profiles emerged of different sizes from interview analysis (Table 4.2). Due to the small sample size, these profiles are exploratory and not based on statistical analysis. The subjects were all graduate students, which generally meant that they have little disposable income with which to purchase wearable devices for personal health monitoring. “Prior measurement” in categories 1 and 2 refers to the use of wearables or phone applications to track health metrics such as steps, heart rate, and sleep. “Adjustments to behaviors” refers to whether subjects said they would consider changing their exercise location or time or their sun-protective practices.

Table 4.2: Behavior profiles based on prior health monitoring and adjusting future behaviors

Profile	Behavior Description	Number of Subjects
1	Prior measurement / adjustments to behaviors	2
2	Prior measurement / no adjustments to behaviors	1
3	No prior measurement / adjustments to behaviors	5[*]
4	No prior measurement / no adjustments to behaviors	4[*]

[*] = includes at least one subject with little or no agency to adjust behavior(s).

The first part of the behavior profiles was assigned to subjects based on whether they have a prior history of using a wearable or phone application that measures a health metric (e.g., steps). For subjects who measured only distance and time when exercising, they did not consider themselves to be using a wearable or measuring health or fitness metrics, so they were not categorized as “prior measurement”. The second part was assigned based on whether subjects said they would consider adjusting their outdoor exercise location or time or their sun-protective practices (Table 4.3). If a subject said that they might change a behavior rather than saying that they will likely change it, the subject was categorized as “no adjustments to behaviors”.

4.3.2 Agency and Behavior Adaptation to Personalized Data

When the graduate student subjects were asked to describe their outdoor exercise behaviors, they mostly discussed activities like walking, jogging, or cycling near their homes, workplace, or on their campus before or after work. Six subjects exercise near their home, and three subjects exercise on campus. Three subjects also mentioned occasional hiking in Arizonan state parks. Hiking was not included in exercise sessions because only regular weekly exercise during the summer was relevant to the study.

Subjects’ work schedules and environmental characteristics such as heat, sun intensity, and proximity influenced how and where subjects participated in outdoor activities. After subjects were shown their personal UV exposure data and asked if they might change their outdoor exercise location or time or SPPs, time and SPP were more adjustable for the interviewees. Only Subject 8 said that they would change their outdoor exercise location, and at the time of the interview, they were already adjusting the location to seek shade and stay out of the sun. Subject 6 said that they might consider changing their exercise location, two subjects said that their main source of exercise was commuting to and from work, and the other eight subjects said that they would not change their exercise location.

Subjects 9 and 12 said that their primary source of exercise was walking or cycling to work, meaning that they had no flexibility in their exercise time or location.

Subject 13 also mentioned constraints in their location because they only exercise outdoors once per week for an extended time (1.5 – 2 hrs) on campus. The exercise location for Subjects 9 and 12 was listed as “fixed”, and Subject 13 was also noted as having a lack of agency with respect to changing their exercise location (Table 4.3). Subject 12 described their weekday exercise opportunities as walks to and from work, with some tracking in the form of laps. This subject does not wear a watch and did not mention using another form of exercise or health metrics tracking, so the laps might have been conceptualized and logged mentally.

> My exercise is mostly walking. So I stay in a place around one mile from my lab. So what I do is, I walk towards my lab and log exercise by laps. So that's the only access. That will be roughly 45 - 50 minutes. So that's the only kind of exercise I have. (Subj. 12)

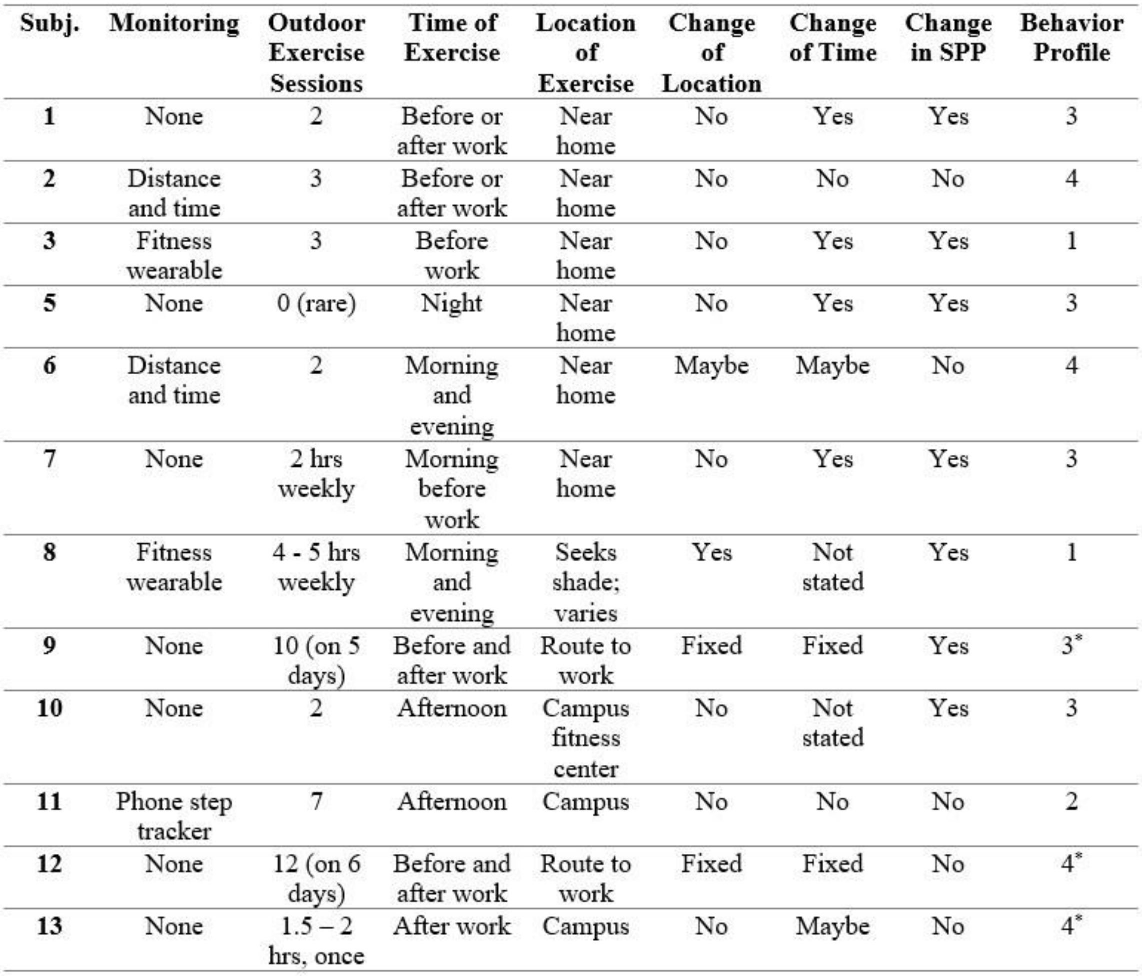
Subject 9 discussed cycling to and from their laboratory five days per week, “…about 25 minutes of biking each day and then another hour of just, like, intentional exercise, other than travel.” When asked about whether they will consider changing their exercise location after seeing their personal UV exposure results, Subject 13 said that “(they) don't know how much (they) will change... because of time constraints. Sometimes (my labmates and I) just walk outside of the lab or something.”

In contrast to subjects not generally being able to change their exercise location, four subjects said that they would adjust their exercise time, and one subject said that they might consider doing so. Subject 5 said that they might consider running outdoors at night even though they said that they did not currently exercise outdoors at the time the interview was conducted. Subjects seemed to have greater agency in changing their outdoor exercise time to avoid excessive sun exposure than in changing their exercise location.

In addition to discussing potentially adjusting their exercise behaviors, some subjects commented on how they had not previously thought about sun exposure during everyday activities. Subject 6 discussed how they would apply sunscreen before swimming in a pool, but not before walking or cycling to a store:

> I routinely go on walks for 30 minutes or bike rides for 30 minutes just to get groceries or go to the store or bike, just to friends or whatever or bike to work, so I didn't… I guess I didn't quite think of that. I never think of that as time where I might get sunburned… You know, that, like that kind of changes my perception of not so much with the exercise activities but like normal community or being just like normal outdoor activities. Just since again when I'm exercising, then I'm usually a little bit more conscious about sun exposure than when I'm just kind of out and about doing errands or something.

Table 4.3: Behavior profiles based on prior history of health monitoring and potential adaptations to outdoor exercise behaviors and sun-protective practices



Subj.	**Monitoring**	**Outdoor Exercise Sessions**	**Time of Exercise**	**Location of Exercise**	**Change of Location**	**Change of Time**	**Change in SPP**	**Behavior Profile**
1	None	2	Before or after work	Near home	No	Yes	Yes	3
2	Distance and time	3	Before or after work	Near home	No	No	No	4
3	Fitness wearable	3	Before work	Near home	No	Yes	Yes	1
5	None	0 (rare)	Night	Near home	No	Yes	Yes	3
6	Distance and time	2	Morning and evening	Near home	Maybe	Maybe	No	4
7	None	2 hrs weekly	Morning before work	Near home	No	Yes	Yes	3
8	Fitness wearable	4 - 5 hrs weekly	Morning and evening	Seeks shade; varies	Yes	Not stated	Yes	1
9	None	10 (on 5 days)	Before and after work	Route to work	Fixed	Fixed	Yes	3^*
10	None	2	Afternoon	Campus fitness center	No	Not stated	Yes	3
11	Phone step tracker	7	Afternoon	Campus	No	No	No	2
12	None	12 (on 6 days)	Before and after work	Route to work	Fixed	Fixed	No	4^*
13	None	1.5 – 2 hrs, once	After work	Campus	No	Maybe	No	4^*

Exercise session = outdoor exercise on weekly basis. Monitoring = wearable or mobile phone application that tracks health metrics. SPP = sun-protective practices. * = little or no agency to adjust behavior.

Seeing their personal UV results from the urban canyon, residential neighborhood, and open sky locations in the Chapter 2 study made Subject 6 consider how they were exposed to UV radiation while they were walking or cycling to and from errand locations. The subject’s estimated exposure to their shoulders (an average of 38% progress towards a sunburn after 30 minutes of activity in the three locations) encouraged them to apply sunscreen before running errands in the future. The subject is behavior profile type 4 because they are unsure about whether they will change their current exercise time, location, or SPPs.

4.3.3 Effects of Intuitiveness and Aesthetics on Preferred Results Format

When describing which results display format they preferred of the cumulative and countdown ring graphs, the cumulative and countdown bar graphs, and overall, all the subjects described whether a graph seemed intuitive or nonintuitive, and seven subjects discussed how they valued aesthetics in their interviews (Table 4.1). Two subjects chose their preferred format based on how they assumed that the future UV-sensing wearable would be circular like a watch, and two others stated their preference based on how the results format made them feel (Table 4.4).

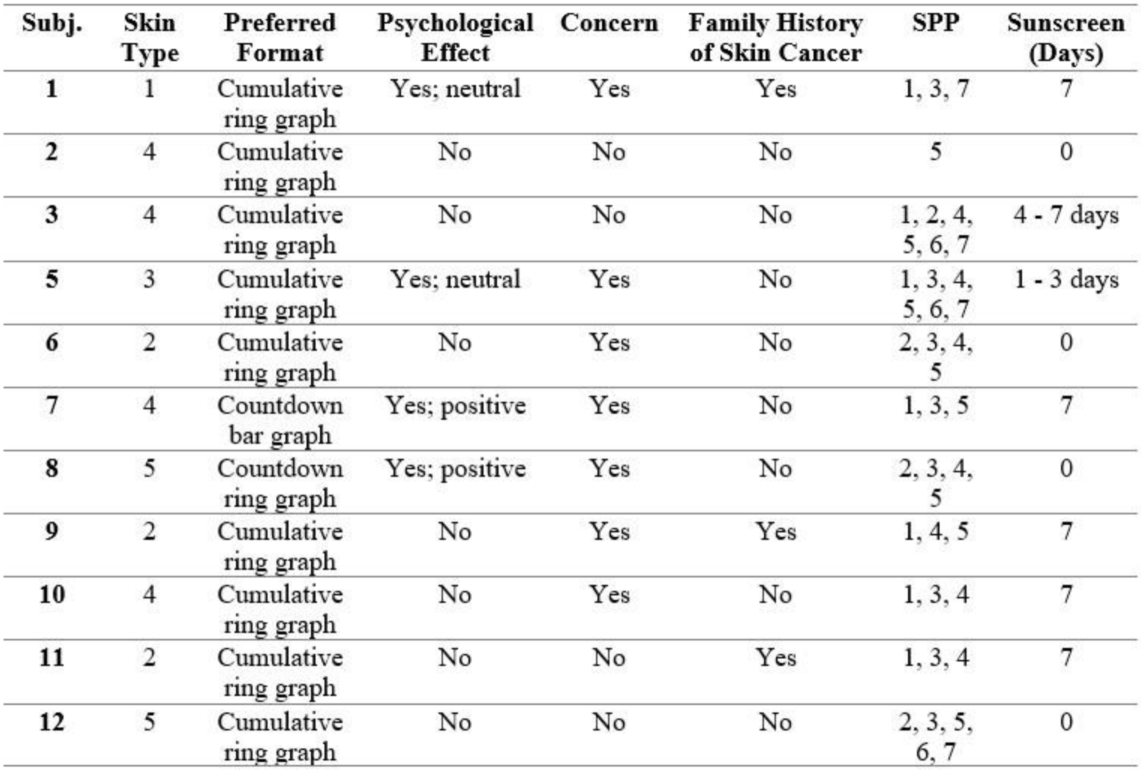
Nine out of twelve subjects preferred to see their personal UV exposure results in the form of a cumulative ring graph (Table 4.4). Four of the subjects mentioned how they valued aesthetics when making this choice, such as when Subject 9 said, “I mean this in a very positive way. It's trendy. It looks trendy.” Two subjects (Subjects 1 and 5) assumed that the future UV-sensing wearable would be in the form of a circular watch. For example, Subject 1 said, “I like the rings. I think it lends itself better to like the circular nature of how the wearable will probably be made.”

In contrast, Subject 2 mentioned that the data displays might be making “a very strong predictive claim” regarding whether the user will become sunburned soon or not. They preferred the cumulative ring graph over the countdown ring graph because it “seemed to me to make that claim a little bit less strongly, even though I recognize that they are, you know, functionally identical.” When they were presented with their results, other subjects had asked questions about how the graphs were made, but only Subject 2 commented on potential overreach. Subject 2 does not use wearable devices and is in behavior profile 4, where they are satisfied with their current exercise location, time, and level of SPP (Table 4.3). Their comment indicates that perhaps those in behavior profile 4 are more likely to question how wearables function and how their results were calculated compared to those in other behavior profiles.

4.3.4 Preferred Results Format and Psychology

When shown their results, some subjects commented on how results made them feel more positive or had the potential to have a psychological effect. Subjects who chose countdown graphs had emotion-based responses compared to others. While two other subjects mentioned that the data displays and their cumulative or countdown nature might have an unspecified psychological effect on the user, the subjects who preferred personal data display formats other than cumulative ring graphs had a notable emotional reaction to their data and how it was displayed. They preferred their results display format to give a positive feeling.

Table 4.4: Comparing interpretations of psychological effects according to subjects' preferred results display format, family history of skin cancer, and sun-protective practices



Subj.	Skin Type	Preferred Format	Psychological Effect	Concern	Family History of Skin Cancer	SPP	Sunscreen (Days)
1	1	Cumulative ring graph	Yes; neutral	Yes	Yes	1, 3, 7	7
2	4	Cumulative ring graph	No	No	No	5	0
3	4	Cumulative ring graph	No	No	No	1, 2, 4, 5, 6, 7	4 - 7 days
5	3	Cumulative ring graph	Yes; neutral	Yes	No	1, 3, 4, 5, 6, 7	1 - 3 days
6	2	Cumulative ring graph	No	Yes	No	2, 3, 4, 5	0
7	4	Countdown bar graph	Yes; positive	Yes	No	1, 3, 5	7
8	5	Countdown ring graph	Yes; positive	Yes	No	2, 3, 4, 5	0
9	2	Cumulative ring graph	No	Yes	Yes	1, 4, 5	7
10	4	Cumulative ring graph	No	Yes	No	1, 3, 4	7
11	2	Cumulative ring graph	No	No	Yes	1, 3, 4	7
12	5	Cumulative ring graph	No	No	No	2, 3, 5, 6, 7	0

Preferred format = ring graph or bar graph with a cumulative or countdown format. Sunscreen use includes face moisturizer and body lotion or spray. SPP (sun-protective practices): 1 = sunscreen, 2 = UV-protective clothing or long shirt or pants, 3 = hat, 4 = sunglasses, 5 = avoid peak sun hours, 6 = umbrella, 7 = seek shadier places.

Regarding the results having a psychological effect that was not stated to feel positive or negative, Subject 5 stated that they thought that the results were " …just psychological." They continued to say, "I think this would help me avoid sunburn because I would be like, oh, I have 23% of a sunburn, or something like that, you know. I would be more, I guess, cognizant of the amount of UV radiation I'm exposed to from this.”

For the two subjects who preferred countdown formats instead of cumulative ones, they commented on how the countdown format helped them see how far away they were from receiving a sunburn. When choosing the countdown ring graph over the cumulative version, Subject 7 said, “…I like to think more positive about how much I'm not getting sunburned versus how much I am getting sunburned.” They liked the countdown version of the bar graph format more than the ring graph because “…(they could) see the difference between side, face, and shoulder for each versus (the cumulative ring graph), where it was kind of confusing which numbers corresponds to which ones.” This subject therefore valued both positivity and intuitiveness in how they wanted their UV exposure results to be presented.

Subject 8 preferred the countdown format of the ring graph the most and described it as being like the fuel meter in a car, where “it always goes down. So you know how much you have left, right?” They further described how the countdown ring graph felt like a more positive way to present their data:

> So the same way (as a fuel gage meter), I prefer knowing how far I am from skin damage, rather than how much skin damage I have faced. And also, I guess it's more positive. So as compared to looking at the negative side, “Oh, you faced so

> much skin damage", rather than saying you're, you know, this far away from facing skin damage.

Subject 8 also said that the cumulative ring graph was more intuitive too, saying that was "compressed" and more easily viewable than a bar graph on a wearable device or a phone screen. They preferred a format that was easy to see at a glance, where "you don't keep looking at your wearable while you're, you know, working out or outside. You just want to have a quick glance at it and figure out."

Subject 13 preferred seeing their results in the form of a cumulative ring graph or bar graph, and they preferred the bar graph overall because bar graphs are used more commonly than ring graphs. The bar graph format also gave them their results "spot on" at a glance. Regarding the countdown format, they preferred it because it would help them plan their exercise time so they do not get a sunburn. They would "restrict" their activities accordingly, and the countdown gave them "a buffer as to how cautious (they) should be."

In summary, the three subjects who preferred results display formats other than cumulative ring graphs valued intuitiveness like the other subjects did, and they preferred the experience of counting down towards getting sunburned because they had a greater sense of how much time they had left to exercise. A total of four subjects perceived that the ring and bar graphs had a psychological effect on the user, and this psychological effect was the strongest factor in whether a subject preferred a countdown format over a cumulative format.

4.3.5 Prior Health Monitoring, Skin Type, and Sun-Protective Practices

Skin type, prior interest in monitoring personal health metrics, and prior SPP behaviors were not strongly associated with indications of behavior adaptations overall (Table 4.3, Table 4.4). It is unclear whether general interest in health monitoring is a significant factor in adapting behaviors after seeing personal UV exposure results because the only subject in Profile 2, Subject 11, is not interested in changing their behaviors (Table 4.3). However, prior use of a wearable was linked to the desire to adapt future exercise and SPP behaviors even though the subjects who used wearables were not at high risk of receiving a sunburn. Those in Profile 1 were of Fitzpatrick skin types IV and V (Table 4.4), which are at low risk of sunburn (Fitzpatrick, 1988; P. Gill & Kalia, 2015).

Interest in health monitoring and skin type also had no effect on future behavior among subjects in profiles 3 and 4. Of the nine subjects who did not use a wearable or monitor other health metrics at the time the interviews were conducted, five indicated that they would potentially adjust their future behaviors, which placed them in Profile 3. These subjects' skin types ranged from Fitzpatrick skin types I – IV (Table 4.4), which further indicates that skin type is not a strong indicator of one's desire to adapt exercise and SPP behaviors. Generally, subjects in Profiles 2 and 4—those who do not plan to change their exercise or SPP behaviors, regardless of whether they are interested in monitoring their health metrics or not—have various skin types and SPPs. Subjects 2, 6, and 12 (Profile 4) do not put on sunscreen because they do not like the feel of it or have a skin condition that prevents them from wearing it, but Subject 11 (Profile 2) puts on sunscreen and has a family history of skin cancer (Table 4.4).

4.3.6 Future Use of Wearables

Subjects were asked whether they would consider using a UV-sensing wearable in the future and given three examples of form factors—electronic wearables that have one UV sensing function, photochromic (described as "color-changing") stickers, and a multi-functional watch. Photochromic adhesive sensors (stickers) use dye-based color outputs to inform the user about their UV exposure levels and alert them to reapply sunscreen. As discussed in the first chapter of this dissertation, electronic wearables that primarily track UV exposure and photochromic stickers that alert users to reapply sunscreen are currently available for purchase, but multi-functional UV-sensing watches are not available yet.

Regarding potentially using UV-sensing wearables in the future, five subjects said that they would only use a watch with an added UV-sensing feature (Table 4.5). In Table 3.5, the columns are codes from interview analysis. When subjects just said that they would potentially use a UV-sensing wearable in the future but did not specify a purpose, it was assumed that they were considering using the device for outdoor exercise activities like the walking, jogging, and cycling that they completed in the study.

Table 4.5: Imagined futures with UV-sensing wearables

Subj.	Wearable Type	Daily Life	Event	Explore
1	Watch only	--	--	--
2	None	--	--	--
3	Watch only	--	--	--
5	Watch, sticker	--	Music festival (stickers)	--
6	Maybe; watch, sticker	Yardwork (watch), children (stickers)		--
7	None	--	--	--
8	Watch, stickers	--	--	--
9	Watch, stickers	--	--	--
10	Watch only	Watch UV alert; uses watch daily		--
11	None	--	--	--
12	Watch only			Visiting an area for first time
13	Watch only	Watch UV alert; uses watch daily	--	--

Watch = multi-functional watch with UV-sensing capabilities. Sticker = photochromic, single-use, and disposable adhesive.

Subjects' perceptions towards wearables and personal health data monitoring affected whether they would consider wearing a UV-sensing wearable in the future. The subjects who said that they would not consider wearing a future UV-sensing wearable had also said that they are not interested in using wearable devices in general. However, two of these subjects use some form of personal monitoring; Subject 2 tracks distance and time during running and cycling, and Subject 11 counts steps with a phone application. Of the two subjects that already wear wearables, Subject 3 said that they would only use a UV-sensing watch, and Subject 8 stated that they would use disposable wearables regularly along with a UV-sensing watch when exercising.

4.3.7 Themes Derived from Interviews

Four themes arose from coding and analyzing the semi-structured interviews:

1. Agency to adapt behaviors after being shown personal results
2. Emotions arising from different result formats
3. The importance of intuitiveness when displaying results on a wearable or phone screen
4. Interest and attitudes towards monitoring health metrics

The themes were developed from codes listed in Table 4.1, and the themes are connected in that they are important for developing a future UV wearable that users feel is helpful and accurate. As shown in Table 4.3, not all subjects felt like they were able to adapt their behaviors after they were shown their personal UV exposure results. Because all of the subjects were graduate students, and because one subject had a skin condition, agency—ability or opportunity to change behaviors—was prevalent in many subjects' exercise and SPP experiences. Only one subject had the flexibility in exercise location to be able to exercise in shady locations rather than nearby ones, and the majority of subjects had their exercise time constrained by graduate school and work obligations.

According to code frequencies, the intuitiveness of results was important to all the subjects regardless of their most preferred data display format. Intuitiveness was crucial because the results were chosen based on which would look best on a small screen, and it was the most significant factor to cumulative ring graphs being the most popular results display format. Subjects with emotional responses to their results still valued intuitiveness; the format that seemed more positive to them also felt more intuitive.

Prior use of wearables was associated with adjusting behaviors regardless of skin type. Further research with a higher number of participants will be necessary to see whether prior health monitoring with phone applications is a significant factor for predicting whether a subject would potentially adapt their behaviors after seeing personalized UV exposure results. Coding for reasons subjects provided for not wanting to wear a wearable revealed personal preferences, health conditions, and concerns about wearable technology. Those who are not interested in wearing wearables state an aversion to anything on the wrist, that the wearables might be making too broad of a claim about their health, or have a skin condition that prevents wearing them.

4.4 DISCUSSION

4.4.1 Exploration of Theme 1: Behavior Profiles and Agency

Four behavior profiles were created that were based on subjects' responses to interview questions about prior use of health monitoring and whether they might consider changing their outdoor exercise and SPP behaviors after viewing their results. Prior health monitoring and being able to adapt outdoor exercise behaviors is associated with income and whether there are safe places to exercise near home. Graduate students do not have much disposable income, and 2 of 12 subjects having wearables aligns with the finding that 12% of Americans making $30,000 or less annually use wearables (Pew Research Center, 2020). Six subjects said that they exercise near their homes, which shows how crucial it is for Arizonan cities to have recreational outdoor spaces in residential areas that encourage SPP, such as parks with trees. Examples of cities taking steps to create shadier recreational spaces include the City of Tempe’s guidelines for park improvements and the City of Phoenix’s urban forest program (City of Phoenix, 2021; City of Tempe, 2021).

Regarding SPP and sunscreen use, the subjects generally either used sunscreen every day or not at all, and regular sunscreen use is associated with higher education level (Kiviniemi & Ellis, 2014). All three subjects with family history of skin cancer used sunscreen 7 days per week, a result that aligns with previous studies that investigated sunscreen use among collegiate student-athletes and adults who are active outdoors (Ally et al., 2018; Kiviniemi & Ellis, 2014). Subjects who did not regularly use sunscreen reported feelings of greasiness, which is in alignment with previous studies on student-athletes and sunscreen use (Ally et al., 2018; Wysong et al., 2012).

4.4.2 Exploration of Theme 2: Perceptions, Results, and Implications for Long-Term Health Tracking

Two subjects preferred countdown formats that they said produced a more positive feeling than cumulative formats did. This preference for results displays that present data in a more positive way indicates that how data makes users feel is important in developing a wearable that helps all users improve their health metrics.

Prior studies have been conducted on how people used electronic UV sensors and photochromic stickers and how the subjects benefitted from them over one summer and during outdoor events that lasted for 2 – 6 days (ClinicalTrials.gov, 2017; Hacker et al., 2019; Horsham, Antrobus, et al., 2020; Horsham, Ford, et al., 2020). An electronic wrist-worn wearable called *Shade* was used in a clinical trial to test whether it reduces new skin cancer lesions in patients with a past history of developing lesions and in another group of patients that had recently had renal transplant surgery, which increases the chance of developing lesions (ClinicalTrials.gov, 2017). A brand of photochromic stickers called *SPOTMYUV*, which start purple, turn clear after applying sunscreen, and then return to a purple color as the sunscreen wears off, has also been tested in a study and two clinical trials where people attended a music festival or sporting events (Hacker et al., 2019; Horsham, Antrobus, et al., 2020; Horsham, Ford, et al., 2020). The result of the *Shade* clinical trial was that over one summer, the patients who used *Shade* had fewer new skin cancer lesions than those who only received gold standard dermatological visits (ClinicalTrials.gov, 2017). The results of the *SPOTMYUV* clinical trials were that participants were significantly more likely to use and reapply sunscreen at outdoor events compared to participants who did not receive a disposable photochromic sensor (Hacker et al., 2019; Horsham, Antrobus, et al., 2020; Horsham, Ford, et al., 2020).

These studies with *Shade* and *SPOTMYUV* stickers showed that tracking UV exposure can work for users over a short period of time, but whether subjects benefit from using these wearables for more than a few days for photochromic disposable sensors or 3 months for electronic wearables is unknown. Positivity can potentially help with encouraging users to track health metrics for long periods of time because there is a one-third abandonment rate for wearable fitness trackers after a few months (Attig & Franke, 2020).

Regarding longer-term use of wearables, obesity, an example of a chronic illness, was only somewhat treatable with wearables over time periods ranging from 6 to 24 months. Clinical trials that included wearables to monitor activity and standard interventions like prescribing a diet and providing counseling sessions showed that while all of the participants generally lost weight over time, wearables did not seem to provide a clear benefit over standard weight loss interventions (Fawcett et al., 2020; Jakicic et al., 2016). To keep users interested and engaged with their wearable devices, a study explored whether "gamifying" wearables increases physical activity outcomes; participants who used wearables during the 24-week study period had significantly higher levels of physical activity, but their activity level was not significantly greater at the end of a 12-week follow-up period (Patel et al., 2019).

In summary, UV exposure tracking has not been studied in clinical trials beyond 3 months, and further research is needed to investigate wearable use and abandonment after longer timer periods. Tracking UV exposure was strongly associated with emotions for some subjects, so future UV-sensing wearables should have both countdown and cumulative data display options in the ring graph format, which 10 of 12 subjects chose. Toggling between cumulative and countdown ring graph formats might help users feel more motivated to adapt their behaviors to reduce UV exposure, if needed.

4.4.3 Exploration of Theme 3: Data Display Aesthetics and Influences of Current Wearables

The health-focused wearables that are currently available for purchase are mostly wrist-worn devices that provide simple health metrics such as step counting, heart rate, and sleep tracking. A survey of 581 people in the United States in 2019 showed that *Fitbit* devices were the most recognized (77%), followed by the *Apple Watch* (73%) and *Samsung Gear* / *Galaxy Watch* (48%) (Clark, 2020). Two subjects in this study used wearables at the time they were interviewed, and the devices that these subjects reported using were *Fitbits*. One subject reported using a *Garmin* Forerunner watch to track distance and time during running and cycling sessions, and the Forerunner was last on the recognized wearables list at 12% (Clark, 2020).

All but one subject preferred ring graphs over bar graphs to display their UV exposure data. Because *Apple Watches* and *Fitbit* devices are well-recognized, subjects' descriptions of ring graphs as "trendy" was likely due to the *Apple Watch* having a "close your rings" campaign (Apple, 2021a). Fitbit devices also have rings as well as bar graphs that track health metrics over long periods of time (Fitbit, 2021a).

The nine subjects who said that they would potentially use a UV-sensing wearable in the future said that they preferred a UV-sensing multi-functional watch over other options. However, all of the electronic wearables on the market primarily track UV exposure. Some have other functions such as displaying the weather, step counting (Eclipse Rx, 2021), vitamin D tracking (QSun, 2021), and skin analysis and product recommendations (Apple, 2021b), but they do not have nearly as many functions as a multi-functional watch does.

4.4.4 Exploration of Theme 4: Perceptions of Personal Health Monitoring

Subjects only identified as a wearables user if they were using a wearable device to track metrics like sleep, steps, and heart rate. For example, one subject used a *Garmin* Forerunner sport watch while exercising but said they did not consider it as a wearable because they only measured distance and did not use the heart rate data. *Garmin* Forerunner sport watches are considered to be fitness wearables, according to a 2019 wearables survey (Clark, 2020).

Regarding whether people choose to use wearables and then continue using them over time, data accuracy is important to reducing the one-third abandonment rate (Attig & Franke, 2020). The existing UV-sensing electronic wearables on the market—the *Eclipse Rx* wristband, the *Shade* wristband, the *QSun* clip, and the *My Skin Track UV* clip—do not generally explain how the user's UV exposure is estimated; only the Shade sensor (through its phone application) explains that people of different Fitzpatrick skin types have different sunburn thresholds (Apple, 2021b; Eclipse Rx, 2021; QSun, 2021; Shade, 2021b). These existing wearables also have outputs like daily % exposure or % "sunstock", which are calculated by proprietary algorithms with unknown accuracy and precision. This is perhaps why a subject commented that their personal UV results seemed to be stating "broad claims" about how much UV they had been exposed to. As stated previously, the existing UV wearables on the market are not classified as medical devices; they just adhere to FCC regulations for electronics that use radio-frequency electromagnetic energy (Federal Communications Commission, 2021).

The interviewer was able to answer subjects' questions about how their UV exposure was calculated according to data provided by the *Scienterra* dosimeter that the subjects wore while exercising and according to their Fitzpatrick skin type. However, the ring graphs and bar graphs just display percentages of UV exposure or exposure remaining until sunburn. This study recommends that future wearables need to be transparent about the calculation process in their user manuals without revealing proprietary information. For example, explanations in the user manual should include how skin type is accounted for after a user fills out a skin type questionnaire in their wearable's phone application.

4.5 CONCLUSIONS

From analyzing the thoughts and perceptions of 12 graduate student study participants, this study makes three recommendations for developing future UV-sensing wearables that will be truly helpful to the user. The first recommendation is that a multi-functional UV-sensing watch would be the best form factor for a future wearable because all 9 subjects who said that they would potentially use a UV wearable in the future would prefer to have a watch with a UV-sensing function. The second recommendation is that this watch should display personal UV exposure results as cumulative and countdown ring graphs that the user can toggle between. Although most subjects preferred their exposure results to be shown in a cumulative graph, two subjects associated positivity with a countdown-style display and preferred their results to be shown in that style. Including a countdown-style graph option would accommodate all potential users and potentially increase the amount of time that users wear and utilize the device. The third recommendation is for device instruction manuals and websites for current and future UV-sensing wearables to be more transparent about how UV exposure results are calculated. Providing more technical information to users will give them more confidence in using the wearable because they can see how their personalized results are calculated and how accurate these results might be.

Because this exploratory study only included feedback from 12 graduate student subjects, a larger study with more subjects from different educational and economic backgrounds is needed to determine the ideal type of UV-sensing wearable, such as a photochromic disposable sensor or a multi-functional watch. Additionally, a larger group of participants would provide more commentary on the ideal visual format to display personal UV explore results. Furthermore, more participants are needed to investigate how previous use of health monitoring—either wearables or phone applications—affect whether subjects consider adapting their behaviors after seeing their results. For a future study with both pre and post-intervention, where subjects could perhaps keep a sun diary (N. J. Downs & Parisi, 2009) of their outdoor activities and SPP for a significant period of time after seeing their UV exposure results, the follow-up interview should also discuss whether cost and reusability would influence whether subjects might use a UV-sensing wearable in the future.

CHAPTER 5

SUMMARY AND CONCLUSIONS

This dissertation reviewed commercially available UV-sensing wearables for personal and for research use and investigated the effects of specific physical activity types on individual-level UV exposure in different outdoor environmental contexts. In addition to investigating current wearable UV sensors, this dissertation is the first to utilize quantitative and qualitative methods to measure and model UV exposure with data from human subjects at 10-sec intervals during 30 minutes of activity in open, residential, and urban canyon environments. The resulting weighted least squares regression models for walking, running, and cycling activities—as would be needed for a sport watch with a UV-sensing function—and themes extracted from interviews create a comprehensive overview of how a future UV-sensing wearable needs to perform in order for it to be accurate and consistently worn by the user.

UV radiation measurement and estimation are useful for skin cancer survivors, urban planners, wearable device developers, and for the general public in minimizing personal UV exposure or potentially adding UV measurement to future devices. The first research study in this dissertation explored how existing wearable UV sensors such as stickers, disposable wristbands, clips, and more durable electronic wrist devices might be useful for different groups of people in meeting their UV measurement goals. The second study investigated how to best measure personal UV exposure when performing three different types of outdoor exercise in urban environments that were either unshaded or shaded by trees and tall buildings. The regression models that were developed in this study describe how solar zenith angle, sky view factor, activity type, and urban environment type contribute to personal UV exposure, and accounting for these factors is important in accurately estimating exposure during common outdoor recreational activities and errands. The third study directly asks human subjects who used UV-sensing wrist wearables about how they interpreted their personalized UV exposure data and about how they would like to see their data shown on a small screen. The interview questions about their weekly outdoor exercise activities, exercise locations, and prior use of wearables examined how UV-sensing wearables could potentially help adults manage their UV exposure by adjusting when or where they exercised outdoors. For future UV-sensing wearables, most of the human subjects preferred that they be in the form of a multi-functional watch so they could be useful in many daily situations.

For future work, larger sample sizes of human subjects ranging from Fitzpatrick skin types I – VI and in income levels should be invited to participate in additional studies on personal UV exposure. Different income levels are necessary for better determining trends in which subjects might use a UV-sensing wearable in the future, since wearables tend to be highly expensive. A limitation of this dissertation research was that subjects were interviewed about potential behavioral changes after seeing their personal UV exposure data, but they were not asked to wear the wrist dosimeters post-interview to determine whether their behaviors changed. The subjects were also asked about their previous use of wearables, but the small sample size prevented conclusions from being drawn about how previous use impacts future use. Further studies on how human subjects utilize UV-sensing wearables in their daily lives should be conducted.

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APPENDIX A

AREA MAP

Supplementary Fig. 1: Google Earth map of the Tempe, AZ area that the Ch. 2 study was conducted in. Map data: Google $^{©}$2019, Landsat/Copernicus. (1) The Open environment, a bicycle path alongside the Salt River; (2) Design North Building where the control UV sensor was placed on the roof; (3) the Urban canyon environment, a path between tall university buildings; (4) the Residential environment, three streets that formed a neighborhood block.

APPENDIX B

PRE-STUDY SURVEY

1. What is your height? ____**ft ____ inches**

2. What is your weight? ______ **lbs**

3. What is your age? ________

4. What is your gender?
    a. Male
    b. Female
    c. Non-binary

5. What is your sex?
    a. Man
    b. Woman
    c. Intersex

6. Do you identify as transgender?
    a. Yes
    b. No

7. Do you have freckles?
    a. Yes
    b. No

8. What is your skin color? (see color swatches)
    a. Ivory
    b. Beige
    c. Light brown

    d. Medium brown
    e. Dark Brown
    f. Very dark brown

9. What is your eye color?
    a. Light blue, light gray, or light green
    b. Blue, gray, green
    c. Hazel, light brown
    d. Dark brown
    e. Dark brown to black

10. What is your natural hair color?
    a. Red or light blonde
    b. Blonde
    c. Dark blonde or light brown
    d. Dark brown
    e. Dark brown to black
    f. Black

11. How does your skin react to the sun?

a. Always freckles, always burns and peels, never tans
b. Usually freckles, burns and peels often, rarely tans
c. Might freckle, sometimes burns, sometimes tans
d. Doesn’t usually freckle, burns rarely, tans often
e. Doesn’t freckle, almost never burns, always tans
f. Never freckles, never burns, tans darkly

12. Do you have a relative with skin cancer?
    a. No
    b. Yes
    c. I don’t know

13. How much time do you spend outside every day during daylight hours in the warm season?
    a. Less than 2 hours per day

    b. More than 2 hours per day

14. When you exercise outside in the summertime, it usually occurs:
    a. During morning hours
    b. Midday
    c. Late afternoon
    d. After dark

15. People who spend a lot of time outside in the sun are at increased risk for skin cancer.
    a. Disagree
    b. Somewhat Agree
    c. Neutral
    d. Agree
    e. Completely Agree

16. How many days per week do you use sunscreen in the warm season?
    a. Never
    b. 1 – 3 days
    c. 4 – 7 days

17. Do you perform any of the following sun-protective behaviors on a daily basis in the warm season? *[check all that apply]*

- ☐ Sunscreen
- ☐ Sun protective clothing
- ☐ Hat
- ☐ Sunglasses
- ☐ Avoid peak sun hours
- ☐ Umbrella
- ☐ Find shadier places to spend time outdoors

APPENDIX C

POST-STUDY INTERVIEW PROTOCOL

The consent statement (not included here) was read prior to starting the interview.

Hi, my name is [NAME]. I am [ROLE IN PROJECT]. Thank you for agreeing to be interviewed. I am conducting a one-on-one interview regarding your participation in my June 2019 research project on wearable UV sensors. My goal is to understand how you feel about your UV exposure results and about wearing UV sensors while exercising. As a reminder, I am audio recording our conversation. This semi-structured interview should not take more than 45 minutes. If you prefer not to answer a question, we can skip it. If at any time you want to stop the interview, we can stop.
Do you have any questions before we begin?

1. How often do you exercise outdoors or indoors every week, on average?
2. Do you wear a wearable device on a daily basis? What functions do you use the most? (e.g., fitness, sleep.)
3.
    a. When exercising outside in the summer, what do you consider when choosing what to wear from a safety and comfort perspective?
    b. How do you decide when and where to go for exercising outside?
4. Last June, you performed [walking, jogging, and / or cycling] at [Noble Library, the neighborhood by Gammage Theater, and / or Tempe Beach Park].

We monitored your UV dose based on your skin type and wrist sensor [show Scienterra Dosimeter] during your activities. I will walk you through your results briefly.
[Title slide] From your data, I calculated an exposure to the side of your body, your face, and body parts facing up (shoulders, ears). I will provide four ways to show your results to you—two types of rings graphs, and two types of bar graphs. These graphs are four different ways of communicating the same information, and I would like to know which kind of graph you would prefer seeing on the face of a wearable or on a phone app.
On the graphs, you'll see that there are six different skin types. Skin type I is pale skin that burns quickly, and skin type VI is dark skin that takes a long time to burn. Based on your survey answers, you are [skin type].

You’ll also see the UV index, which predicts the level of solar UV radiation in Tempe during the time that you exercised. A UV index of 7 – 8 means that there is a high amount of UV radiation.

[Rings] These rings are showing your UV exposure during 30 minutes of activity in [location(s)]. As you can see, I have listed the date, location, time that you spent exercising, your skin type, and the UV index while you were outside.

a. Note that these results assume the sun hitting bare skin without sunscreen. The first set (1A) is your cumulative dose showing how far on your way you were to skin damage from the sun between 0-100% [*let them look, maybe they will ask a question*]. Now I will show you the same data, but inverse, where you see how much you have left before you get skin damage. [*let them look, maybe they will ask a question*].
b. Do you prefer (1A): cumulative dose (going up) on your way to sun damage or (1B): the amount of exposure you have left before potential sun damage (going down)? Why?

[Bars] Now we will look at another way to visualize the data. These bar graphs are showing the exact same information—your UV exposure during 30 minutes of activity in [location(s)].

a. The first set (2A) is your cumulative dose showing how far on your way you were to skin damage from the sun between 0-100% [*let them look, maybe they will ask a question*]. Now I will show you the same data, but inverse, where you see how much you have left before you get skin damage. [*let them look, maybe they will ask a question*].
b. Do you prefer (2A) cumulative dose (going up) on your way to sun damage, or (2B) the amount of exposure you have left before potential sun damage (going down)? Why?
c. Which version (rings vs. bars) would you prefer seeing on the face of a wearable or phone app, and why?

   d. If you could change how these results were portrayed, what would you like to see?
   e. Would such information be useful to you in your sun-protective behavior practices?

5. After viewing your results, do you feel concerned about how much UV you are exposed to while exercising outside in the Phoenix area in the summertime?
6. After viewing your results, would you change where you exercise?
7. Do you perform any of the following sun protective behaviors daily during the warm season?
   a. Sunscreen
   b. Sun protective clothing
   c. Hat
   d. Sunglasses
   e. Avoid peak sun hours
   f. Umbrella
   g. Find shadier places to spend time outdoors
   h. Other
8. After viewing your results, will you increase the amount of sun protective behaviors you perform? Why or why not?
9. How many days per week will you use sunscreen in the warm season?
   a. Never
   b. 1 – 3 days
   c. 4 – 7 days
10. People who spend a lot of time outside in the sun are at increased risk for skin cancer.
   a. Disagree
   b. Somewhat Agree
   c. Neutral
   d. Agree

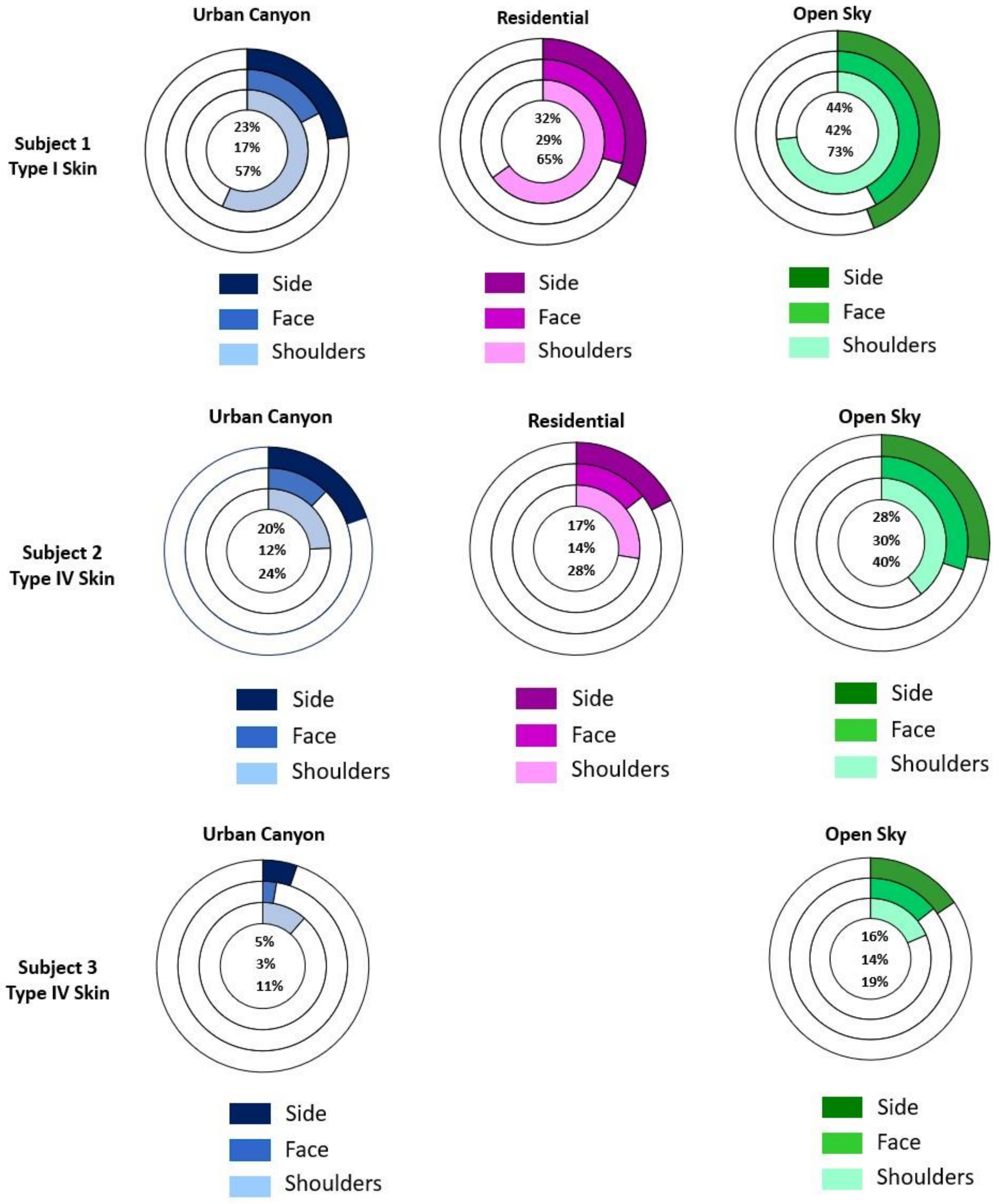
    e. Completely Agree

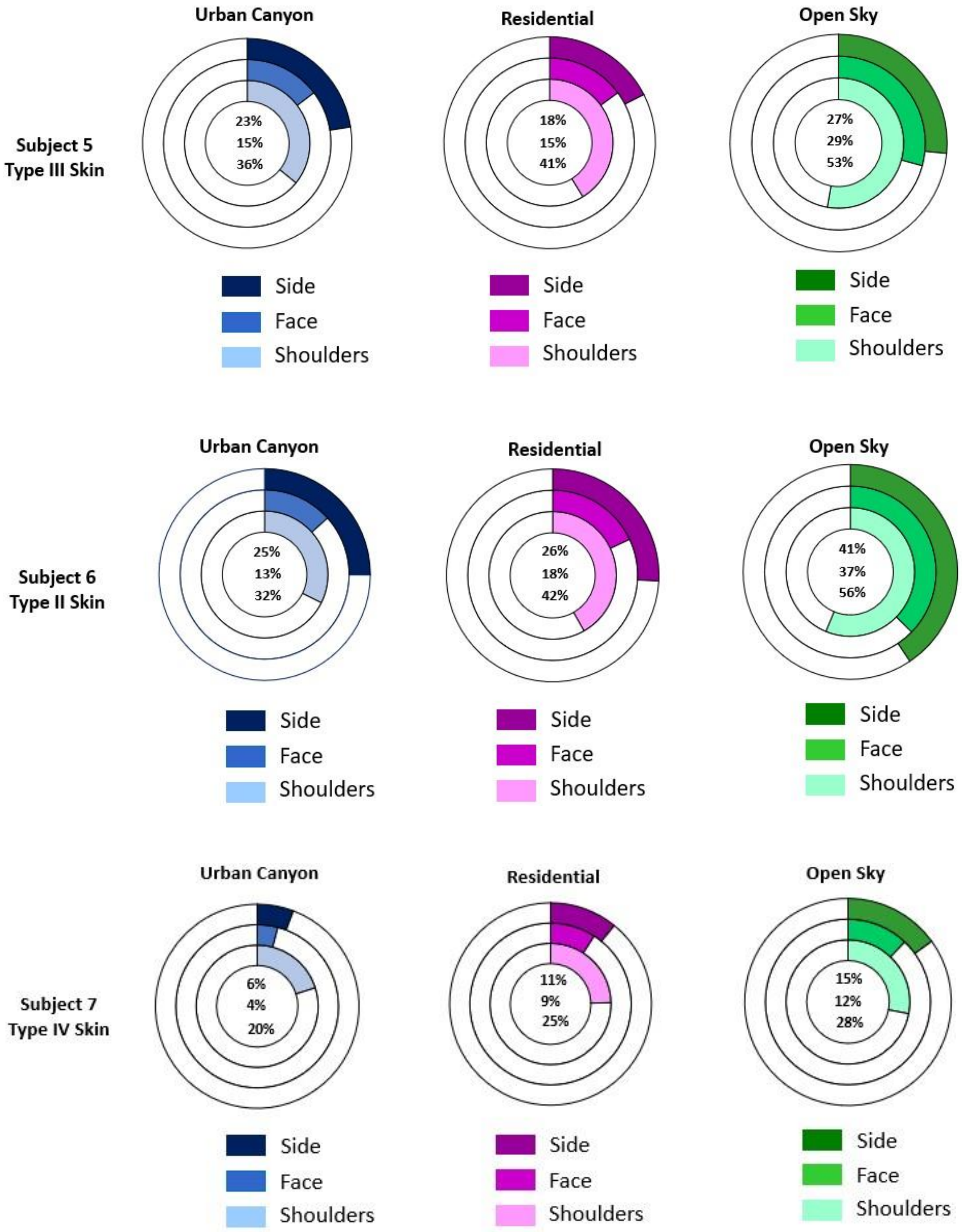
11. If a wearable device (such as a sticker, patch, or watch) was available that monitored and reported your sun exposure to UV radiation from sunlight, how likely would you be to use it to guide your sun protective behaviors?

Is there anything else that you would like to add?

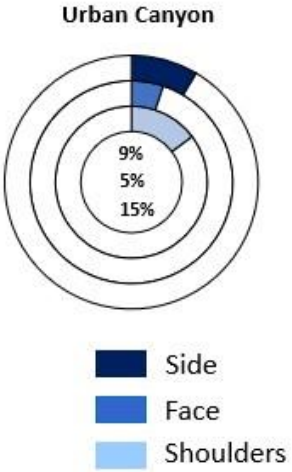
APPENDIX D

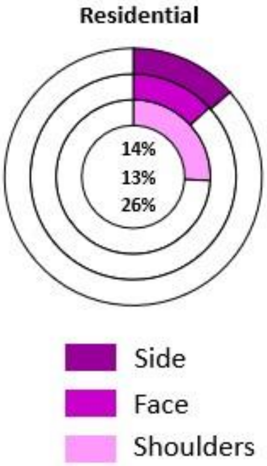
ADDITIONAL RING GRAPHS FOR UV EXPOSURE BY BODY AREA FOR HUMAN SUBJECTS

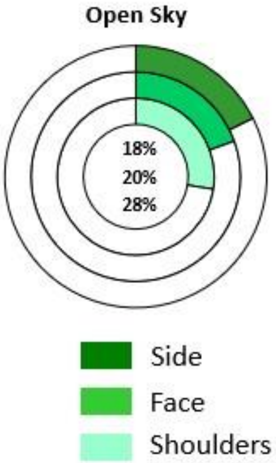

Urban Canyon
Residential
Open Sky
Subject 1
Type I Skin
23%
17%
57%
32%
29%
65%
44%
42%
73%
Side
Face
Shoulders
Side
Face
Shoulders
Side
Face
Shoulders
Urban Canyon
Residential
Open Sky
Subject 2
Type IV Skin
20%
12%
24%
17%
14%
28%
28%
30%
40%
Side
Face
Shoulders
Side
Face
Shoulders
Side
Face
Shoulders
Urban Canyon
Open Sky
Subject 3
Type IV Skin
5%
3%
11%
16%
14%
19%
Side
Face
Shoulders
Side
Face
Shoulders


Urban Canyon
Residential
Open Sky
Subject 5
Type III Skin
23%
15%
36%
18%
15%
41%
27%
29%
53%
Side
Face
Shoulders
Side
Face
Shoulders
Side
Face
Shoulders
Urban Canyon
Residential
Open Sky
Subject 6
Type II Skin
25%
13%
32%
26%
18%
42%
41%
37%
56%
Side
Face
Shoulders
Side
Face
Shoulders
Side
Face
Shoulders
Urban Canyon
Residential
Open Sky
Subject 7
Type IV Skin
6%
4%
20%
11%
9%
25%
15%
12%
28%
Side
Face
Shoulders
Side
Face
Shoulders
Side
Face
Shoulders

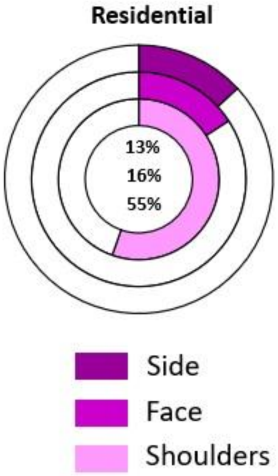
Subject 8
Type V Skin



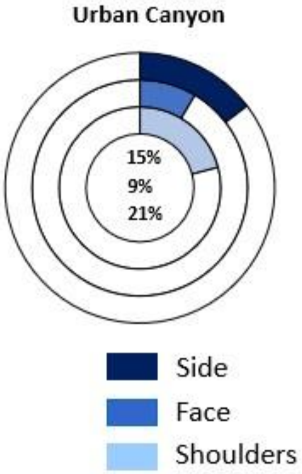


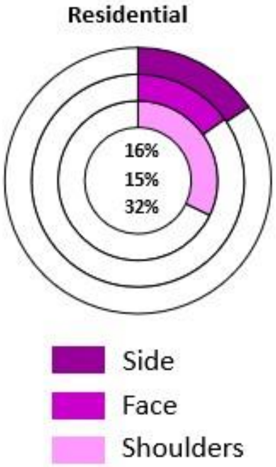


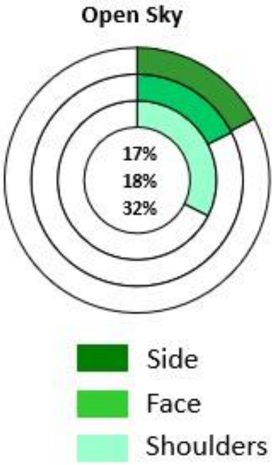
Subject 9
Type II Skin



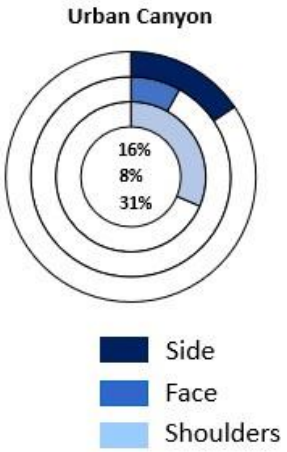
Subject 10
Type IV Skin

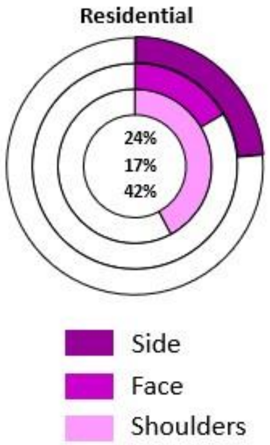


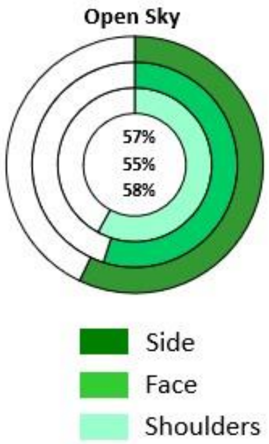




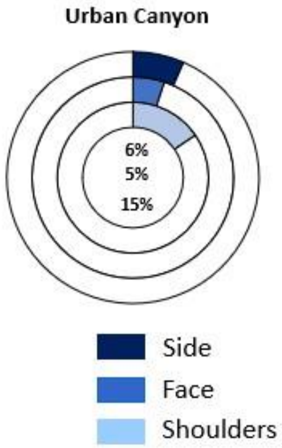
Subject 11
Type II Skin



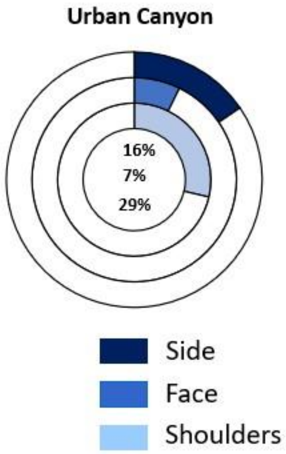




Subject 13
Type IV Skin

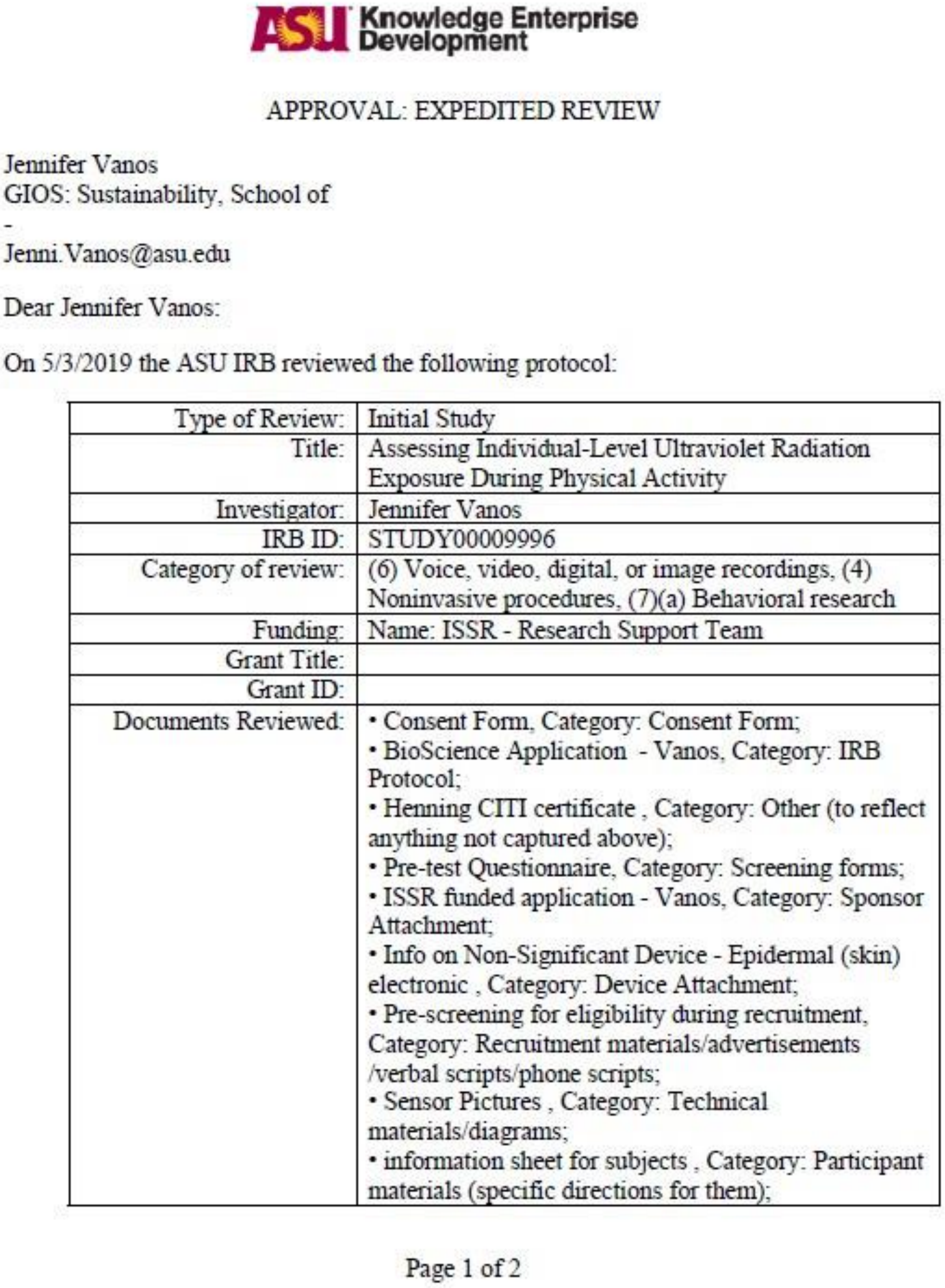


Subject 14
Type II Skin



APPENDIX E

ARIZONA STATE UNIVERSITY HUMAN SUBJECTS INSTITUTIONAL REVIEW BOARD DOCUMENTS



ASU Knowledge Enterprise Development

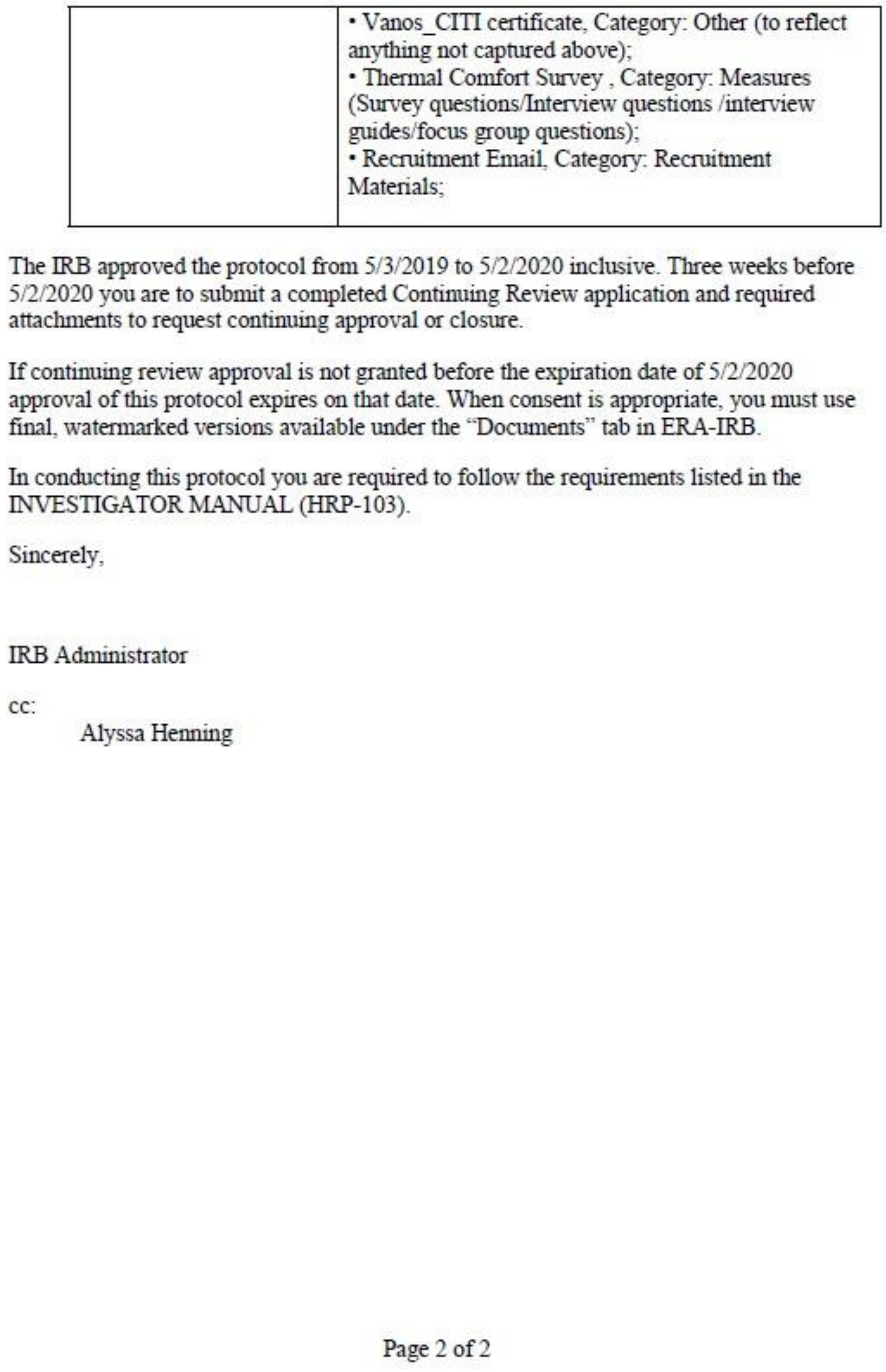
APPROVAL: EXPEDITED REVIEW

Jennifer Vanos
GIOS: Sustainability, School of
-
Jenni.Vanos@asu.edu

Dear Jennifer Vanos:

On 5/3/2019 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Assessing Individual-Level Ultraviolet Radiation Exposure During Physical Activity
Investigator:	Jennifer Vanos
IRB ID:	STUDY00009996
Category of review:	(6) Voice, video, digital, or image recordings, (4) Noninvasive procedures, (7)(a) Behavioral research
Funding:	Name: ISSR - Research Support Team
Grant Title:	
Grant ID:	
Documents Reviewed:	• Consent Form, Category: Consent Form; • BioScience Application - Vanos, Category: IRB Protocol; • Henning CITI certificate , Category: Other (to reflect anything not captured above); • Pre-test Questionnaire, Category: Screening forms; • ISSR funded application - Vanos, Category: Sponsor Attachment; • Info on Non-Significant Device - Epidermal (skin) electronic , Category: Device Attachment; • Pre-screening for eligibility during recruitment, Category: Recruitment materials/advertisements /verbal scripts/phone scripts; • Sensor Pictures , Category: Technical materials/diagrams; • information sheet for subjects , Category: Participant materials (specific directions for them);



	• Vanos_CITI certificate, Category: Other (to reflect anything not captured above); • Thermal Comfort Survey , Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Recruitment Email, Category: Recruitment Materials;

The IRB approved the protocol from 5/3/2019 to 5/2/2020 inclusive. Three weeks before 5/2/2020 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 5/2/2020 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:
Alyssa Henning

Page 2 of 2

APPENDIX F

PUBLICATION STATEMENT

The second chapter of this dissertation, Wearable Ultraviolet Radiation Sensors for Research and Personal Use, will be published in the *International Journal of Biometorology*. The journal’s editor-in-chief accepted it on October 25, 2021. The author of this dissertation is the primary author. The co-authors, Dr. Jennifer Vanos and Dr. Nathan Downs, who are also a dissertation co-chair and a committee member, respectively, approve of the upcoming journal article being included in this dissertation. The dissertation chapter is the most current version of the article pre-publication.