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Citation: Danry, Valdemar Munch, Chicos, Laura, Fonseca, Matheus, Kazi, Ishraki and Maes, Pattie. 2024. "Synthetic Visual Sensations: Augmenting Human Spatial Awareness with a Wearable Retinal Electric Stimulation Device."

As Published: 10.1145/3652920.3652932

Publisher: ACM

Persistent URL: <https://hdl.handle.net/1721.1/155201>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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Synthetic Visual Sensations: Augmenting Human Spatial Awareness with a Wearable Retinal Electric Stimulation Device

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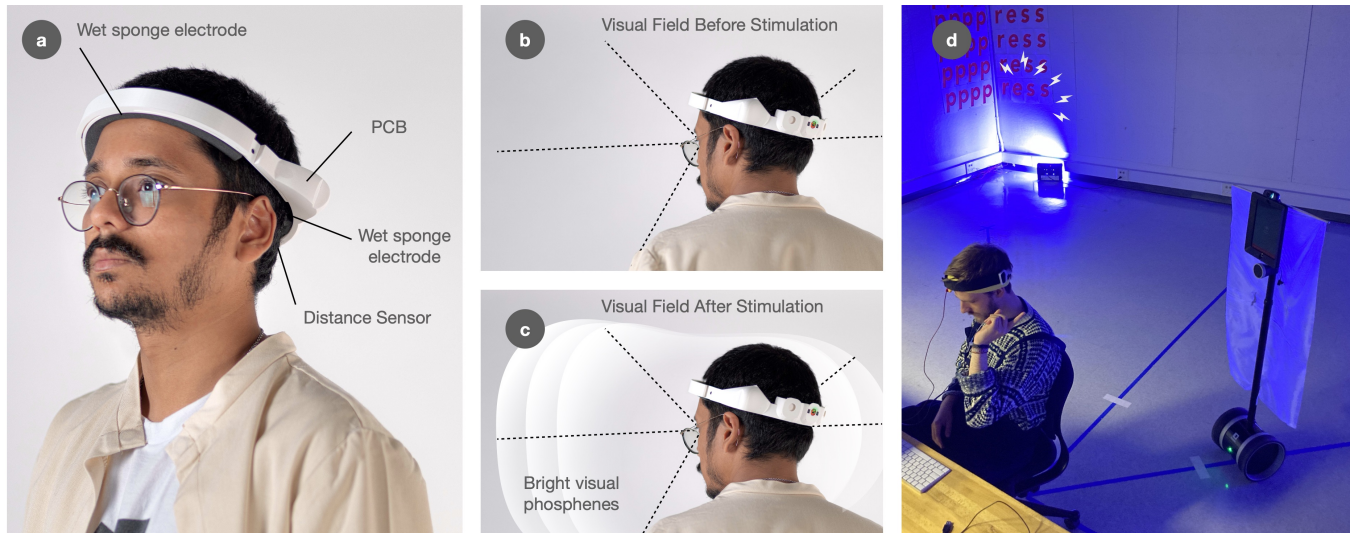


Figure 1: Overview of the system that elicits synthetic visual sensations to "see" behind the user. (a) A user wearing the system. (b-c) The phenomenology of the visual sensations (phosphenes). (d) User study evaluating object detection accuracy.

ABSTRACT

Alternating current stimulation of the retina (rACS) can non-invasively induce visual sensations called phosphenes (bright flashes) in the visual field. We explore the use of rACS to elicit visual sensations and explore the use cases of "seeing" objects behind the user. We designed a wearable rACS system and conducted a study to understand the visual sensations we could elicit and their efficacy when applied to augmenting a user's spatial awareness. We found that our device reliably generated synthetic sensations and, when applied in an object avoidance task, significantly augmented users' awareness of objects approaching them from behind compared to users with no stimulation feedback. Our results demonstrate how

future research can use electrical stimulation in wearable systems for sensory enhancement.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Interactive systems and tools**; **HCI design and evaluation methods**.

KEYWORDS

transcranial electrical stimulation, sensory augmentation, phosphenes, spatial awareness



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AHs 2024, April 04–06, 2024, Melbourne, VIC, Australia
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ACM ISBN 979-8-4007-0980-7/24/04
<https://doi.org/10.1145/3652920.3652932>

ACM Reference Format:

Valdemar Danry, Laura Chicos, Matheus Fonseca, Ishraki Kazi, and Pattie Maes. 2024. Synthetic Visual Sensations: Augmenting Human Spatial Awareness with a Wearable Retinal Electric Stimulation Device. In *The Augmented Humans International Conference (AHs 2024)*, April 04–06, 2024, Melbourne, VIC, Australia. ACM, New York, NY, USA, 13 pages. <https://doi.org/10.1145/3652920.3652932>

1 INTRODUCTION

Human-computer integration is at a frontier where technology not only enhances human functionality but also starts to align more closely with human phenomenological experiences [9, 20, 21, 40]. For example, in enhancing sensory capabilities, the focus shifts from sensory substitution via proxy sensations, such as haptic feedback mimicking vision [4, 5], to leveraging biological sensory pathways such as the neurons in the retinal, the optical nerve or visual cortices to expand on the innate structures of perception — potentially leading to more natural interactions and increased user adoption [7, 9, 10]. While sensory substitution approaches often compromise the user's existing sensory modalities or impose high cognitive demands by directing one sensory modality through another [18], augmenting vision by directly stimulating visual neural pathways could provide a more elegant solution.

Recent advances in neuroscience enable the direct augmentation of vision through neural stimulation. In particular, visual sensations known as phosphenes can be elicited non-invasively via stimulation techniques such as transcranial alternating current stimulation (tACS), a technique that can apply specific electric frequencies and currents to the scalp to induce perception of light in the absence of a visual stimulus [15, 30]. These phenomena have been studied not only for their potential to restore sight in cases of visual impairment but also to augment the sensory experience of the visually capable [13]. Mapping spatial information in real-time to visual sensations could greatly increase spatial awareness across a range of applications such as driver safety by alerting to blind spot hazards, improve navigation for the visually impaired, and offer a protective advantage in situations requiring awareness of fast-approaching objects, such as in martial arts or navigating in low-light conditions. However, developing a wearable tACS system for sensory augmentation, aimed at inducing phosphenes, poses significant challenges. These include creating portable hardware, optimizing stimulation for safety and comfort, converting sensor data reliably into visual experiences, dynamically adjusting stimulation to change visual phenomenology, and understanding user perception.

In this paper, we introduce a wearable tACS device designed to expand visual perception by using electrical retinal stimulation that allow users to "see" behind themselves. By integrating a distance sensor with retinal stimulation, the device induces phosphenes of varying frequencies based on object proximity, aiming to extend the user's field of view and depth perception. In two human subjects experiments, we evaluate the effects of stimulation amplitude and frequency on the phenomenology of the induced phosphenes, and assess the system's potential to improve spatial awareness in an object avoidance task with the device acting as a "sixth sense". Our findings show that our wearable tACS system can effectively produce synthetic visual sensations that significantly enhance the user's ability to perceive and react to stimuli from their blind spots, compared to traditional sensory capabilities. This suggests that tACS-induced phosphenes may serve as a closed-loop feedback mechanism to improve navigation and spatial awareness, offering a novel approach to significantly augment human sensory perception and interaction with the environment.

Our principal contributions through this research are manifold:

- (1) The design of a non-invasive wearable system that maps distance sensor data into visual sensations using retinal stimulation, allowing users to 'see' behind themselves.
- (2) Characterizations of retinal stimulation amplitude and frequency effects on sensation outcomes.
- (3) Results demonstrating that the wearable retinal stimulation device increases spatial awareness in a human subjects experiment object avoidance task compared to no system.
- (4) Qualitative interviews revealing the experience of using the wearable retinal stimulation device for active perception.

2 RELATED WORK

2.1 Sensory Augmentation

Sensory augmentation aims to enhance human sensory capabilities through technology, traditionally employing haptic feedback mechanisms like vibration or force to substitute for vision, hearing, or spatial awareness. Devices such as tactile vests, belts, and bone conduction headphones have been developed to translate visual or auditory information into tactile or spatial auditory cues, aiding those with sensory impairments and enhancing situational awareness in hazardous environments [5, 28, 31, 35, 37]. However, these approaches often compromise existing sensory modalities or impose high cognitive demands by rerouting one sensory modality through another [18] and have suffered from low adoption [12]. In contrast, direct stimulation of visual neural pathways could present a more integrated approach to sensory augmentation.

2.2 Neural Stimulation

Neural stimulation encompasses a range of techniques that directly modulate neural activity to alter sensory perception or cognitive functions. Electrical muscle stimulation (EMS) is one such technique that electrically induces muscle contractions, which has been used to provide haptic feedback for spatial awareness [23] or guiding user hand or head movement [22, 41]. Another technique is galvanic vestibular stimulation (GVS) that targets the vestibular system to influence balance and orientation, which can be leveraged for navigation [8] or reducing motion sickness [39]. Another technique is trigeminal nerve stimulation (TNS), which has been used for treating neurological disorders [36], or for eliciting olfactory and irritation sensations [3, 26]. Electrical stimulation of the tongue has also been used to elicit taste sensations such as saltiness, sourness and umami [32].

In contrast to neural stimulation that modulates sensory perception, transcranial direct current stimulation (tDCS) and transcranial alternating current stimulation (tACS) are non-invasive brain stimulation techniques that can modulate cortical excitability. tDCS applies a constant low-intensity current to the scalp, which can either enhance or inhibit neuronal activity, while tACS uses alternating current to influence brain oscillations and has been associated with improvements in cognitive functions such as memory [16, 33, 42], attention [2], intelligence [34], and may also evoke visual, auditory, vibration and pressure sensations [13, 15, 43].

While techniques such as EMS, GVS, TNS, and others have contributed significantly to the field of sensory augmentation, they do not leverage the high-bandwidth capabilities of the visual system, which could provide a more intuitive, rich and seamless form of

visual augmentation, directly coupling with our most dominant sensory modalities. However, the practical application of retinal and visual cortex stimulation for visual sensations is still in its infancy, with challenges in optimizing stimulation parameters and integrating artificial sensations with natural perception.

2.3 Retinal Stimulation and Phosphenes

Neural stimulation can also be used to elicit visual sensations known as phosphenes, perceived as flashes or spots of light without actual light entering the eyes. This can be achieved through electrical stimulation of the retina or magnetic stimulation of visual cortex [27]. With transcranial electrical stimulation (tES) techniques like tDCS and tACS being more portable, they have been explored for their potential to induce phosphenes continuously via retinal stimulation, making them suitable for sensory augmentation [15, 30]. While initial research suggested cortical stimulation from tES was responsible for phosphene generation, further studies revealed that the stimulation might actually target the retina or peripheral nervous system, leading to the concept of retinal alternating current stimulation (rACS) as a means of inducing phosphenes [19].

The application of rACS for sensory augmentation, particularly in visual perception and augmented reality (AR), has demonstrated potential in guiding user movement and providing navigational cues through induced phosphenes [13]. However, the dynamic presentation of phosphenes in relation to moving objects and the integration with sensors to enable comprehensive spatial awareness remain underexplored. Further research is needed to investigate the conveyance of detailed environmental feedback through phosphene variations and to address the real challenges of navigating in dynamic environments. Additionally, qualitative user feedback is crucial for understanding the perceptual and ergonomic implications of such systems in practical applications.

3 ELICITING VISUAL SENSATIONS WITH RETINAL STIMULATION

The successful elicitation of phosphenes through rACS depends on several factors, including the type of electrodes used, their placement, the parameters of the current applied, and the frequency of the stimulation.

3.1 Electrode Type

The type of electrode used can significantly impact the effectiveness of rACS/tACS in eliciting phosphenes. Plate electrodes are typically larger and can cover a broader area, while cup and tip electrodes are smaller and can target specific areas more precisely. Cup electrodes have been found to have lower impedance, which can enhance the effectiveness of the stimulation [43]. The choice of electrode type can also depend on the specific application and the comfort of the user. For instance, gel or Clearode electrodes can be used to ensure good contact with the skin and reduce discomfort.

3.2 Directionality of Phosphenes via Electrode Placement

The placement of electrodes is crucial, as it determines the location at which phosphenes appear in the visual field. By varying the

electrode montage, the perceived location of phosphenes can be altered within the visual field, with participants most often perceiving phosphenes near the stimulated electrodes [13]. For example, montages around the right eye led to visual sensations in the right visual field, montages around the left eye led to visual sensations in the left visual field, and montages in the center led to visual sensations across the visual field [13] (see Fig. 2). Moreover, one might be concerned as to whether the phosphenes hinder actual field-of-view (FOV), therefore degrading regular vision. However, as phosphenes only comprise increases in brightness rather than obstruct the visual field and are only present for a fraction of the time when using frequency-modulated tACS.

3.3 Waveform Parameters

The waveform of the stimulation current can also impact the sensory quality and intensity of the phosphenes. Different waveforms, such as square [13], sinusoid [43], random noise, and triangle [11], can all be used with different effects [43]. The choice of waveform can depend on the specific application and the desired sensory experience. For instance, a square waveform might be used to elicit a sudden, sharp sensation, while a sinusoidal waveform might be used to elicit a more gradual, smooth, rhythmic sensation [11].

3.4 Frequency Parameters

The frequency of the stimulation current can significantly affect the sensory quality and intensity of the phosphenes. Frequencies within 14-22 Hz have been found to most prominently induce phosphenes in light conditions, whereas frequencies within 8-14 Hz have been found to most prominently induce phosphenes in darker conditions [15]. Moreover, changing the frequency can lead to different visual sensations, with phosphenes appearing to flicker, dance randomly, or slowly oscillate in the visual field depending on frequency [15]. Frequencies below 10 Hz have not been found to elicit any visual sensations [15, 43]. Therefore, the frequency of the stimulation current can be adjusted based on the desired sensory experience and the environmental conditions.

3.5 Subjective Perception

The sensation of phosphenes is subjective, and participants often report the perceived location and intensity of the visual flash to vary [13]. Some people might be more sensitive to high currents and feel pain, while others may not [43]. Ensuring that the impedance is low and that the current is adjusted for each individual is important for optimizing the sensory experience and minimizing discomfort.

3.6 Designing for Safety

The application of transcranial alternating current stimulation (tACS) for retinal stimulation must adhere to stringent safety guidelines to mitigate the risks of electric shocks and thermal effects on sensitive body parts such as the eyes [17]. According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP), safe current levels for general public exposure at frequencies up to 110MHz should not exceed 20mA [29]. The IEC standards (IEC 60479-1:2018) further delineate that for frequencies ranging from 15-100Hz, the perception threshold is at 0.5mA, while currents exceeding 10mA may pose a significant risk of fibrillation.

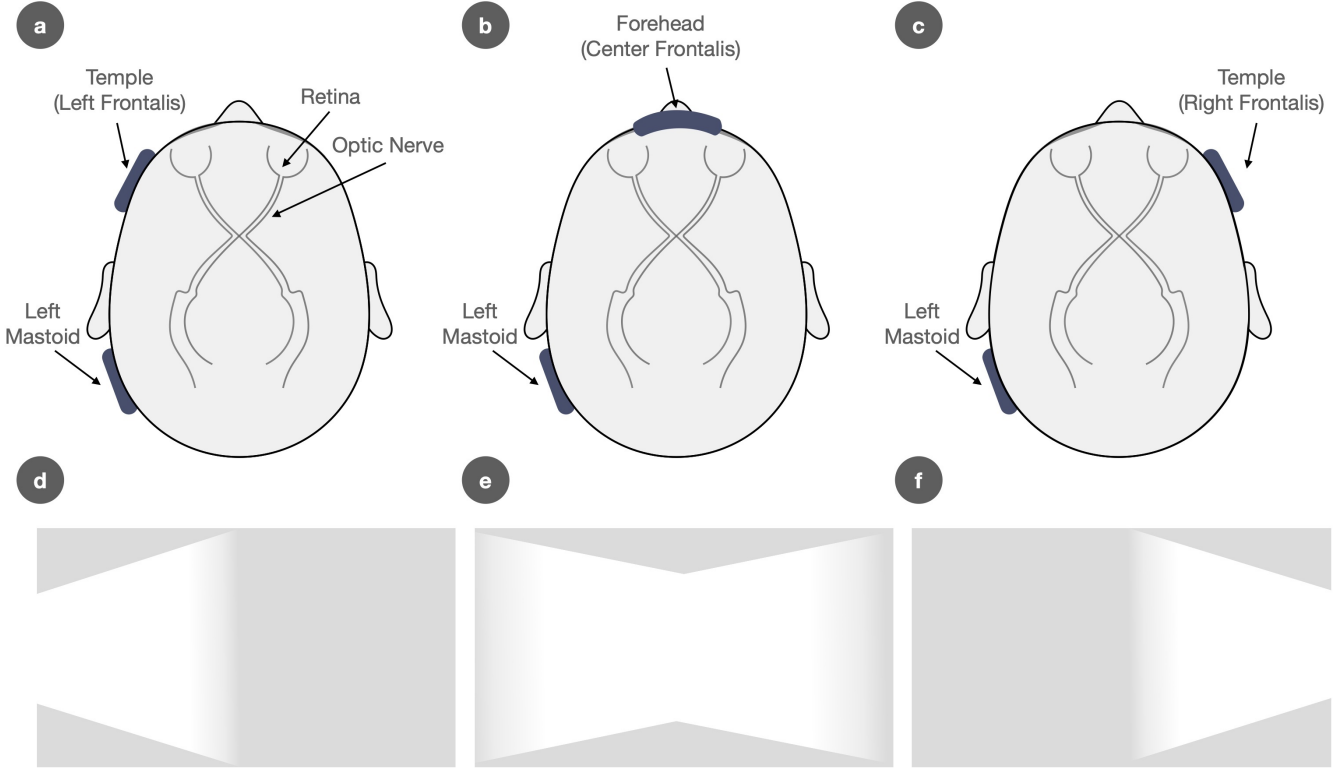


Figure 2: Electrode configurations and their resulting sensations in the visual field. (a, b, c) Various electrode configurations in which the ground electrode is maintained on the left mastoid and the electrode is positioned on either the left, center, or right part of the forehead. (d, e, f) Qualitative representation of the size, location, and brightness of the visual feedback (the box perimeter represents the visual field) that is elicited as a result of the electrode configuration in the diagram directly above.

Given the heightened sensitivity of the eye and the potential for cataract formation due to heat [38], tACS for retinal stimulation must operate well within these limits, ensuring that the frequency and current administered do not cross the safety thresholds. For precautions for tACS see [17].

4 ETHICS & SAFETY

Any stimulation method, including tACS, should adhere to safety standards and ethical guidelines. Low-intensity transcranial electrical stimulation (tES) has been used in thousands of studies without serious adverse effects being reported, and its safety is well established for conventional low-intensity tES, as long as peak currents do not exceed 4 mA and stimulation duration is kept under 60 minutes per day [1]. Moderate adverse effects are rare, and for normal healthy subjects usually consist in skin lesions, but most adverse effects are mild and disappear after stimulation. Particularly for tACS, no persistent adverse effects have been reported [25]. Our stimulation system complied with safety standards and ethical standards and was approved by the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects, IRB #2203000604.

5 IMPLEMENTATION

To evaluate the potential effects of synthetic visual sensations on spatial awareness, we built a head mounted retinal alternating current stimulation (rACS) system to sense objects behind a person’s back and elicit visual sensations (or phosphenes). The system consists of tACS hardware component (that becomes rACS when electrodes are placed near the retina), open and closed loop software implementation, and a wearable design to house the electronics. For an overview of commercial tACS and reasoning for implementing a tACS device from scratch see Appendix A.

5.1 Hardware Design and Implementation

Our own tACS system consists of a series of components that takes in data from a distance sensor, feeds it through a micro-controller whose code maps the data into a waveform with a frequency between 10-40 Hz depending on the distance measured using a waveform generator, the waveform is fed through a buffer for safety reasons, then a voltage divider and transconductance amplifier which turns the signal in an alternating current for the stimulation electrodes on the scalp (See Fig 3 for a block diagram of the device).

First, the design is powered by two regulated DC *power supplies* (+15V and -15V) but for a more portable configuration, a small 9V battery coupled with a voltage regulator and a voltage doubler

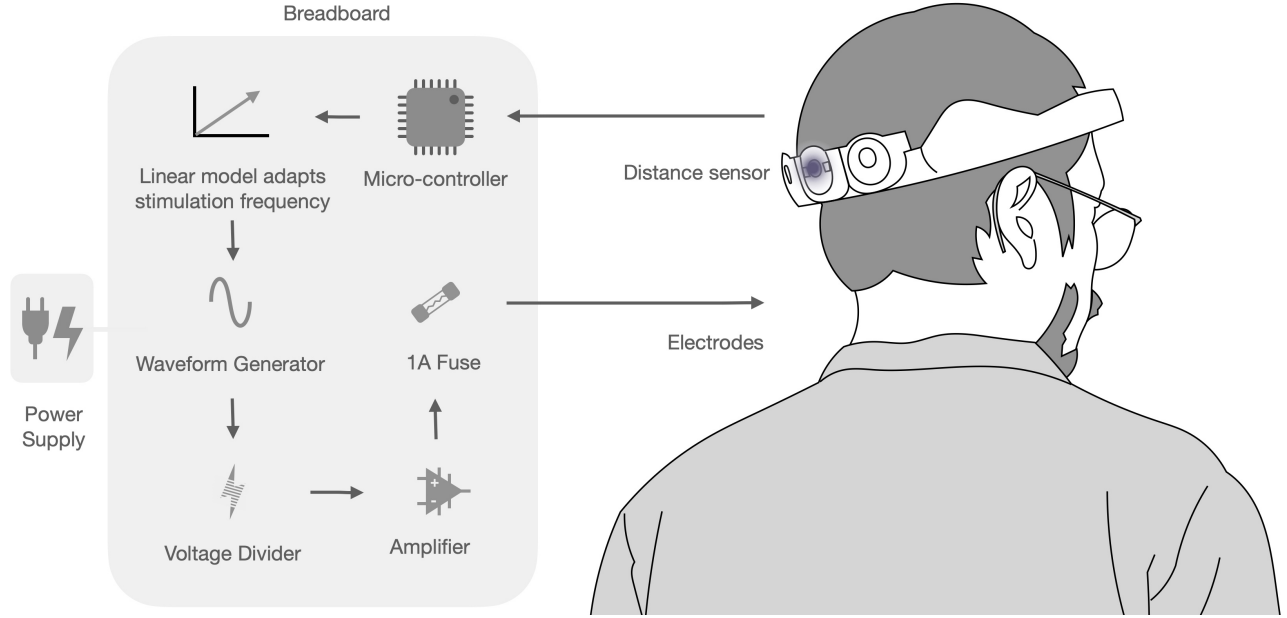


Figure 3: Hardware of our tACS device implementation. A block diagram of the device is shown in the region shaded in gray.

can be used. A VL53L4CD infrared laser *distance sensor* was used to measure the distance from the target object to the user. The VL53L4CD is appropriate for small distances (4m) and has a narrow beam (15° angle), allowing it to only detect the object directly in front of the laser. The distance sensor signal was next received by a *microcontroller* that linearly maps the distance signal to waveform frequency and controls waveform generator chip. For our study, we decided to use the Arduino Micro due to low power consumption, low price and wide availability. The *Waveform Generator Chip* then converts the digital signals from the microcontroller into a variety of analog waveforms (e.g., sine, triangle, pulses) with precise frequency and amplitude. For our study, we used the AD9833 chip and sine waveforms. To ensure safety from sudden changes in current, a *buffer* was used to create a layer of isolation in the circuit and to limit output voltages and currents. We used the INA128 due to its precision and widespread usage on medical devices applications. For the INA128 any current exceeding 3mA (i.e., 3V across R_{si} is $3V/1000\Omega = 3mA$) deactivates all electrodes, thus ensuring the device current level to remain under safety levels. A *voltage divider* was then used to reduce the analog signal received from the buffer in order to meet the transconductance amplifier specifications and allowing us to control amplitude of the output signal. Finally, a *transconductance amplifier* was used to transform the voltage input into current output, ensuring current level even as electrical resistance between electrodes vary and isolating input and output between users. We used the LM13700 for this application. Although unnecessary, we added a 1A fuse to create an additional layer of safety, breaking circuit in case of excess currents. Wet sponge electrodes (5.08x5.08cm) in a rubber casing were then used to transport the final electric current to the subject's head. Before each use, the sponges were soaked in a sterile 0.9% saline solution with banana plug cables inserted into the rubber casing. In an ideal form factor,

dry electrodes could be used. However, dry electrodes have higher resistance than wet electrodes and are this potentially less painful, we chose wet electrodes given the exploratory nature of this paper.

Finally, the micro-controller was programmed to operate in two configurations: an open-loop one, in which the frequency and current were set as constant, and a closed-loop one, in which the current was constant and the frequency was set according to the distance measured by the distance sensor. The full design schematics, code and 3D model can be found on the GitHub repository¹.

Before actual connection to the subject in each experiment, a $1,000\Omega$ resistor was connected to the output of the current source to calibrate the maximal output of the entire setup to be exactly 2 mA peak amplitude (or 4 mA peak-to-peak). Under no circumstance, would the current exceed 2 mA. Skin impedance typically averages around $10,000\Omega$ but can significantly vary among individuals [1]. The calibration with a $1,000\Omega$ resistor was conducted to ensure safety across a wide range of potential skin impedance values, particularly accounting for individuals with unusually low skin impedance. This step was crucial for establishing a safe baseline for electrical output under extreme conditions. It's important to note that the $1,000\Omega$ resistor was only used during the calibration phase and was disconnected for the actual testing sessions. This approach allowed us to verify that our device operates safely and effectively, even in scenarios where a participant's skin impedance might be lower than average.

5.2 Software Implementation

For the purposes of the study, two operational modes were designed: an open loop mode and a closed loop mode. Table 4 provides a

¹<https://github.com/mitmedialab/synthetic-visual-sensations>

summary of the operational modes and the waveform settings available for each mode.

Open Loop Mode. For the first part of the experiment, we tested the strength of the visual sensations generated at different current amplitudes and frequencies in what we call an “open loop system”. To do this, we implemented a program where we could manually vary frequencies of stimulation between 10, 20, and 40 Hz. Similarly, we could manually program the resistance of the digital potentiometer to vary between currents of 0.5, 1.0, 1.5 and 2.0 mA.

Closed Loop Mode. For the second part of the experiment, we tested the capacity of the device to allow the user to sense objects behind them. To do this, we implemented a closed loop stimulation system that adjusted the frequency output, at the optimally chosen current, based on the control signal from the distance sensor. This optical laser sensor has a 4 meter range with a 15 degree field-of-view, and is robust to various ambient lighting conditions. The 15 degree field-of-view was chosen for feasibility testing. Ideally, the system could increase the field-of-view by using multiple distance sensors. However, people can scan a larger area by rotating their head so that the sensor reaches more than 15 degrees. A moving-average filter was applied to the input signal to smooth out noise. This control signal was then fed into a linear model that produced a frequency output based on a max distance of 2.6 meters which can be changed to alter sensitivity and sensory space (fixed to 2.6 m in our experiment). For the upper and lower bound, we used low frequency-modulated tACS in our experiments. The maximum of 40 Hz was selected as the upper frequency threshold and 10 Hz as the lower limit based on Section 3.4. As such, a frequency of 30 Hz was kept constant when assessing intensity from different current levels. Effects of frequencies higher than 40 Hz were not tested due to study time constraints.

5.3 Wearable Device Housing Design

The housing and general wearable form factor for the wearable device was designed in fusion360 and 3d-printed using a Formlabs Form 3 printer. The inside of the 3d-printed design was then fitted with a 1cm foam sheet to ensure comfort over longer periods of wear. The 3D design files are available on our GitHub repository².

6 EXPERIMENT 1: EVALUATING SYNTHETIC VISUAL SENSATIONS

We conducted an experiment (n=12) to understand the types of sensations resulting from our wearable tACS system and to determine the optimal parameters for reliably eliciting strong visual sensations.

6.1 Participants

All subjects for the first and second experiment were recruited and consented under the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects, IRB #2203000604. The participants for this experiment consisted of 12 healthy adults (age 18-54, mean = 25-34; gender 50% male and 50% female). Before recruitment, participants were asked to fill out a

pre-screening questionnaire to ensure their safety as test subjects, according to standard tES exclusion criteria [1]. For instance, we asked whether participants had had any head related surgery or illnesses such as implanted metal devices, a history of epilepsy or anxiety, or were possibly pregnant. If they answered no, they were recruited for the study.

6.2 Procedure

At the beginning of the experiment, participants were randomly assigned to either a control or experimental group (control n=6, experiment n=6). In both groups participants were fitted with the retinal stimulation device. The device was only turned on for participants in the experimental group, whereas it was turned off for the participants in the control group. For this experiment, the open loop system was used. The electrodes were placed on the forehead and mastoid in configurations in Fig. 2b to elicit sensations across the visual field.

After the participants were fitted with the device, they were told that they were going to be incrementally stimulated at 4 different currents levels with increasing intensity, starting at 0.5 mA and ramping up to 2.0 mA (although only participants in the experimental group would actually be stimulated). For the experimental group, under no circumstance was the current ever above the reported safety level (2 mA) [1], and participants were told that they could stop us at any time. Moreover, during the stimulation at each current level for the experimental group, the peak to peak voltage (VPP) was noted.

Following the methodology of [43], for each of the fixed currents (0.5 mA, 1.0 mA, 1.5 mA, and 2.0 mA), participants indicated the type of sensation they received for “visual”, “auditory”, “pain”, “touch”, “vibration”, “pressure”, “movement”, or “other” (1 = sensation, 0 = no sensation), and indicated the overall sensation magnitude on a 10-point likert scale (1 = unnoticeable, 10 = unbearable). For a definition of each sensation type and sensation magnitude see Zeng et al. (2019) [43]. The highest current at which the subject felt comfortable while maintaining strong sensations was then noted as the threshold current parameter and maintained for the rest of the study (median current selected: 1.5 mA).

The procedure was then repeated for frequency of the frequency of stimulation (10, 30 and 40 Hz). Here, the threshold current from earlier was kept fixed, while the frequency would be gradually increased through each step. During the stimulation at each stimulation frequency, the peak to peak voltage (VPP) was noted. After the stimulation at each frequency, participants would also reported the sensation type and magnitude. Throughout the experiment, the order of the current intensities and frequencies were not randomized due to the potential harm that might occur for sudden increases in current or frequency without knowing the user’s personal tolerance.

6.3 Results

The results of our wearable system on eliciting visual sensations (phosphenes). Overall, results showed strong effects of the system on users’ visual sensation occurrence and magnitude (Fig. 5). First, we found that the average impedance remained relatively constant

²<https://github.com/mitmedialab/synthetic-visual-sensations>

Mode	Parameters Adjusted	Settings Used in Experiments
Open Loop	Waveform, Frequency, Current Intensity	Frequencies: 10, 20, 40 Hz Constant Frequency: 30 Hz (<i>when measuring intensity</i>) Waveform: Sine wave Currents: 0.5, 1.0, 1.5, 2.0 mA
Closed Loop	Frequency	Frequency range: 10-40 Hz based on sensor input Waveform: Sine wave Current: <i>Optimally chosen level</i> Max Distance: 2.6 meters (<i>sensitivity and sensory space</i>)

Figure 4: Summary of Operational Modes and Waveform Settings.

around $10k\Omega$ despite frequency changes, suggesting robust contact of the electrodes for the duration of experimentation (Fig. 5a). During stimulation, we found that across all current and frequency levels, visual sensations were on average reported 96% of the time across subjects (10 Hz: 88%, 30 Hz: 100%, 40 Hz: 100%), while vibration was on average reported 80% of the time (10 Hz: 75%, 30 Hz: 88%, 40 Hz: 78%) (Fig. 5b). Higher frequencies were associated with increasing occurrence of all types of sensation, including undesirable byproducts such as pain. Further, changes in stimulation frequency and current was found to have an impact on the magnitude of the sensations (Fig. 5c). For all current levels except 0.5 mA, higher frequencies suggests a trend towards increased sensation magnitude.

6.4 Discussion

These results demonstrate the ability of our system to successfully elicit visual sensations when worn across participants. Across frequencies the system was 96% effective in eliciting visual sensations, with higher currents leading to more intense sensations. However, the stimulation also comes with unwanted byproduct sensations such as vibration, pain, and pressure. As this was a preliminary pilot study, our goal was to understand the sensory outcomes from alternating current stimulation of the retina. Further, in this experiment sensation magnitude and pain was conflated into a single measure across sensation types. In future experiments, sensation magnitude should be separated into a pain magnitude measure and sensation magnitude measure for each sensation type. Moreover, since it could be difficult for participants to distinguish between sensation types, proper definitions along with specific examples or descriptions of sensations could be provided to participants to help them understand and differentiate between the types of sensations.

7 EXPERIMENT 2: ELICITING VISUAL SENSATIONS TO GAUGE OBJECT AWARENESS

We hypothesized that we could augment a user’s spatial awareness with our device by giving them enhanced awareness of when an object was silently approaching from behind. In this experiment, the wearable closed loop implementation was used to map distance

sensor data from the back of the device to frequency-modulated stimulation. The frequency of the phosphenes increased linearly according to the increasing proximity of the object approaching the user from behind. The closer the object was to the user, the higher the frequency, and thus the higher the perceived intensity of the sensation.

7.1 Participants

The participants for this experiment consisted of 10 healthy adults (age 18-54, mean = 25-34; gender 40% male and 60% female) who had successfully completed Experiment 1. Two participants were late to experiment 1 and hence could not participate in experiment 2 due to scheduling conflict with the next participants.

7.2 Procedure

Participants were kept to the same randomly selected control or experimental group as experiment 1 (control = 5 and experimental = 5). In both groups, participants were fitted with our device, programmed in “closed-loop mode”, which modulated stimulation frequency based on distance. However, the system was only turned on for participants in the experimental group, whereas for the participants in the control group it was turned off.

The participants were then asked to perform two tasks for gauging their spatial awareness of objects moving behind them. The procedures for these tasks are adaptations of the procedures put forth by [6] with objects being physical (a robot) instead of virtual, objects only being behind the user instead of both behind and in front, the speeds being slower due to limitations in the robots movements, and the awareness task being split into two separate tasks: a distance estimation task and an angle estimation task. Moreover, it is possible that participants may be able utilize subtle auditory cues present in the experiment setup to anticipate the robot’s movements. To control for such effects, participants were asked to wear earplugs.

After the two tasks, each participant engaged in a phenomenological interview (approximately 10-15 minutes) with an interviewer familiar with phenomenological concepts of relevance. In a phenomenological interview, the interviewer engages collaboratively with the participant to arrive at very precise descriptions about the

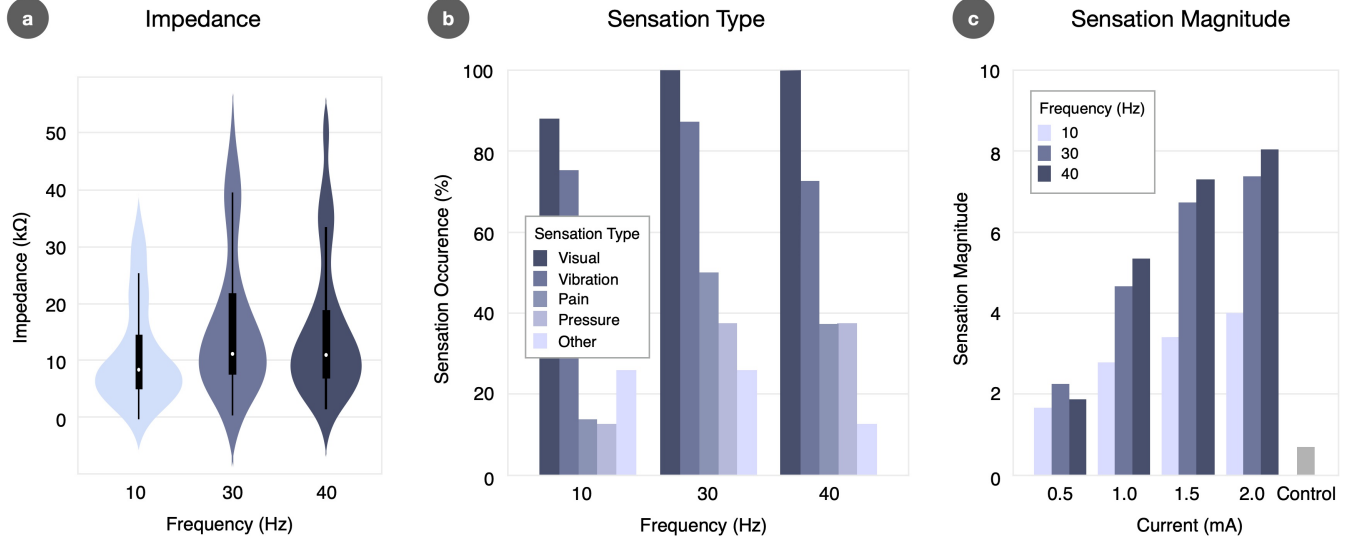


Figure 5: Sensations from tACS stimulation, as reported by the $n=6$ experimental subjects in experiment 1. (a) Device impedance during each frequency testing segment. (b) The types of reported sensations from stimulation at different frequencies and fixed current. (c) The sensation magnitude at various currents and frequencies, compared to control (no current & frequency).

participant’s lived experience (during the experiment) [14]. Following Martiny et al.’s [24] recommendation, we modified the technique to code and identify experiential categories and/or themes rather than aligning results with phenomenological concepts. Descriptions elicited from the interviews were recorded through a microphone and transcribed to text using Microsoft Word’s built-in transcription feature. After transcription, descriptions were filtered based on “how” rather than “what” was experienced, and coded into particular experiential themes independently by two authors of this paper. After coding, the findings were aligned, discrepancies resolved, and central themes were selected.

7.3 Task 1: Distance Awareness

In the first task, participants were asked to estimate the distance of objects approaching them from behind. The task consisted of one training block with 5 trials and one real block with 10 trials. In each trial an object approached the participant from directly behind at one of three randomly designated speeds (0.5, 0.8, and 1.2 km/h — following Bajpai et al. (2019) [6]) 2.6 m from the center of the game.

In order to reliably keep the speed of the approaching objects constant, we used the commercially available Double robots³ and modified their source code to change their speed.

For each trial, the participants were tasked with detecting the robot when it was as close as possible to the hit area 1m from the subject (see hit area marker on Fig. 6). First, a speed for the robot was randomly selected (0.5, 0.8, and 1.2 km/h). Next, the robot approached the participants directly from behind starting at a distance of 2.6 m from the user. When the participants thought that the robot was close to them, they would press the “space bar” key on the keyboard. When pressing space bar their reaction time

and robot speed were recorded, and then robot would move back to the original start position and the next trial would start. If the participants failed to press the space bar before the robot got into a marked zone on the ground 1m radius from the participant, we would then record that the user “got hit” and thus failed the trial (0% accurate).

7.4 Task 2: Angle Direction Awareness

In the second task, participants were asked to estimate the location of stationary objects placed behind them. The task consisted of one training block with 5 trials and one real block with 10 trials. The same robot from task 1 was used for task 2. After making a guess, participants were asked to tilt their head down so that the sensor could not pick up the movements of the robot as it was being relocated.

For each trial the robot was moved 2m behind the participant at a randomly selected angle of either a 45° (to the left of the user), 90° (right behind the user), or 135° angle (to the right of the user). The participant was then told to move their head from side to side and use the presence or absence of the phosphenes to locate the robot. When the participants thought they knew where the robot was, they pressed the “space bar” key on the keyboard and pointed over their shoulder in the direction of where they thought the robot was placed. Each guess was then recorded as well as the time from trial start to participant response (i.e. when space bar was pressed).

7.5 Statistical Analysis

The experiment aimed to evaluate the influence of our device on the user’s ability to (a) accurately determine the distance of an object behind the user, (b) accurately determine the angle of an object behind the user, and (c) the time it takes for the user to make a guess about the location of the object behind them. Hence, the key

³<https://www.doublerobotics.com/>

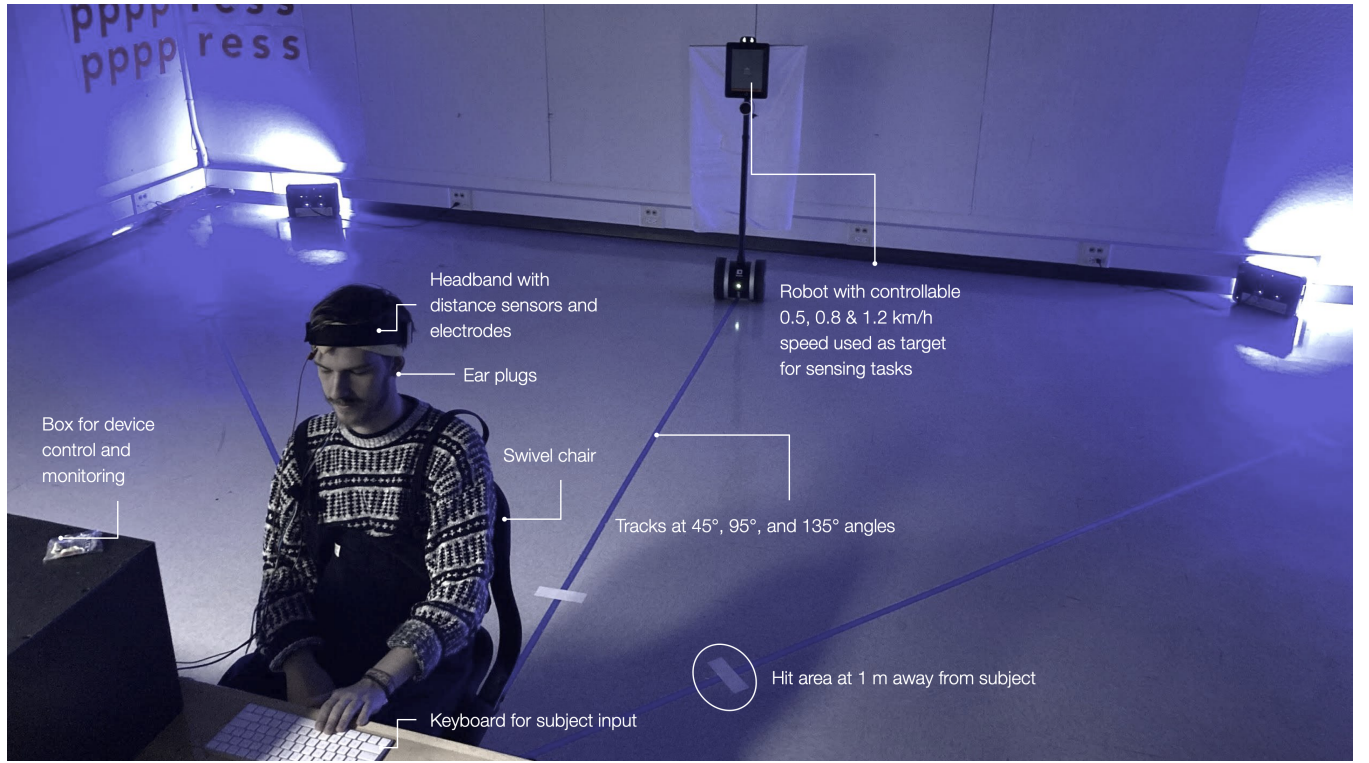


Figure 6: Setup for experiment 2: Eliciting visual sensations to gauge object awareness.

dependent variables (DVs) for the experiment were (a) Distance Accuracy (continuous variable, measured as the distance of the robot from the marker right behind the user when making a guess, with values from 0% Accurate - Furthest away from the marker" to "100% Accurate - Exactly at the marker"), (b) Angle Accuracy (binary 0 or 100 per rating, measured as the degrees of their guess from the actual angle location of the robot from "0 % - Wrong Angle" to "100% - Correct"), and (c) Decision making time (Reaction time in seconds). The independent variable (IV) measured against each dependent variable was the condition ("Control" and "Experiment (Visual Sensations)"). The distance in Task 1 was calculated with the formula $dist = s * t$, where $dist$ (m) is distance, s is speed (km/h), and t is time (h). Distance accuracy was calculated with the formula $Dist_{accuracy} = (2.6m - dist) / 2.6m$, where $2.6m$ is the max distance. Angle accuracy was calculated as 100% if $Angle_{Guess} = Angle_{Actual}$ or 0% if $Angle_{Guess} \neq Angle_{Actual}$.

To determine the appropriate statistical test, first normality and homogeneity of the data was evaluated using a Shapiro-Wilk test and Levene test. Running the Levene's test for equality of variances, we found that the homogeneity assumption was met for "Distance Accuracy (%)" ($s = 1.02$, $p = 0.31$) but not for "Angle Accuracy (%)" ($s = 118.30$, $p < 0.0001$) and "Decision Making Time" ($s = 28.89$, $p < 0.0001$). Running a Shapiro-Wilk test, we found that the normality assumption was not met for neither the distance accuracy ($w = 0.89$, $p < 0.0001$), angle accuracy ($w = 0.53$, $p < 0.0001$), nor decision making time ($w = 0.68$, $p < 0.0001$) DVs. Based on these tests, we determined a Basic ANOVA followed by a post-hoc Dunn test using

the Bonferroni error correction to be the most appropriate test for the "Distance Accuracy (%)" DV, and ANOVA Welch followed by a post-hoc Games-Howell test for both the angle accuracy and decision making time DVs.

Moreover, to test whether our results had statistical power given our relatively small sample size, we also calculated Cohen's d effect size for each test.

7.6 Results

Our results show that participants in the distance task with the device turned on were significantly more accurate at predicting when the robot was close (mean = 55.3%, SD \pm 31.9%) compared to control (mean = 25.0%, SD \pm 26.7%, $F(2, 10) = -5.0$, $p = 0.001$, $d = 1.03$) (Fig. 7a). For the angle prediction task (task 2), we found that participants with the device turned on were better at determining the location angle of the object behind them (mean = 93.3%, SD \pm 24.9%) compared to individuals without the device feedback (mean = 50.0%, SD = \pm 50.0%, $F(2, 10) = -5.7$, $p=0.001$, $d = 1.10$) (Fig. 7a). Further, we also found participants in task 2 with the device turned on to be faster at predicting the object angle (mean time (seconds) = 13.7, SD \pm 13.7) compared to controls (mean time (seconds) = 53.0, SD \pm 48.1, $F(2, 10) = 5.915$, $p=0.001$, $d = -1.11$) (Fig. 7b).

7.7 Discussion

The accuracy in predicting the distance of the robot approaching from behind was on average 2.2 times higher in the experimental

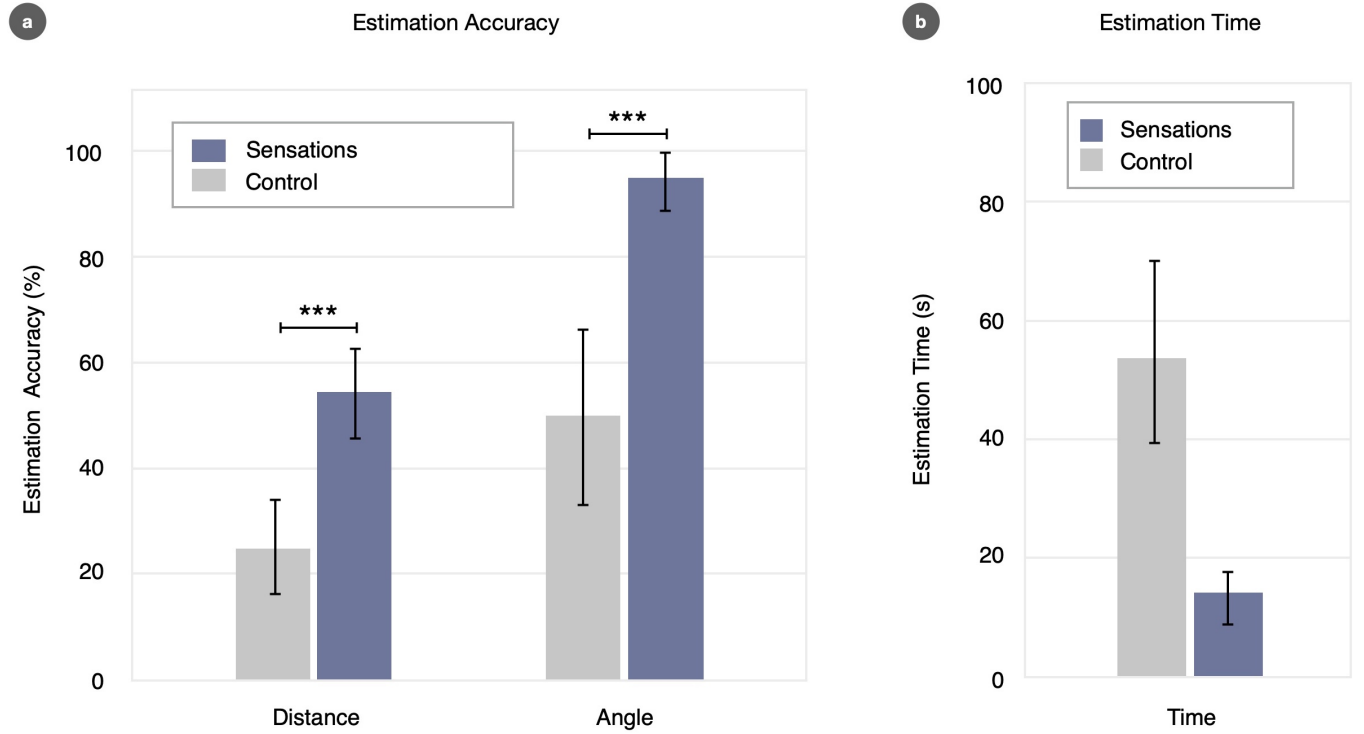


Figure 7: User awareness of objects behind them with system turned on (visual sensations) compared to system turned off (control). (a) The accuracy of estimating the distance of robot approaching from behind and estimating the angle within which the robot is located. (b) The time spent before making an estimation on where the robot is located.

group than in the control group. However, the control group participants were still able to predict that the target was approaching them in 25% of the trials. Explanations for the above 0% accurate prediction of the target in the control group could be that the participants were able to predict the robot speed and mentally count and estimate its distance, or randomly pressed the space bar preemptively.

For the direction awareness task, the experimental group predicted the correct angle for the robot almost 2 times more often than the control group. The control group still predicted the correct angle in 50% of the trials, which is above the expected value for random chance (33%). This could be explained by subtle environmental cues like light leaks from the robot's screen, despite wearing earplugs and having their eyes closed. Moreover, it is also possible that residual noises could have filtered through the earplugs. Future work could control for these factors by using better lighting and white noise to mask audio noise. Moreover, the effect sizes for all tasks were greater than 1, indicating a large effect according to Cohen's conventions. This suggests that the differences between groups (device on vs. control) are substantial and therefore likely to be of practical significance, underscoring the effectiveness of the device in enhancing participants' spatial awareness of objects approaching from behind. However, given the relatively small sample size, these results should be interpreted with caution. While the effect sizes suggest a strong effect of the device on performance in these tasks, the small sample size may limit the generalizability of

these findings. Overall, the differences found in both the accuracy of distance and angle predictions, as well as the decision-making time, highlight the potential of the device in improving spatial awareness. The substantial improvement in performance with the device turned on suggests that it could be a valuable tool for individuals who require enhanced spatial awareness in their daily activities or for specific professional tasks.

8 QUALITATIVE INTERVIEW RESULTS

From the phenomenological interviews after the two experiments, particular experiential themes across participants were identified.

The feeling of synthetic visual sensations: One of the themes that came up consistently in the interviews were descriptions of how the visual sensations felt. Aside from being felt both when the participants' eyes were open or closed (P2), participants reported that the visual sensations felt "not artificial [but rather like] happening naturally in your eyes" (P1, P2). Some participants even reported feeling like they had a "superhero kind of superpower" (P8) and that the visual sensations left them amazed: "It was new like... Just closing my eyes and feeling these lights. [I felt] amazed... I would say like: wow, this kind of technological thing is incredible." (P7).

One participant further reported the visual sensations got "a little bit difficult to notice" at high frequencies, and that the sensations were most vivid at lower frequencies (P1). Further, another participant stated that the visual sensation also became less vivid if they were constantly elicited: "[In the distance awareness task],

the visual sensation was very strong at the very beginning, but it degrades overtime" (P6).

Tingling sensations: Another frequent theme was the presence of a tingling sensation during the study often associated with the visual sensations. According to some participants, there were at points a tingling sensation felt at the location of the electrodes that felt "like a small particle hitting on your forehead continuously with a high frequency" (P1) or "like there were little needles sometimes" (P2). Participants reported that this feeling was frustrating and irritating (P1) when present but that it became less strong and more "normalized" after a while (P3, P1).

Perceiving the robot: Another theme was the ability that some participants reported to "perceive" the robot after using the system for awhile. For instance, one participant stated that you become "able to deduce quite distinctly where the robot is" and characterized it as "knowing what's coming from behind" (P1). Another participant characterised the feeling as a "change in sensation" when the robot was close (P2).

Tingling and visual sensations had different qualities: While most participants stated that the visual sensations "helped them understand what direction to move [in the angle task]" (P3) and "understand when the robot was approaching" (P6), some participants also stated that the tingling sensations were helpful too (P1, P3): "[Although] I would get these blank lights guiding me towards the object, whenever the object was very, very close, the tingling was stronger than the blinking lights, so the blink lights disappeared a little bit. But to understand to what direction to move and whether it was coming towards me or not, the blank lights helped." (P3). This sentiment was echoed by other participants as well, stating that the visual sensations were helpful to notice when the robot was coming towards them (P1, P3, P6) but noticed that the visual sensations would become imperceptible when the robot was close, making them rely on the vibration instead (P1, P3, P8): "I would initially notice the visual strobe experience first, and then if I really wanted to go 'OK, how strong is it?', then I could cast my awareness up to the [electrode] and go OK, yeah that was a little sharper [vibration] than earlier." (P8). Another participant reported that "the flashes are a nice way to suggest that something is approaching" and not as disruptive as the tingling sensations (P1).

9 DISCUSSION & FUTURE WORK

In this study, our aim was to give a preliminary evaluation of the types of sensory outcomes that could be generated by a wearable non-invasive rACS device and demonstrate its efficacy in augmenting spatial awareness. Our results demonstrate that the system could effectively elicit visual sensations across participants and increase their ability to tell the distance and angle of objects moving behind them. However, the study also revealed several areas for future research and improvement.

Optimizing Stimulation Parameters: While our study found effective parameters for eliciting visual sensations, further research could explore a wider range of stimulation frequencies, waveforms, and electrode placements as described in 3 to optimize the quality and utility of the induced sensations.

Decreasing Byproduct Sensations: In the study, many of the reported visual sensations were associated with byproduct sensations such as vibration and tingling which can increase discomfort or be annoying. In experiment 2, we found that some participants used these byproduct sensations when estimating the location of the robot, demonstrating a potential confounding factor in our results — especially at high frequencies. In order to understand the influence of visual sensations alone, future studies should incorporate a condition with only vibration feedback. At the same time, researchers should also explore alternative methods to diminish these secondary effects such as tuning the frequency-modulated stimulation to find the optimal intensity that will elicit visual sensation while minimizing any perception of tingling or pain. Different currents, waveforms and duty-cycles could also be explored to help diminish secondary effects.

Comparison with Baseline Augmentation Systems: Another limitation was the lack of comparison to a state-of-the-art modality such as vibrotactile feedback as a baseline to fully contextualize the efficacy of our device. To understand if the proposed system over or under-performs such systems, future research should directly compare the device with a vibrotactile feedback device to comprehensively evaluate its performance and utility in context compared to synthetic visual sensations.

Additional Electrodes and Sensors: Follow-up research could also investigate a device with multiple electrodes on either side of the forehead. could give the user directional visual sensations, or deploy an additional sensor array on the back of the wearable headband to increase the field of view without the user needing to turn their head to detect where an object is located. It will also be important to evaluate long-term safety of retinal stimulation in animal studies, as well as ways to limit potential side effects.

9.1 Applicability of Findings in Practical Scenarios

Our experiments demonstrated the device's efficacy in controlled settings, where variables such as object speed, direction, and environmental conditions were tightly regulated. However, real-world scenarios are far more unpredictable, with varying lighting conditions. For instance, the effectiveness of the device in bright daylight versus low-light conditions could vary, as the visual contrast of phosphenes might be less pronounced in well-lit environments.

Moreover, the real-world applicability of the device would also depend on its ability to adapt to the user's movements and the dynamic nature of the environment, such as crowded spaces. The device's sensor array and stimulation parameters would need to be finely tuned to provide accurate and timely feedback that can assist the user in navigating complex environments safely and effectively.

Another important consideration is the long-term use and safety of the device. Continuous or frequent stimulation over extended periods could potentially lead to adaptation or desensitization, where users might become less responsive to the induced phosphenes. Additionally, the long-term effects of retinal stimulation on eye health and visual function warrant thorough investigation.

Feedback from our study highlighted the novelty and potential utility of the device, with participants describing the experience of using the device as akin to having a "superpower." This suggests

that, despite the limitations and potential biases in the experimental setup, the concept of enhancing spatial awareness through retinal stimulation is compelling and holds promise for practical applications. Transitioning from a controlled experimental environment to real-world use will require addressing these challenges.

10 CONCLUSION

In this paper, we investigated the use of tACS to elicit visual sensations and we explore potential use cases. We designed a wearable tACS system and conducted a study to understand the visual sensations we could elicit and their efficacy when applied to augmenting a user's spatial awareness. We found that our device reliably generated synthetic sensations and, when applied, significantly augmented a user's ability to perceive objects approaching from behind compared to users with no feedback. This is the first study we know of to study possible tACS applications for sensory augmentation. Future work should explore cognitive load of synthetic visual sensations, different synthetic sensations, and other novel applications — not only for healthy adults, but also for people with perceptive disabilities such as blindness.

REFERENCES

- [1] A. Antal, I. Alekseichuk, M. Bikson, J. Brockmüller, A.R. Brunoni, R. Chen, L.G. Cohen, G. Dowthwaite, J. Elrich, A. Flöel, F. Fregni, M.S. George, R. Hamilton, J. Haueisen, C.S. Herrmann, F.C. Hummel, J.P. Lefaucheur, D. Liebetanz, C.K. Loo, C.D. McCaig, C. Miniussi, P.C. Miranda, V. Moliadze, M.A. Nitsche, R. Nowak, F. Padberg, A. Pascual-Leone, W. Poppendieck, A. Priori, S. Rossi, P.M. Rossini, J. Rothwell, M.A. Rueger, G. Ruffini, K. Schellhorn, H.R. Siebner, Y. Ugawa, A. Wexler, U. Ziemann, M. Hallett, and W. Paulus. 2017. Low intensity transcranial electric stimulation: Safety, ethical, legal regulatory and application guidelines. *Clinical Neurophysiology* 128, 9 (Sept. 2017), 1774–1809. <https://doi.org/10.1016/j.clinph.2017.06.001>
- [2] Daria Antonenko, Miriam Fixel, Ulrike Grittner, Michal Lavidor, and Agnes Flöel. 2016. Effects of transcranial alternating current stimulation on cognitive functions in healthy young and older adults. *Neural plasticity* 2016 (2016).
- [3] Kazuma Aoyama, Nobuhisa Miyamoto, Satoru Sakurai, Hiroyuki Iizuka, Makoto Mizukami, Masahiro Furukawa, Taro Maeda, and Hideyuki Ando. 2021. Electrical generation of intranasal irritating chemosensation. *IEEE Access* 9 (2021), 106714–106724.
- [4] Paul Bach-y Rita, Carter C Collins, Frank A Saunders, Benjamin White, and Lawrence Scadden. 1969. Vision substitution by tactile image projection. *Nature* 221, 5184 (1969), 963–964.
- [5] Paul Bach-y Rita, Mitchell E. Tyler, and Kurt A. Kaczmarek. 2003. Seeing with the Brain. *International Journal of Human-Computer Interaction* 15, 2 (April 2003), 285–295. https://doi.org/10.1207/S15327590IJHC1502_6
- [6] Aakash Bajpai, Justine C Powell, Aaron J Young, and Anirban Mazumdar. 2019. Enhancing physical human evasion of moving threats using tactile cues. *IEEE Transactions on Haptics* 13, 1 (2019), 32–37.
- [7] Elaine Biddiss and Tom Chau. 2007. Upper-limb prosthetics: critical factors in device abandonment. *American journal of physical medicine & rehabilitation* 86, 12 (2007), 977–987.
- [8] Richard Byrne, Joe Marshall, and Florian 'Floyd' Mueller. 2016. Balance ninja: towards the design of digital vertigo games via galvanic vestibular stimulation. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*. 159–170.
- [9] Valdemar Danry, Pat Pataranutaporn, Florian Mueller, Pattie Maes, and Sang-won Leigh. 2022. On Eliciting a Sense of Self when Integrating with Computers. In *Augmented Humans 2022*. 68–81.
- [10] Giulia Dominijanni, Solaiman Shokur, Gionata Salvietti, Sarah Buehler, Erica Palmerini, Simone Rossi, Frederique De Vignemont, Andrea d'Avella, Tamar R Makin, Domenico Prattichizzo, et al. 2021. The neural resource allocation problem when enhancing human bodies with extra robotic limbs. *Nature Machine Intelligence* 3, 10 (2021), 850–860.
- [11] James Dowsett and Christoph S Herrmann. 2016. Transcranial alternating current stimulation with sawtooth waves: simultaneous stimulation and EEG recording. *Frontiers in human neuroscience* 10 (2016), 135.
- [12] Giulia V Elli, Stefania Benetti, and Olivier Collignon. 2014. Is there a future for sensory substitution outside academic laboratories? *Multisensory research* 27, 5-6 (2014), 271–291.
- [13] Daiki Higuchi, Kazuma Aoyama, Masahiro Furukawa, Taro Maeda, and Hideyuki Ando. 2017. Position shift of phosphene and attention attraction in arbitrary direction with galvanic retina stimulation. In *Proceedings of the 8th Augmented Human International Conference*. 1–6.
- [14] Simon Høffding and Kristian Martiny. 2016. Framing a phenomenological interview: what, why and how. *Phenomenology and the Cognitive Sciences* 15, 4 (2016), 539–564.
- [15] Ryota Kanai, Leila Chaieb, Andrea Antal, Vincent Walsh, and Walter Paulus. 2008. Frequency-dependent electrical stimulation of the visual cortex. *Current Biology* 18, 23 (2008), 1839–1843.
- [16] Nicholas Ketz, Aaron P Jones, Natalie B Bryant, Vincent P Clark, and Praveen K Pilly. 2018. Closed-loop slow-wave tACS improves sleep-dependent long-term memory generalization by modulating endogenous oscillations. *Journal of Neuroscience* 38, 33 (2018), 7314–7326.
- [17] Michinari Kono, Takumi Takahashi, Hiromi Nakamura, Takashi Miyaki, and Jun Rekimoto. 2018. Design guideline for developing safe systems that apply electricity to the human body. *ACM Transactions on Computer-Human Interaction (TOCHI)* 25, 3 (2018), 1–36.
- [18] Árni Kristjánsson, Alin Moldoveanu, Ómar I Jóhannesson, Oana Balan, Simone Spagnol, Vigdis Vala Valgeirsdóttir, and Rúnar Unnthorsson. 2016. Designing sensory-substitution devices: Principles, pitfalls and potential 1. *Restorative neurology and neuroscience* 34, 5 (2016), 769–787.
- [19] Ilkka Laakso and Akimasa Hirata. 2013. Computational analysis shows why transcranial alternating current stimulation induces retinal phosphenes. *Journal of neural engineering* 10, 4 (2013), 046009.
- [20] Sang-won Leigh, Harpreet Sareen, Hsin-Liu Cindy Kao, Xin Liu, and Pattie Maes. 2017. Body-borne computers as extensions of self. *Computers* 6, 1 (2017), 12.
- [21] Pedro Lopes, Josh Andres, Richard Byrne, Nathan Semertzidis, Zhuying Li, Jarrod Knibbe, Stefan Greuter, et al. 2021. Towards understanding the design of bodily integration. *International Journal of Human-Computer Studies* 152 (2021), 102643.
- [22] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++ allowing objects to communicate dynamic use. In *Proceedings of the 33rd annual acm conference on human factors in computing systems*. 2515–2524.
- [23] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 1471–1482.
- [24] Kristian Moltke Martiny, Juan Toro, and Simon Høffding. 2021. Framing a phenomenological mixed method: from inspiration to guidance. *Frontiers in Psychology* 12 (2021), 602081.
- [25] Hideyuki Matsumoto and Yoshikazu Ugawa. 2017. Adverse events of tDCS and tACS: a review. *Clinical neurophysiology practice* 2 (2017), 19–25.
- [26] Hiromi Nakamura and Homei Miyashita. 2013. Controlling saltiness without salt: evaluation of taste change by applying and releasing cathodal current. In *Proceedings of the 5th international workshop on Multimedia for cooking & eating activities (CEA '13)*. Association for Computing Machinery, New York, NY, USA, 9–14. <https://doi.org/10.1145/2506023.2506026>
- [27] Daniel Edward Novy. 2019. *Programmable synthetic hallucinations: towards a boundless mixed reality*. Ph.D. Dissertation. Massachusetts Institute of Technology.
- [28] Alex Olwal and Bernard Kress. 2018. 1D eyewear: peripheral, hidden LEDs and near-eye holographic displays for unobtrusive augmentation. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. 184–187.
- [29] International Commission on Non-Ionizing Radiation Protection et al. 2009. ICNIRP statement on the “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)”. *Health physics* 97, 3 (2009), 257–258.
- [30] Walter Paulus. 2011. Transcranial electrical stimulation (tES–tDCS; tRNS, tACS) methods. *Neuropsychological rehabilitation* 21, 5 (2011), 602–617.
- [31] Colline Poirier, Anne De Volder, Dai Tranduy, and Christian Scheiber. 2007. Pattern recognition using a device substituting audition for vision in blindfolded sighted subjects. *Neuropsychologia* 45, 5 (2007), 1108–1121.
- [32] Nimesha Ranasinghe, Thi Ngoc Tram Nguyen, Yan Liangkun, Lien-Ya Lin, David Tolley, and Ellen Yi-Luen Do. 2017. Vocktail: A virtual cocktail for pairing digital taste, smell, and color sensations. In *Proceedings of the 25th ACM international conference on Multimedia*. 1139–1147.
- [33] Robert MG Reinhart and John A Nguyen. 2019. Working memory revived in older adults by synchronizing rhythmic brain circuits. *Nature neuroscience* 22, 5 (2019), 820–827.
- [34] E Santarnecchi, T Muller, S Rossi, A Sarkar, NR Polizzotto, A Rossi, and R Cohen Kadosh. 2016. Individual differences and specificity of prefrontal gamma frequency-tACS on fluid intelligence capabilities. *Cortex* 75 (2016), 33–43.
- [35] Eldon Schoop, James Smith, and Bjoern Hartmann. 2018. Hindsight: enhancing spatial awareness by sonifying detected objects in real-time 360-degree video. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

- [36] Pedro Shiozawa, Mailu Enokibara da Silva, Thais Cristina de Carvalho, Quirino Cordeiro, André R Brunoni, and Felipe Fregni. 2014. Transcutaneous vagus and trigeminal nerve stimulation for neuropsychiatric disorders: a systematic review. *Arquivos de neuro-psiquiatria* 72 (2014), 542–547.
- [37] Peter B. Shull and Dana D. Damian. 2015. Haptic wearables as sensory replacement, sensory augmentation and trainer – a review. *Journal of NeuroEngineering and Rehabilitation* 12, 1 (July 2015), 59. <https://doi.org/10.1186/s12984-015-0055-z>
- [38] Zenon Sienkiewicz, Eric Van Rongen, Rodney Croft, Gunde Ziegelberger, and Bernard Veyret. 2016. A closer look at the thresholds of thermal damage: workshop report by an ICNIRP Task Group. *Health physics* 111, 3 (2016), 300.
- [39] Misha Sra, Xuhai Xu, and Pattie Maes. 2017. GalVR: a novel collaboration interface using GVS. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*. 1–2.
- [40] Shriya S Srinivasan, Greta Tuckute, Jasmine Zou, Samantha Gutierrez-Arango, Hyungeun Song, Robert L Barry, and Hugh M Herr. 2020. Agonist-antagonist myoneural interface amputation preserves proprioceptive sensorimotor neurophysiology in lower limbs. *Science translational medicine* 12, 573 (2020), eabc5926.
- [41] Yudai Tanaka, Jun Nishida, and Pedro Lopes. 2022. Electrical Head Actuation: Enabling Interactive Systems to Directly Manipulate Head Orientation. In *CHI Conference on Human Factors in Computing Systems*. 1–15.
- [42] Johannes Voskuhl, René J Huster, and Christoph S Herrmann. 2015. Increase in short-term memory capacity induced by down-regulating individual theta frequency via transcranial alternating current stimulation. *Frontiers in human neuroscience* 9 (2015), 257.
- [43] Fan-Gang Zeng, Phillip Tran, Matthew Richardson, Shuping Sun, and Yuchen Xu. 2019. Human sensation of transcranial electric stimulation. *Scientific reports* 9, 1 (2019), 1–12.

A COMMERCIAL TES HARDWARE

A wealth of Transcranial Electrical Stimulation (tES) FDA-approved experimental devices exist in the market capable of producing tDCS

and tACS, using low electrical currents (<5 mA) that non-invasively modulate neural activity. Some notable ones are the Neurostym tES, the XCSITE100, and the 1x1 tES. These devices are highly versatile, having modes for transcranial Direct Current Stimulation (tDCS), transcranial Oscillating Direct Stimulation (tODCS), transcranial Pulsed Current Stimulation (tPCS), transcranial Alternating Current Stimulation (tACS), and transcranial Random Noise Stimulation (tRNS). Researchers are able to create different stimulation programs with these devices, setting desired waveform, current level, modulation frequency, stimulation duration and other parameters. Most of these devices have the same characteristics for maximum stimulation current (4mA), maximum stimulation duration (typically 30 minutes), and maximum output voltage, keeping in line with the established protocols for safe tES.

For our application, we decided to fabricate our own tES device for two reasons: first, we only intended to use the tACS mode and it ended up being cheaper to build a more limited device rather than buying a more powerful tES device, and second, most commercial tES devices do not support signal control by an external source, and this feature was needed in order to generate signals that respond to changes in the environment (an object approaching the subject).