Exploration of Alternative Vision Modes Using Depth and Thermal Cameras

Yomna Abdelrahman[1], Pawel Wozniak[2], Pascal Knierim[3], Niels Henze[4], Albrecht Schmidt[3]
[1]VIS, University of Stuttgart and Bundeswehr University Munich, Germany
[2]University of Utrecht, Netherlands, [3]LMU Munich, Germany, [4]Univeristy of Regensburg, Germany
[1]{firstname.lastname}@vis.uni-stuttgart.de,[2]p.w.wozniak@uu.nl, [3]{firstname.lastname}@ifi.lmu.de,
[4]niels.henze@ur.de

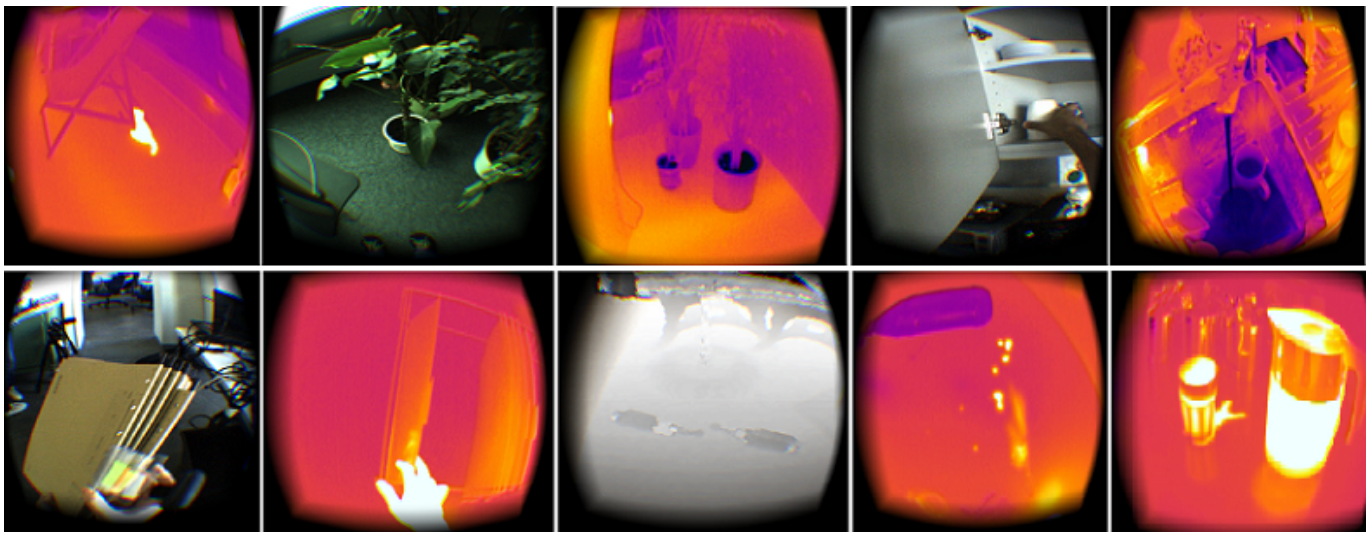

Figure 1: Images taken with *TriSight* by participants during the study that investigated infrared cameras as a daily alternative vision. Showing potential usage in finding the pet, checking and watering the plant and detecting leakage (from upper left to right).

ABSTRACT
Human vision is limited to a small band of the electromagnetic spectrum. It has been shown that extending visual perception can be beneficial, but it is unclear if this is useful for a broader range of applications. In this paper, we explore user reactions to extended visual perception. We describe the design and implementation of *TriSight*, a head-mounted display that allows the user to perceive the environment in the visual spectrum, the thermal spectrum, and through depth maps. In a study, we asked participants to perform everyday tasks in a created home, kitchen, office and basement with *TriSight*. Through analyzing videos, interviews, questionnaires and logs we chart the users’ feedback towards the augmented visual perception. Our findings, imply the positive impact of extended vision, as well as the potential of thermal vision as alternative perception mode in performing daily tasks. Finally, we discuss the implications for designing devices that extend human’s visual perception beyond the visual spectrum.

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CCS Concepts
•**Human-centered computing** → **Human computer interaction (HCI); Displays and imagers;**

Author Keywords
Amplified Vision; Thermal Imaging; Depth Sensor; Head Mounted Displays

INTRODUCTION
Our eyes can only perceive light falling in the visible light spectrum, which comprises less than 1% of the electromagnetic spectrum. Thereby the information about our surrounding we can perceive through the electromagnetic spectrum is naturally

limited. Evolution shaped human's visual system making it very well suited to enable human survival in nature. Other animals, such as bees and snakes, had other requirements and evolution consequently enabled them to perceive other parts of the electromagnetic spectrum. Modern society radically changed the environment we live in.

Technology enables humans to extend their abilities given to them by nature. Imaging technology has shown promising advancement in visualization and perception of the environment. For instance, depth cameras (e.g. Kinect) allow sensing the environment in 3D by utilizing near-infrared spectrum. Recently, thermal imaging (far-infrared) has become affordable for commercial and personal use in terms of cost and size, to the extend thermal imaging has been integrated in mobile phones[1]. Hence, enabling an extension of how we perceive, visualize and interact with the surroundings. As well sa novel HCI research [1, 3, 5, 18] Thermal imaging provides a heat map for the scene to the user in a contact-less and in real time, as it operates in a robust manner (e.g., light independent). Moreover, infrared imaging (including both near- and far-Infrared) enhances and extends the perception of our visual sensing. By using these cameras, we are capable of perceiving light outside the limited visible spectrum. Concurrently, head-mounted display (HMDs) and augmented reality (AR) have shown significant advancement in visualization and interaction challenges in multiple domains, e.g. gaming, medicine, manufacturing. Despite the advancement of AR applications, it is under-explored in daily life.

In contrast to traditional RGB cameras integrated in HMD and glasses, the design and integration of infrared cameras, especially in daily usage, have not been explored yet. In this paper, we investigate the potential of thermal and depth imaging for daily use. We build an initial prototype to explore the feasibility of vision extension and switching system with currently available technology. We conducted a study using the prototype to explore the temporarily of task scenarios and how users switch between vision modes. We determined practical and technical challenges for the development of tools that augment visual perception.

In this work, we are using a proof-of-concept prototype and created situations and environments. This work aim to inform technology and human factors design decisions towards a real interactive vision extension system for evaluation. We used the approach to achieve the fullest involvement of the user's in the design of the vision extension systems.

The contribution of this paper is threefold:

1. We present *Trisight* a proof-of-concept wearable augmented vision device, allowing users to see the environment in RGB, depth and thermal views.
2. An evaluation of *Trisight*, which shows the technical and practical challenges for systems that augment visual perception.
3. The discussion of challenges and implications for the design of future vision extension systems and tools.

[1] http://www.catphones.com/en-gb/phones/s60-smartphone

RELATED WORK

Previous research proposed several systems that enhance human visual perception in special scenarios and setups. In the following, we present prior work in research aimed to provide an extended visual perception using depth and thermal cameras.

Extending visual Perception

Research has been done to extend our visual perception, for instance Kimber et al. [13] used mirrors to augment user perception. Others looked into extending the perception via extending the field of view [9, 16, 17]. Recent research explored the visualization of electromagnetic radiation emitted from wireless technology such as Wi-Fi hotspots [10, 11].

One of the limiting factors in visual perception is the ability to infer exact depth information, for instance for navigation and obstacle avoidance. Biswas and Veloso used depth information for obstacle avoidance for autonomous navigation [8]. Their system work on the depth information alone and does not require RGB data. Izadi et al. presented KinectFusion, a system that allows users to hold a Kinect to generate 3D models of a scene in real-time [12]. Researchers argue that 3D maps have many applications, ranging from elderly support [22] robotics, telepresence, gaming and AR. They further state that they believe that the price of RGB-D cameras will decrease in the future, allowing the cameras to enhance different kinds of application scenarios, as well as human perception. Depth cameras have been explored and utilized in various applications and domains. However, there is limited research investigating the domestication of depth cameras beyond gaming.

Concurrently, thermal cameras operating in the far-infrared spectrum and can be used to extend the spectrum that is perceivable. Researchers highlight that thermal cameras are continuously getting cheaper and more and more cameras appear on the market. This enables thermal cameras to be used in a diverse set of applications, by enhancing existing application scenarios and opening new ones. Matsumoto et al. use KinectFusion and combine RGB-D camera with a thermal camera. This system allows a visualizing the thermal distribution in the environment [14, 15]. Vidas et al. combined a range sensor with a thermal-infrared camera in a hand-held system to generate dense 3D models of building interiors. Combining a low-cost RGB-D camera and a thermal-infrared camera enables generating 3D models that contain surface temperature information [20]. Van Baar et al. highlight how thermal cameras can be used to improve object segmentation [19]. Using thermal cameras has also been explored for expert users. Previous work explored how to extended visual perception in special situations and environments. For instance, it has been targeted for firefighters usage [2, 6, 7] Abdelrahman et al. discussed the potential of extending mountain climbers' vision using thermal cameras attached to a head-mounted display [4]. On the other hand, there is limited work on the usage of imaging technologies for novice users.

Past research shows that while users can benefit from additional vision modes [9], solutions that effectively deliver

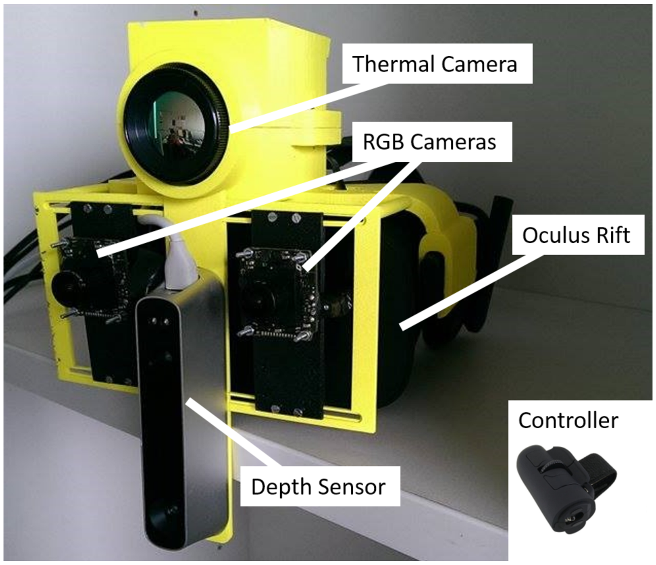

Figure 2: TriSight consisting of an OculusRift, two mvBlueFOX RGB cameras and an Optris thermal camera.

additional vision information are yet to be delivered. Thus, understanding if and how interactive systems can convey content beyond the regular vision spectrum emerges as a challenge for HCI. Here, we perform an initial exploration of this design space by building a proof-of-concept prototype and evaluating in a study. We conducted a mixed-methods lab study to explore initial reactions to an extended vision system and investigate its potential for domestication. Consequently, we explore the following research questions:

- **RQ1**: What is the potential for domesticating augmented vision systems?
- **RQ2**: What are user attitudes and design challenges for developing systems that support alternative vision modes?

TRISIGHT: A PROOF-OF-CONCEPT PROTOTYPE

To answer our research questions, we built *TriSight* that extends the user's visual perception. It enables users to perceive the environment in three different modalities; visual view recorded through RGB cameras, depth view recorded by a depth image sensor, and a heat view recorded by a thermal camera.

Through the attached different cameras; RGB, Depth and Thermal cameras, the HMD presentes the camera feed to the user, where the RGB is used to allow having a see-through experience, to be able to see the environment, the depth and the thermal viewed the heat information of the environment. Users can select one view at a time using a wireless controller depicted in Figure 2. Users can freely switch back and forth between the three views with a simple click.

TriSight puts three different image sensors into service. For the visual spectrum, we utilize two Matrix Vision mvBlueFOX-MLC202b cameras to enable stereo vision. The cameras operate at a resolution of 1280×960 pixels with a field of view (FOV) of 118°×87°, running at up to 90 frames per second (fps). For thermal imaging, we used an Optris PI450 camera with an optical resolution of 382×288 pixels. The spectral range is between 7.5 and 13μm with a noise equivalent temperature difference of 40 mK at 80 fps. The thermal camera is equipped with a 7.3 mm lens with 80° horizontal and 58° vertical FOV. The third sensor is the structure sensor from Occipital [2]. It operates with a of 640×480 pixels and FOV of 58°×45° at 60 fps.

All image sensors are attached to a custom designed printed chassis (yellow part in Figure 2). This frame connects all sensors with the Oculus Rift CV1 which we used as output device. We ordered the sensors in a way that enabled the largest view overlap as shown in Figure 2. The dimensions of *TriSight* were 20×16×14 cm (w×h×d) and total weight of 1.2 kg including the HMD. Both the Oculus Rift and all imaging sensors are connected to a MSI-GT72 [3] notebook. The notebook powered the attached hardware and does all the processing. The notebook was placed in a backbag.

We used the Unity 3D game engine for image stream processing since it offers powerful Oculus Rift support. The image processing pipeline consists of three steps. Each stream from one of the camera systems is loaded separately, cropped to compensate the different FOVs and lastly rendering a split-screen stereo with distortion correction for each eye. Only one stream is visible at a time. The user can switch between the streams with a press of one of the 2-buttons of an ergonomic finger mouse (controller in Figure 2).

METHOD

We Used a proof-of-concept prototype in created environments aiming to achieve the fullest involvement of the user's in the design of the vision extension systems. It allows the investigation and evaluations of user experience, and qualitative as well as quantitative measurements of usage, e.g. the time spent in each views.

The study was comprised of two parts. In the first part, we studied the usage of the three different views in daily tasks, by creating three lab environments: kitchen/home, office and basement.

1. Office Tasks:
   (a) organizing and archiving files.
   (b) identify connected plugs.
2. Basement Tasks:
   (a) locating an object
   (b) detecting leakage
   (c) detecting disconnected pipe
3. Kitchen & Home Tasks:
   (a) finding a pet
   (b) checking the plant

[2] www.structure.io/
[3] https://www.msi.com/Laptop/GT72-6QD-Dominator-G.html

Figure 3: Participants while performing kitchen and office tasks.

(c) preparing hot drink

The second part was a post-task interview evaluating their experience with *TriSight*. We conducted the interview in the lab after the participant explored the three home-like setups. In the interview, participants were asked about their experience with *TriSight*, and how a similar device could be used in their daily life. Additionally, they reported the reasoning of the view selection to perform the task. The post-task interviews were recorded for later transcription and thematic analysis, to better understand the content of the interview.

Participants and Procedure

We recruited six participants (3 female, with an average age of 29.17 years, SD=10.83). Participants had a diverse background, we had one secretary, one doctor and four students in different majors (Table 1). Two participants had previous experience with augment reality, one participant had experience with depth cameras and none had any experience with thermal cameras.

	Age	Gender	Profession
P1	Male	20	Engineering Student
P2	Female	45	Secretary
P3	Female	24	Computer Science Student
P4	Male	27	Management Student
P5	Female	19	Linguistics Student
P6	Male	40	Doctor

Table 1: Participants Information.

After welcoming the participants in the lab, we asked them to sign a consent form and explained the purpose of the study. The experimenter then asked them to fill in a questionnaire concerning their experience in using HMDs, RGB and thermal cameras. Throughout the study we recorded the views displayed to the participants as shown in Figure 1.

We recorded their state using the Positive and Negative Affect Schedule questionnaire(PANAS) [21] before the start of the study and after each environment. Moreover, we logged the time spent in each view. The participants were encouraged to speak their thoughts out loud, and comment on the views used to perform the tasks. These notes where recorded by the experimenter for later analysis. The order of the environments was counter balanced using a Latin-square. The study took approximately 120 minutes (30 minutes in each environment and 30 minutes for the post-task interview) per participant. The whole experiment was recorded using a Gopro Hero3 RGB video camera.

RESULTS

We collected 540 minutes of video, 199.53, 158.51, and 181.56 minutes in RGB, Depth and Thermal views respectively. Further, 163 minutes of qualitative interviews were collected along with the comments recorded during the study from the participants. We analyzed the PANAS scores after using *TriSight* in the different environments, (2) time spent in each view, (3) the views used to perform the given tasks and (4) the conducted interviews.

PANAS

We assessed the positive and negative affect at the beginning of the experiment as an indicator for the initial/baseline of the user's state. Scores were recorded after each environment aiming to asses the experience of *Trisight* and whether it influenced the user's state negatively or positively. As shown in Table 2, participant's overall positive affect increased and their negative affect score dropped.

	Positive Affect	Negative Affect
Baseline	23.83±5.93	21.67±4.07
Office	26.00±8.29	21.17±5.67
Basement	29.33±9.57	21.00±6.44
Home & Kitchen	29.00±7.96	21.17±5.54

Table 2: Mean and Standard Deviation of the PANAS scores.

Time Spent in Each View

We used the logging of switching between views to compute the time spent in each view. Figure 4 presents the percentage of time spent in each view. In the home and office environments, participants spent most of the time using RGB view 42% and

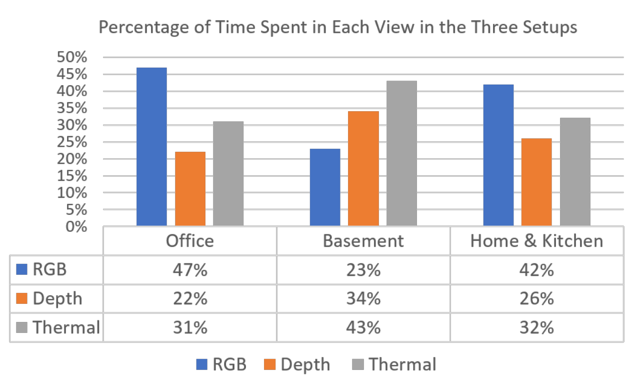

Figure 4: Time spent in each view, where the total time is 30 minutes.

	Home & Kitchen			Office		Basement		
	Find the Pet	Check Plant	Prepare Drink	Organize Files	Identify Connected Plugs	Locate an Object	Leakage Detection	Find Disconnected Pipes
P1	Thermal	Thermal	Thermal+RGB	RGB	Thermal	Thermal	Thermal	Depth
P2	RGB+thermal	Thermal	Thermal+RGB	RGB	RGB	Depth+Thermal	Thermal	Thermal+Depth
P3	Depth+RGB	RGB+Thermal	RGB	Thermal+RGB	RGB+Depth	Thermal	Depth+Thermal	Depth
P4	Depth+thermal	Thermal	RGB+Depth	RGB	Thermal+RGB	Thermal	Thermal	Thermal
P5	RGB	RGB+Thermal	RGB	RGB+Thermal	RGB	Depth	Depth+Thermal	Depth+thermal
P6	RGB	Thermal	Thermal+RGB	RGB+Thermal	RGB	Depth+Thermal	Thermal	Thermal

Table 3: Views used by Participants to Perform the Given Task.

47% respectively. However they still spent time viewing the surroundings with thermal and depth view.

However, when the information provided by their visual sense failed to provide sufficient information they tended to switch to the other views as depicted by the time spent in the other views. For instance, participants used the thermal view to check the soil of the plants to know if it had been watered or not, others used it to search for the pet, by utilizing the heat emitted from the cat-shaped bottle.

Interestingly, participants utilized the depth and thermal views in the situation where the normal RGB view has limited capability. As shown in table2, in the basement, where there was limited light, they only spent 23% of the time in the RGB, and the rest was spent in the depth and thermal views, 34% and 43% respectively. As observed in the views used to perform the tasks and time spent in each view, thermal imaging showed a higher potential as an alternative vision mode.

Views used

Participants were instructed to name the views used to perform the tasks in each environment. The experimenter recorded the views used to perform the tasks, aiming to access the potential usage of the presented views. Figure 1 depicts examples of the different views used to achieve the tasks. As shown in table 3, participants used different and sometimes combined views.

Confirmation for the time spent in each views, the RGB was mostly used in the familiar environment (office and home), however, participants also utilized other views. For instance, one participant used the thermal view to identify the last used file, utilizing the heat trace left behind. Other, used it for detecting if the plants need to be watered based on the temperature of the soil. Participant used the thermal and RGB views to prepare the hot drink, to be able to view the hot spots of the cup and the water to better handle it. The comments of the participants as well as the views used reflects the potential benefit of extending the human visual perception beyond the limited light spectrum.

Interviews

The post-task interviews were recorded and transcribed for analysis. We used thematic analysis to better understand the content of the interview. Overall, 163 minutes of recordings were analyzed. Two coders coded 15% of the corpus independently using nVivo [4]. Afterwards, they met to assess differences and constructed the final coding tree. The rest of the corpus was coded by a single coder. The final themes emerged from the coded quotations in a final session with two researchers. We present the four themes below.

Future form factor

The users noted that our current prototype was rather bulky and difficult to wear over extended periods of time. However, participants were also eager to envision how a future device offering multiple vision modes could look like. They considered what they would see as key features of such a device. P3 reflected that effectively using multiple vision modes would require highly developed wearable technology:

> [It should] look like normal glasses, light weight, the setup doesn't need much space or doesn't have problems with mobility. It doesn't drain power. *(P3)*

Participants also anticipated that devices that offer alternative vision modes will soon be offered as smartphone accessories. One participant assumed this and speculated on how the device would connect with their mobile device

> It has to be smaller, lighter and something wireless. The data can be send over... wirelessly over Bluetooth or the Internet for example. *(P1)*

Reflecting on future use

Participants were eager to speculate on how alternative vision modes could be useful in their future everyday lives. P2 commented they often struggled with leaks and excessive humidity and would benefit from easily accessible thermal vision. P5 noted that they would happily turn on thermal vision when under stress, in order to identify objects quickly:

> It would be useful to have a device like that in stress situations where I have to find something very quickly, when I am under time pressure. *(P5)*

Participants remarked that tangible benefits of introducing alternative vision modes in specific settings could result in swift acceptance. They often related the new capabilities of our prototypes to tasks they perform regularly. For instance, P6, a physician, remarked:

> I would use it in the future, as it is a good additional way to examine my patients. *(P6)*

Sensing the environment

Users often reflected on how they understood the different properties of the environment that they could perceive by using multiple vision modes. They were eager to illustrate possible benefits with scenarios:

> If I were on holiday I could check the water temperature and decide if I want to swim. I could look at a bench

[4] http://www.qsrinternational.com/nvivo-product

> that's far away and check its temperature, if it were super hot I wouldn't go over there. *(P2)*

Similarly, they appreciated how alternative vision modes allowed for enhanced perception of environments with which they were already familiar. The participants wondered how additional vision modes could build their new understanding of their everyday environments:

> [in the basement] I could finally know how these pipes are connected. *(P4)*

Social aspects

Finally, users wondered how head-worn enhanced vision devices would affect social encounters. One participant recognized that thermal images may be linked to one's physiological state and thus may generate privacy issues:

> Maybe it will generate another [type of] discrimination — I walk down the street and I have a fever so people will try to avoid me. *(P2)*

Some participants were also worried that thermal vision may create issues related to gender and sexuality

> It will embarrassing, because, I think, if wear something thin, people will be able to see through. *(P2)*

Furthermore, participants agreed that others should not be made aware if one's using augmented vision. One participant remarked that transparency was not an issue:

> In the future, maybe, everyone will be using it on daily basis, so we shouldn't show [what mode one's using]. *(P1)*

While another believed that showing the state of an augmented vision device was needed as it is only a sensor:

> I don't think they need [a way to show status] as it has nothing to do with other people, it won't invade others privacy or harm them. *(P3)*

DISCUSSION

Our study demonstrated that augmented reality technologies may be appropriate for communication augmented vision information. We observed that non-expert users were able to easily understand and utilize the way thermal cameras work through an HMD. As users reported no major difficulties performing the tasks and exploring the environment, we can conclude that AR offers the potential for easy and fast deployment of thermal imaging. Further, HMDs may reduce the need for training. Further, we found that *TriSight* improved the participants' subjectively reported affective state as reflected in the PANAS scores. This indicates that an augmented vision technology may be perceived as beneficial while performing domestic tasks, thus showing potential in terms of **RQ1**.

Our study also revealed a number of opportunities and challenges for future development of augmented vision systems (**RQ2**). As we observed in the views used to perform the tasks and time spent in each view, thermal imaging showed a higher potential as an alternative vision mode. Thus, future design should explore how to offer a experienced balanced between different vision modes and offer vision mode changes when appropriate. The usage of different views reflect the participant's understanding of the other spectrum bands, although most of them did not have previous experience with this technology. Interestingly, all participants used the extended vision in the basement. It appears that participants used extended vision when the RGB (i.e. our visual perception) shows limited capabilities as reflected in the time spent in each view, as participants spent more time in using the depth and thermal cameras in contrast to the RGB. Thus, we see an emerging need for finding ways to communicate the properties of different augment vision modes to users effectively to foster their implicit awareness of enhanced perception available. An intuitive understanding of alternative vision modes appears to be a necessary condition for effortless vision mode switching.

Where we only considered explicit vision mode switching, our findings highlights the need to explore implicit and context-aware switching techniques for instance based on the lighting conditions. As the explicit switching relies on the understanding of the user of the technology in hand, however having implicit mechanism would enhance the understanding of the imaging technology as well as assist in the appropriation of the extended vision.

Extended vision is influenced by knowledge bias, in terms that users must have an initial understanding and knowledge to best utilize the extended vision. In our exploration participants intuitively explored the different vision modes to have an impression of the capabilities of each mode. Future design should support a "learning/introductory phase" prior to usage or during setup to ensure full understanding of the alternative vision modes. Further challenges lie in the image and information representation. Presenting raw image data might not be intuitive for novice users. Therefore, designing such tools should consider processing the raw image data and try to present the users more meaningful information. The thermal images are considered to be straight forward. Hence, as shown in the time spent and views used, participants preferred the usage of thermal camera rather than the depth camera to augment their vision.

Participants displayed increased awareness on the social aspects and privacy implications of having such a layer of extra information at hand and commented on how it could be a potential means of discrimination (i.e., detecting and avoiding peers having fever based on their temperature). This opens an HCI challenge in designing such tools, as privacy and ethical considerations are raised by using such a tool.

In summary, our findings highlight the potential of alternative vision modes, participants reflected on how these modes provided a new information layer, enhancing their perception and understanding of their everyday surroundings. Interestingly, participants were eager to utilize the extended visual perception when their own was a limiting factor like in a dark basement, with hidden objects and non-visible traces. However, researchers and designers mush consider set of challenges and considerations while designing such vision extension tools.

LIMITATIONS AND FUTURE WORK

As our work offered the first exploration of augmented vision on an HMD, we used a proof-of-concept prototype to conduct our study. Below, we outline some limitation inherent in our approach that we hope can inspire further research. The cameras we used had different FOV than the Oculus HMD, which might influence the quality of the camera feed. While *TriSight* used high-quality cameras and provided a vivid experience, the image was different from regular vision. Additionally, we presented a single stream at a time rather than an overlay, as we aimed to leverage different types of visual information. However, in future work, it is worth investigating the use of thermal or depth information overlay on the visual spectrum.

Further limitation, that might have had an impact on our work includes the knowledge bias (i.e. the understanding of the operating spectrum of the cameras used in the alternative vision modes), where depth and thermal properties differs from the light properties e.g. thermal reflection and transfer. This might have hindered the creativity of the participants in imaging further potential use cases.

Our findings highlights the potential of thermal imaging as vision extension tool and the need of future extensive research of how such a technology could be deployed and used domestically. This, in turn, poses clear technical challenges in terms of how such a technology could be miniaturized to a wearable format.

CONCLUSION

This paper described an exploration of users' attitudes towards augmented vision interfaces built with AR. We developed a proof-of-concept prototype named *Trisight* that enabled smooth switching between RGB, infrared and depth vision modes. We conducted a lab study in three created environments (office, kitchen and basement) to collect and analyze usage data, including; time spent in each imaging technology, views used to perform daily tasks along with user's state using PANAS responses. Additionally, we conducted semi-structured interviews post the participants' experience to gain deeper insights. Our analysis revealed that participants were able to understand and accept non-traditional imaging (depth and thermal imaging) and used it to explore and perform daily tasks. Participants used the vision extension mode when their visible image failed them or didn't reveal sufficient information about the environment. Also, they preferred the thermal on the depth extension. Furthermore, we had insights concerning participants' preferences regarding the form factor and vision enhancement tools. We hope our work can serve as an initial building block to understanding what role enhanced vision can play in our future lives.

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