Beyond Visible Light: User and Societal Impacts of Egocentric Multispectral Vision

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Abstract. Multi-spectral imagery is becoming popular for a wide range of application fields from agriculture to healthcare, mainly stemming from advances in consumer sensor and display technologies. Modern augmented reality (AR) head-mounted displays already combine a multitude of sensors and are well-suited for integration with additional sensors, such as cameras capturing information from different parts of the electromagnetic spectrum. In this paper, we describe a novel multi-spectral vision prototype based on the Microsoft HoloLens 1, which we extended with two thermal infrared (IR) cameras and two ultraviolet (UV) cameras. We performed an exploratory experiment, in which participants wore the prototype for an extended period of time and assessed its potential to augment our daily activities. Our report covers a discussion of qualitative insights on personal and societal uses of such novel multi-spectral vision systems, including their applicability for use during the COVID-19 pandemic.

Keywords: Multi-spectral Vision · Augmented Reality · Optical See-Through Head-Mounted Displays · Extended Perception · Thermal Vision · Ultraviolet Vision · User study.

1 Introduction

With new developments in low-cost imaging sensors that can be tuned to different wavelengths of the electromagnetic spectrum, sensors are becoming more affordable and attractive for potential users and practitioners in different application fields. At the same time, we are also seeing advances in novel display technologies. Consumer augmented reality (AR) displays, in particular optical see-through head-mounted displays (OST-HMDs) such as the HoloLens 1 and 2 or the Magic Leap One, have been released over the last few years that integrate a variety of visual and auditory sensors, displays, and processing hardware. While these solutions already combine a multitude of sensors, including infrared (IR) and RGB cameras, these display platforms are capable of easily integrating additional sensors that cover more or different parts of the electromagnetic spectrum.

Several different systems and research prototypes have been developed over the last several years that incorporate additional sensors onto an AR HMD in an effort to augment the user's visual capabilities by feeding data from multi-spectral imaging sensors into user's view of their environment. Most prominent are thermal displays, such as a FLIR thermal camera integrated into the DAQRI Smart Helmet or the U.S. Army's IVAS version of the HoloLens 2. Another example is a research prototype by Erickson et al., who integrated a HoloLens with two FLIR thermal cameras that could be overlaid stereoscopically over the user's view of the real world [16]. Orlosky et al. also developed a framework called VisMerge that supports developers in spatially and temporally calibrating HMDs with infrared cameras [37].

While these multi-spectral imaging sensors are relatively new in combination with AR displays, they are already widely used in different professional application fields. A prominent example is in healthcare, where we have seen thermal infrared sensors used in many contactless thermometers during the current COVID-19 pandemic. Near-infrared wavelength sensors are also used to determine the amount of blood in a given area of tissue and the amount of blood that is oxygenated [10,49]. Another example is in agriculture, where IR or ultraviolet (UV) multi-spectral imaging sensors, sometimes mounted on airborne sensor platforms [40], are widely used to determine variations in the texture of soils to identify different soil zones and locating variability in crop emergence and biomass [23,28,44]. Beyond these domains, multi-spectral sensors tuned to the human body temperature among the thermal wavelength IR band have also been widely used for many defense or disaster management applications [5,43].

Because of the diverse range of domains that utilize these sensors and the ease of their integration into AR HMDs, it is possible that consumer grade AR HMDs will incorporate such sensors into their designs in the near future. This means that users of the AR HMD have access to these sensors for use in not only professional domain-specific applications, but also for daily use under otherwise normal circumstances. This raises interesting research questions about how having access to multi-spectral vision can affect the daily lives of users:

1. What are the possible use cases that regular consumers can benefit from this multi-spectral vision?
2. How does having access to this multi-spectral vision affect the behavior of users?
3. What are the social implications of widespread usage of this technology?

In this paper, we present our methods of implementing a prototype multi-spectral vision AR HMD that incorporates consumer off the shelf (COTS) thermal infrared and ultraviolet sensors onto the Microsoft HoloLens 1. We also present an exploratory user study where users were tasked with wearing the prototype system for an extended period of time, and we discuss the results in terms of the above research questions.

This paper is structured as follows. Section 2 presents an overview of related work. Section 3 describes the our multi-spectral vision prototype and study design. Our findings are presented in Section 4 and are discussed in Section 5. Section 6 concludes the paper.

2 Related Work

In this section, we discuss related work on the uses of IR and UV imaging sensors in the scope of our multi-spectral AR research. As discussed earlier, most of the previous work in this domain has focused on professional applications with hand-held or drone-mounted imaging sensors, with limited work investigating AR displays and daily activities.

2.1 Thermal Infrared Spectrum

With the advent of low-cost commercial off-the-shelf (COTS) thermal IR cameras over the last years, e.g., from FLIR, thermal IR images have been utilized extensively for applications spanning across a wide range of domains, including medical applications [24], defense [2,8,3], surveillance [47,56], and firefighting [45]. While the resolution of these cameras is still far behind the state of the art in RGB camera technologies, it has greatly improved over the last years, as has their form factor and developer support [11,14,26].

In medical diagnostics, the use of thermobiological information traces back to the writings of Hippocrates around 480 BC [24], and IR-based thermography has been used for decades due to the ability to monitor the temperature distribution on human skin. Jones pointed out the usefulness of such IR imaging to detect abnormalities in physiology while summarizing the methodology and applications for body temperature detection and analysis [25]. Non-invasive near-infrared spectroscopy (NIRS) methods have been introduced to monitor muscle oxygenation and blood flow and detect tissue vasculature problems, such as vascular sarcomas [10,49].

In the context of disaster control or first responder activities, thermal IR cameras have been used by firefighters for a long time [7]. Recently, Sosnowski et al. developed a prototype firefighter helmet that integrates both an OLED display and thermal IR cameras [45]. Such a design enables firefighters to see through the blinding thick smoke that often fills the environments that they work in. Enhanced perception with such devices can protect the firefighter from stepping into unseen danger and allow them to be more efficient in rescuing people trapped in danger. Rudol and Doherty integrated the thermal imaging system in unmanned aerial vehicles (UAVs) and found that the thermal images could improve the human (victim) detection rate in rescue missions from a distance [43].

Such thermal IR-based human body detection are further used in defense and surveillance applications, where the narrow band of normal human body temperature of 36.5–37.5$°C$ can be identified [2,8,3]. Beyond body detection, thermal images can also be used for emotion detection in social contexts. Pavlidis et al. suggested an IR-based anxiety detection method to identify suspects engaged in illegal or harmful activities in military or civilian installations [39]. Military systems have also been utilizing IR sensors to detect and track non-human targets for space and missile defense [5].

Thermal images have also been used in many other application domains. In building diagnostics, thermal cameras have a long history of being used to detect structural defects and design flaws [4,46,27]. In agriculture, IR images have been utilized to monitor plants and detect diseases [44,23,13,36]. Urban heat distribution, such as urban head island effects, can be analyzed by the integration of IR images in geographic information systems (GIS) [29]. The automotive industry uses thermal images to detect humans or animals based on their body heat in the dark [18,55].

Despite the large volume of professional IR use cases, not much research has focused on daily activities or its effects on human perception.

2.2 Ultraviolet Spectrum

Compared to IR, the UV spectrum is largely unexplored with respect to the field of AR. This mainly stems from UV light being near-absent in the indoor spaces where AR was used traditionally.

However, UV light has several interesting properties that have been examined in the past. UV rays primarily come from the sun and are categorized in UV-A, B, and C, each corresponding to a specific wavelength. UV-A and B are responsible for causing sunburns, but can also induce eye conditions, such as cataracts and macular degeneration [42], and skin conditions like melanoma [35].

Fulton described how UV-filtered photos show the effects of UV exposure, which are now commonly used in dermatology clinics to educate patients on the dangers of UV exposure [17]. Zhang et al. developed a prototype AR HMD that detects the presence and amount of UV in the user's environment through UV sensors and alerts them to the dangers of UV exposure by changing the user's skin color through the AR display to appear as though it had burned from UV exposure [54]. Their users, in general, agreed that the system was helpful in alerting them to the presence of UV, and they felt that they were better protected from UV by this system.

UV rays are not always harmful and have benefits for human health such as vitamin D synthesis when exposure is moderated [30,53], and in medicine such as in ultraviolet germicidal irradiation (UVGI), which has been historically used as a means of decontamination [41], and dental inspection [21,38]. UV fluorescence imaging is further used to detect flaws in insulators of transmission lines [1] and in photovoltaic plants [32], the latter showing superior performance compared to the common inspection techniques using thermography [33].

Wilkes et al. pointed out that the high cost of such systems is affecting their widespread use and to remedy this issue they developed a low-cost UV imaging system marketed for cellphone cameras [50]. With volcanology as one of the main areas utilizing UV imaging [31,9], Wilkes et al. deployed a modified version of their previous low cost system to measure the sulphur dioxide gas emissions of volcanoes, finding that their system's performance was comparable to more expensive scientific cameras [51].

There is a lot of potential for the use of the UV spectrum for educational, art, and interactive purposes. Munnerley et al. discussed the benefits of augmenting students' senses with multi-spectral imagery to challenge them about the limitations of their vision and how it affects their perception and understanding [34]. Eck et al. used multi-spectral sensors (UV, x-ray and IR) to perform art inspections (e.g., underdrawings in paintings [6]) in an interactive museum experience, where visitors were able to switch between these multi-spectral images and reveal the effects of each image captures on the digital replicas of the paintings by using a spray can interface with an IR light which was tracked by a Wiimote [48]. They pointed out that even with some technical limitations such as tracking issues, visitors exhibited a lot of enthusiasm.

3 Experiment

In this section we describe our implementation of a prototype multi-spectral vision AR HMD and present an exploratory experiment that was conducted to better understand the potential benefits and drawbacks of AR multi-spectral vision for daily activities.

3.1 Multi-spectral Vision OST-HMD Prototype

For the purposes of this experiment, we developed a prototype multi-spectral AR OST-HMD that consists of a Microsoft HoloLens 1, augmented with two pairs of spectral imaging sensors:

- **Thermal Infrared Cameras:** Two FLIR Lepton 3.5 Radiometric thermal IR cameras (housed in PureThermal 2 I/O modules) and
- **Ultraviolet Cameras:** Two XNiteUSB2S-MUV 2 Megapixel UV cameras.

The prototype display is shown in Figure 2. Effectively, we turned a COTS AR display into a multi-spectral display using COTS IR and UV cameras. The thermal cameras have a resolution of 160×120 pixels and a field of view of $56°$ horizontally and $44°$ vertically, which is slightly larger than the HoloLens ($30°$ horizontally and $17°$ vertically). These IR cameras sense a range of 8–14 μm in the infrared spectrum known as thermal vision. The Lepton 2 breakout boards were attached to the top of the headset, 0.08 m above the participant's eyes and at a separation of 0.17 m apart. The UV cameras sense the range of light between 365–380nm, with a resolution of 1920×1080 pixels and a field of view of $163°$ horizontal and $92°$, vertical. They were mounted on a bracket alongside the thermal cameras 0.08 m above the participant's eyes, at a slightly greater separation of 0.245 m.

Due to the lack of USB ports on the HoloLens itself, the cameras were tethered to a backpack computer (MSI, Intel Core i7-7820HK 2.9 GHz CPU, 16 GB RAM, Nvidia GTX 1070 graphics card, Windows 10 Pro) which utilized a cellular mobile hot-spot to stream imagery to the HoloLens via Unity version 2018.2.11f1 in holographic remoting mode. We used the FLIR Lepton user app to connect and configure the infrared cameras, and the UV cameras were used as plug-and-play web-cams with default settings, then the camera streams were accessed through Unity. In our Unity implementation, the sensors were treated as USB webcams, which allowed imagery to be streamed in real time over the network where it was presented on built-in Unity UI canvas and rawimage game objects.

We aimed to test the prototype both indoors and outdoors, however the imagery presented by the HoloLens 1 is difficult to observe outdoors due to the limited luminance capabilities of the display [15]. For this reason, we created a visor that could be attached to the HoloLens when outside. This visor consists of two stacked sheets of neutral density filters, one with an optical density of 0.6 and another with a density of 0.9. This combination blocks 37.5% of all incoming light and greatly improves the contrast between the virtual imagery and user's physical environment.

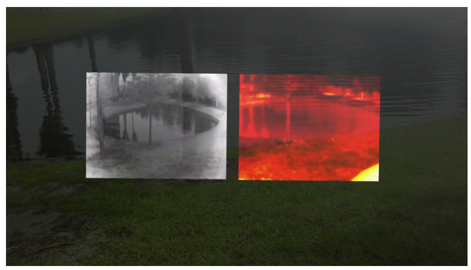

Fig. 1. The combined display mode features side by side views of the UV imagery (left) and thermal imagery (right).

Multi-spectral Vision Modes Three different display modes were implemented, which could be toggled by pressing a button on a wireless mouse that users carried with them while using the prototype system. These views included stereoscopic views of the thermal infrared or ultraviolet sensors separately, and also included a combined view where a single camera stream from one thermal infrared sensor was shown on the right portion of the display and the stream from one ultraviolet sensor was shown on the left (see figure 1.) A stereoscopic view of both sensor pairs simultaneously was tested, but ultimately was not used due to running into network limitations when attempting to stream imagery from all four sensors simultaneously.

We further implemented a scaling feature that allowed us to use the scroll wheel on the wireless input device to scale the size of the image regions depicting the camera feeds in the field of view. We included this feature to allow us to get a closer view and inspect features in the camera feeds or reduce them in the visual field. Screenshots of these display modes, taken via the HoloLens' mixed reality capture, can be seen in Figures 1 and 6.

The thermal IR camera feed was presented to the participants using a shader that mapped the temperature of the scene to particular colors. The camera also made use of an automatic gain control feature that would find the hottest

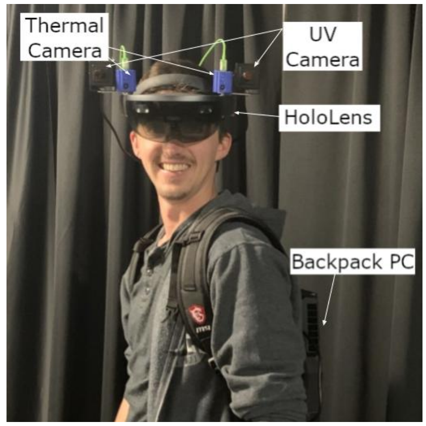

Fig. 2. Annotated photo showing the multi-spectral HoloLens prototype we used in the experiment, including the backpack computer and attached thermal IR and UV cameras.

and coldest areas of the scene, and automatically calibrate the shader so that the coldest object appeared black and the hottest appeared white, which thus maximizes the discernible range of temperatures within each view. The shader uses a linear mapping of temperatures to colors from coldest to warmest, where black is used to depict the coldest temperatures, followed by red, orange, yellow, and then white.

The UV camera feed was presented to the participants in standard grayscale, offering a distinct contrast in imagery between the footage from the UV and thermal IR cameras.

3.2 Participants

Five male and two female (ages between 19 and 37, $M = 28.6$, $SD = 7.0$) participated in our exploratory study. All had normal or corrected-to-normal vision. Four participants wore glasses during the experiment. None of the participants reported known visual or vestibular disorders, such as color or night blindness, dyschromatopsia, or a displacement of balance. All participants were students, researchers, or professionals in AR/VR sensor and display technologies.

3.3 Methods

We asked our participants to explore the usefulness of the multi-spectral vision prototype for daily activities and societal uses for at least 45 minutes with the option to continue on for up to two hours. We instructed participants to take notes and/or take screenshots on the HoloLens when they observed an interesting use of the IR/UV views. We also used retrospective probing, in which an experimenter asked questions during short breaks and after completion of the experiment. At the end of the experiment, everyone filled out a demographics and experience questionnaire with open questions.

Following the completion of the study by all participants, we had a debriefing session where all of the participants discussed their experience and observations.

4 Results

Based on the observations of the participants, we see two main advantages of multi-spectral vision for our daily activities and society at large (not focusing on professional applications):

1. **A1** Simplifying tasks that would have otherwise required more time or effort.
2. **A2** Providing novel signals that have the potential to be useful as cues for interpersonal communication, in daily activities, or personal health.

In the following section, tags (such as **A1** or **A2**) will be placed at the end of sentences that support these advantages of multi-spectral vision.

Identifying Medical Conditions Due to the narrow band of 36.5–37.5$^{\circ}C$ of normal human body temperature, most peoples' skin temperature looked roughly the same in thermal vision, however if their temperature was changed to be out this range it was a very apparent change on the display. During the experiment, we came across a specific situation that indicated a person's skin temperature appeared much lower than that of other people. We first attributed this to other effects, e.g., environmental or activity-related, but we investigated it further in different environments and found an explanation in the person's known medical condition of low blood pressure. Figure 3 shows a side-by-side comparison of a person's normal temperature on the right and the person's decreased temperature on the left. These differences remained consistent and apparent over different environments and on other days following the study; they were most apparent on the face and the hands. Furthermore, that person had a history of subjectively feeling colder than other people in the lab, which is a known by-product associated with low blood pressure, just as high blood pressure is associated with subjective feelings of warmth or heat. While low blood pressure is usually no reason for concern, according to the CDC, 32% of Americans have high blood pressure, which is a primary or contributing cause of death for more than 1,100 deaths/day in 2014 [12]. Only 54% of people with high blood pressure have their condition under control, e.g., by taking medication.

Beyond this example, we could see thermal skin temperature measures being used to identify symptoms for other medical conditions, and even prevent the spread of diseases such as COVID-19 [**A2**]. While this was not encountered during our study, the multi-spectral vision prototype should be able to easily detect people running fevers, which could alert the user to avoid contact with them. Several participants noted that they "could see a reflection of [their] body while looking at see-through glass, but the reflection was a heat image of [their]

Fig. 3. Identifying medical conditions: Example thermal IR view with the person on the left having low blood pressure compared to normal blood pressure on the right.

body." It became apparent that the thermal feed could also be examined via reflections off specular surfaces similar to traditional RGB wavelengths. If such a property is exploited, it could potentially alert a user if they themselves are running a fever when checking their reflection in the bathroom mirror in the morning, or future AR mirrors might include thermal IR imagery to facilitate this health feature without the need to wear an AR HMD (e.g., see Microsoft's Holoflector [52]) [**A1, A2**]. The ability to see one's own temperature with AR displays, e.g., when checking one's thermal reflection in a mirror in the morning, could provide a quick and useful measure in maintaining a healthy life [**A1,A2**].

Measuring Temperatures at a Glance A practical aspect of seeing thermal IR was that it allowed users to make objective measurements of temperature without physically being in contact, or even near, the object of interest [**A1**].

In several situations, in particular occurring at home during the study, participants were alerted of hot toasters and stoves in thermal IR vision that appeared to be normal room temperature when viewed in the visible light spectrum. By being able to know the temperature prior to coming into contact with the appliance or object, accidental burns could be prevented. Practically, just by looking around with thermal vision, one could not help but be situationally aware of potential threats due to visual areas that are noticeably too hot (bright yellow; could burn oneself if touched) or too cold (black; could freeze oneself if touched) [**A2**]. Participants indicated that for the goal to *prevent accidents*, a simplified color scheme would be sufficient or even better suited, e.g., glowing blue for "too cold" and glowing red for "too hot." Using such a color scheme, normal room temperature objects could be ignored and left un-annotated in terms of AR effects.

One participant completed their entire trial around their home, and was surprised by the wealth of information that could be gathered by using the multi-spectral vision device. They stated that they were "able to notice wet spots on the carpet" with the thermal vision that were unseen to the naked eye (a scenario many pet owners are likely familiar with) [**A1**]. With the device, the user was able to locate the exact position of the mess as well as see that it had been cleaned up properly, all by examining the differences in temperature between the affected portion of carpet and the unaffected area around it. The same participant also noticed that they could "identify which houseplants were watered recently" by their spouse and which had not. The recently watered plants had cool dark-colored soil when observed with thermal IR vision, whereas the soil surrounding the plants in need appeared to be at room temperature [**A1**].

When examining doorways and windows under thermal vision, several participants had interesting observations. One participant noted that they "could tell exactly where the doors leading outside were because of the intense heat on the door". Another participant noted that it was possible to "see which doors were letting heat in from outside" [**A1**]. Upon close inspection of the latter it was noted that the weather strip was not making an airtight seal between the door and the frame. Such a feature may be useful to people who are interested in keeping air conditioning and heating costs down, by helping them find the specific places that could be better sealed or insulated. Similarly, when opening a door or window, it became possible to see how the room temperature changed, e.g., seeing a progression of colors in the room that were in line with being drained of warmth or heating up depending on the temperature outside, before it "leveled out" and remained at a constant temperature level.

One of the participants spent their trial during lunch time, and wore the multi-spectral vision device while walking across the street to a local smoothie restaurant. One of their observations was that they could "tell how much smoothie [they] had left in [their] opaque cup without needing to touch it or take the lid off," which is related to a difference in surface temperature on the cup as shown in Figure 4 [**A1**]. This same participant also ordered a hot lunch, and noted that they were able to see how hot the food was upon receiving it from the server, as well as see it cool down over time as it was left on the tray. Spending their time in an office environment, other participants reported as useful that they could see if their coffee was already cold in their mug without having to taste it [**A1**].

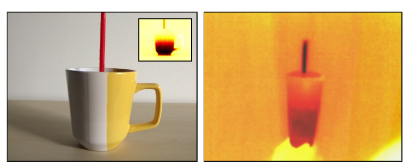

Fig. 4. Opaque mugs and cups and their thermal representation. In particular, the right image shows how much of the smoothie is left inside the cup.

Residual Heat Affects Behavior When walking around their work environment, participants noted that they could tell which furniture was recently used by observing the residual heat left over on the cushion [**A1,A2**]. This information might further affect one's behavior by avoiding a chair when entering a meeting room that is clearly warmer than the others due to a feeling of "someone else is/was sitting there," which is shown in Figure 5. In that sense, the residual heat could be associated with a *residual presence* of that person [19]. Residual heat could even be seen on the floor if someone had stood in the same place for an extended period of time.

Fig. 5. *Which chair would you sit in?* RGB and thermal IR views showing office chairs of which one has been occupied recently.

Heightened Sensitivity to Security Concerns During the study, several participants performed routine tasks while seeing the thermal IR imagery that increased their sensitivity to security related issues, e.g., led them to be more careful when interacting with keycode or password protected doors or computers. For instance, one participant observed that they transferred heat between themselves and keypads/keyboards. This transfer of heat was clearly visible in the thermal IR spectrum, and can give the user an idea of what buttons were pressed recently, e.g., within the last minute (usually between 25 and 50 seconds) [**A1**]. Further, we noticed that the transfer of heat can go in either direction, such as leaving a hot fingerprint behind as seen in Figure 6, or by touching the keyboard of a hot laptop computer, in which case a colder dark fingerprint is left instead of the former. After noticing how easy it was to pick out the characters or numbers in a password, participants became more conscious of this and one even noted that they adopted behaviors to compensate for this, e.g., by typing faster or wiping the panel.

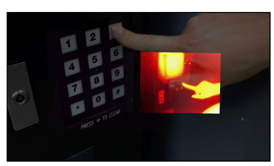

Fig. 6. Sensitization to security concerns: Residual heat from button presses on a keypad.

Enhanced Visibility of Humans and Other Entities As mentioned previously, due to their comparatively high body temperature, humans are easy to spot when looking at them through the thermal IR display mode in the multispectral vision device. This phenomena is not limited to people, and also occurs for certain animals and other dynamic entities. Two participants in the study noted that they were able to clearly make out the warm bodies of a flock of birds that were meandering about outside [**A1**]. The birds were clearly visible against the even coloration of the grass they were walking over. Another participant noticed that they were even able to pick out an airplane flying overhead in the same manner, where the plane appeared hot against the even background of the sky [**A1**]. Contrary to most participants' expectations, most smaller animals could not be made out in the thermal IR mode. In particular, reptiles, amphibians, and insects were not directly visible in the thermal IR view since their body temperature depends largely on the environment. Similarly, not many smaller animals maintain a high body temperature as humans and thus were less easy to make out in the environment.

Understanding Sunscreen and UV Light We conducted the experiment during the summer and several participants applied sunscreen during their trial, and observed the effects with the UV vision mode. The left picture in Figure 7 shows an (anonymized) UV image that illustrates the effects of sunscreen (sun protection factor SPF 60) applied to half of the person's face. The sunscreen-protected areas appear darker and a clear line is visible on the person's nose, forehead, and chin that shows the difference between the presence of sunscreen and the absence of it. The right picture shows one of the participants applying a small stripe of sunscreen to their outstretched arm. The sunscreen appears darker in UV light, so it is possible to see exactly where it has been applied. While usually transparent in normal human vision, it became possible to see if one missed a spot when applying sunscreen on one's body before one went out into the sun, which has the potential to avoid sunburns and improve personal health [**A1,A2**].

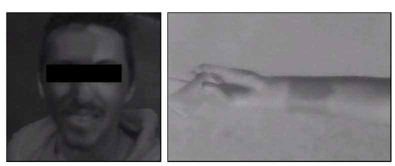

Fig. 7. Effects of sunscreen on the appearance of one's skin in UV vision. Skin areas protected by sunscreen appear darker in UV vision.

Reducing UV Light Pollution During the course of their trial, several participants noticed that many different lights emit small amounts of UV radiation. This was noticed in both overhead fluorescent lights, and traditional bulbs, but was not observed on any computer monitors or phone displays. Additionally, they found that certain equipment around the environment such as in tracking systems emitted small amounts of UV light. Similarly, several smart phones were observed, and while the phones themselves appeared pitch black in indoor environments, there was often a flashing LED on the front of the phone that emitted UV light but was invisible to the naked eye. Indoor sources of UV light were easy to make out in the UV vision mode, and replacing light bulbs with ones that emit no UV light could potentially improve personal health [**A1,A2**]. An indoor UV sterilization lamp was observed by one of the participants of the study, who thought that it may be possible to observe its area of effect through use of the UV sensor. They found that while the lamp itself was clearly visible on the display, it was not possible to see its area of effect via illumination of any of the surrounding surfaces.

A similar observation was made by one of our participants in that the UV cameras did not pick up any ambient UV from within indoor environments, even when positioned near large windows. Participants could see the ambient UV from the sun through the window, however the UV light was not apparent at all on any indoor surfaces.

5 Discussion

In this section, we discuss the main lessons-learned in terms of potential benefits and drawbacks for our society.

5.1 Societal Benefits

Most of the observations we made during the study were positive and suggested that multi-spectral vision could **make tasks easier** to accomplish in our daily life and save time. A primary example is the ability to directly see information, e.g., temperature, without having to find the information using some other means such as a smartphone app to check the weather or a thermostat to check the temperature in one's office. For instance, we often used it to answer the recurring question in our air-conditioned office spaces, "Is it cold in here or is it just me?" Before using thermal vision in our study, we had no proof that temperature actually varied a lot between a thermostat's location and the rest of the room.

A related benefit is that multi-spectral vision can **prevent accidents**, e.g., when we directly see the temperature of a hotplate or the interior of our car that was standing in the sun, which we otherwise would have to touch to know if the surfaces could burn us. Similarly, being able to see people and animals while driving at night or in other low-visibility conditions in the natural human spectral bands can prevent collisions that otherwise would be difficult to avoid. In the same sense, being able to see and avoid potentially dangerous animals that are well-camouflaged and unseen in the visible range of light could save one's life.

Further, multi-spectral vision can **improve situational awareness**. Having direct access to visual information from other spectral bands allowed us to see people and animals in low-visibility conditions, see if animals are hiding among the vegetation around us, see if other people in social situations are feeling hot or cold, see if IR-based tracking equipment in the laboratory is powered and active, or see how much potentially unwanted UV light is being emitted from equipment and lights within the laboratory.

We believe that having access to multi-spectral vision also has the potential to **improve personal health**. As mentioned previously, participants of the study were able to use thermal IR vision to identify abnormal temperature readings on themselves through the use of reflections and on others in the environment. They were able to notice signs of low blood pressure through decreased body temperature and might be able to pick out people who have unusually high temperatures which could be associated with a fever. By having easy access to this information, users could make more informed decisions on their own state of health, as well as point out abnormalities to others in their environment that they may have missed or ignored.

On the UV spectrum, participants were able to observe which areas were receiving the most UV exposure, and either avoid such areas or protect themselves from it by visualizing the places on their body that were not covered in sun screen. Participants were also able to note sources of UV emission in their home or working environments such as fluorescent and overhead lighting, and could use this information to reduce this amount of UV exposure they were experiencing indoors and better protect their eyes and skin from harm. As certain skin and eye conditions are linked to long term exposure to UV light, having access to this UV information may help prevent or slow the onset of some of these conditions, such as macular degeneration and cataracts [42], and skin conditions like melanoma [35].

While not being essential for our society, we believe that such benefits could increase public demand and become a driving force behind commercial products with multi-spectral vision integrated in future ubiquitous AR displays, ranging from personal AR goggles to in-car AR head-up displays.

5.2 Societal Drawbacks

Since our human sense of vision is limited to the red, green, and blue spectral bands, it is not possible to add other spectral information without changing or replacing other sensory information. In this study, participants toggled between different spectral bands or looked at insets in their visual field, but it will be an important challenge for the scientific visualization research community to identify methods to avoid **sensory or cognitive deprivation or overload** that stems from toggling through different bands or trying to compress information from the entire electromagnetic spectrum into the limited human spectral channels. If not solved, it is possible that we will see negative societal examples, such as **more accidents**, where people are distracted by the multi-spectral vision imagery and are not fully aware of their surroundings. This could be exaggerated by displays that are not lined up one-to-one with the user's environment or do not convey appropriate depth information to the user. Such issues may be addressed in future work by compressing relevant multi-spectral information into a single vision mode and by hiding non-relevant information, such as room temperature objects in thermal vision or areas with no UV light. However, such techniques are largely dependant on the user's task at hand and preferences could vary from user to user.

Some participants noted a feeling of **distraction or detachment** from conversations and social interaction while wearing our multi-spectral vision prototype. The HMD and different vision modes made it hard to make eye contact with another person and see the traditional (RGB vision) social cues as they occur during the interaction. The effect likely goes both directions, as the person that the participant is interacting with is likely feeling like they are not completely connecting with the participant due to the barrier of the HMD being between them. However, the participant who went out to lunch during their trial interacted with the cashier at the restaurant and reported that "the cashier didn't even mention the HMD or backpack computer. It was like they didn't even notice." While we found this example to be particularly humorous, it is likely the case that the cashier was simply being polite. As AR technology becomes smaller and more ubiquitous, the barrier between the user of the AR technology and the person they are interacting with will likely diminish, however as we make our way to that point it is important to consider these effects and barriers when designing user interfaces for these type of interactions.

We further have to point out that it is not universally positive that multi-spectral vision allows us to see more information that people in our society traditionally do not have access to, since some of this could be considered **private information**. An example are medical conditions that have discernible symptoms in different spectral bands such as low or high blood pressure, skin conditions, or strong cases of fever. By having access to this information, the user may inadvertently or purposely change their behavior towards that person, which may help prevent the spread of disease if the person actually had a fever, but may also damage interpersonal relationships if the cause of the temperature change was something benign (such as being caused by the environment or as a side effect of a medication).

In the UV spectrum, certain skin features such as freckles and moles are more prevalent than they are in the visible spectrum [17]. Some people do not like the appearance of these features even in visible light, and take measures to cover or obscure them from the people they interact with. These people will likely feel uncomfortable being around users of multi-spectral vision devices, as they will feel self-conscious about the appearance of these features in the UV spectrum. As multi-spectral vision becomes more common, we are likely to see people such as the ones described above, who want to keep certain personal or medical information to themselves, and therefore shy away from multi-spectral vision users due to privacy considerations. Due to issues such as the ones described above, we see a potentially transformative aspect of ubiquitous AR goggles with multi-spectral vision for our society in that it could **change societal norms and behaviors**.

5.3 Limitations

Observations in this study were limited to what the participants could visually perceive with the thermal IR and UV visualization techniques. Human vision is excellent in detecting differences and patterns in three wavelengths and with respect to luminance, but in this study it was capped by the temporal and spatial resolution of the available consumer thermal IR and UV cameras. Future versions of these cameras will likely provide more discernible features and lead to more information gained from these vision modes.

We would also like to note that human vision falls short in identifying certain features with respect to thermal IR and UV that machine learning approached are more suitable for. For instance, He et al. developed a system capable of classifying facial expressions from thermal imagery using a machine learning approach [20]. Additionally, Hu et al. developed a multi-camera system that combined IR and thermal sensors and is capable of monitoring both human heart rate and breathing rate simultaneously [22].

As multi-spectral vision technology and AR displays become more ubiquitous, such machine learning methods could be utilized along with the sensors and displays in order to make full use of the multi-spectral information.

6 Conclusion and Future Work

In this paper, we presented a qualitative report on lessons learned about potential societal uses and implications of AR-based multi-spectral vision enhancements focusing on the thermal IR and UV spectral bands during daily activities. We described a multi-spectral AR prototype based on a Microsoft HoloLens 1 with attached thermal IR and UV cameras. We presented a human-subject study, in which participants performed daily activities while wearing the HMD prototype. We discussed the potential of such AR multispectral vision enhancements with respect to different use cases, e.g., personal health, preventing accidents, and improving situational awareness.

For future work, we believe that more exploratory research is necessary to identify uses and drawbacks of such technologies to understand their societal implications, in particular with respect to vision augmentations that stem from different multispectral visualization methods for the camera streams or AR visual information created based on the output of machine learning approaches.

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