The Human Eye as a Camera

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***Abstract*—We propose the use of SSVEP (Steady State Visual Evoked Potentials) in such a way as to cause the eye itself to function as a camera. By recording brainwaves in response to flickering visual stimuli, we read the "mind's eye" and are able to successfully reconstruct a visual image of subject matter that a person is looking at. In addition to causing the eye itself to function as a camera (see Fig 1), we also propose a new way to visualize and photograph human vision and human perception, i.e. a new way to see and understand human vision. This new "meta-vision" (vision of vision) has many applications in healthcare, from testing human vision to furthering our understanding of the brain.**

I. Introduction

The field of wearable and mobile computing, as well as body-sensor networks [1] and implants [2], [3] is increasingly being applied to healthcare [4] and prosthetics [5]. Smart technologies like smart homes [6] and smart cities [7] with dense wireless networks are evolving into a mesh of sensors and communications networks that span entire cities, with cameras and microphones in every streetlight to monitor the health of the city, through wireless mesh routing [7]. At the individual human scale, sensors are working their way into the fabric of everyday life, improving our health and well-being through the Internet-of-Things [8]–[10], as well as through sensing in almost all living things, not just humans [11]. In the future, nearly every light fixture will have a camera in it to sense occupancy and adapt its light output, and nearly every person will wear at least one camera. There will be challenges to overcome regarding privacy, security, and trust [12]–[14]. In the future there may be a camera in every room, not only for playing games, but also to measure and sense our health [15]. Thus, understanding vision (human vision as well as machine vision) is of vital importance to health, well-being, and the modern world in general.

A. Meta-sensing (the sensing of sensing)

In this paper, we wish to photograph, explore, and understand in new ways a human's capacity to see. Let us begin by reviewing previous work on photographing and understanding a camera's ability to "see" (sense). This sensing of sensors is called meta-sensing.

We have previously shown that it is possible to visualize the sensory capacity of sensors, such as video cameras, by way of video feedback with a television display or even simply one or more light bulbs or other sources of light [16], [17]. See Fig 2.

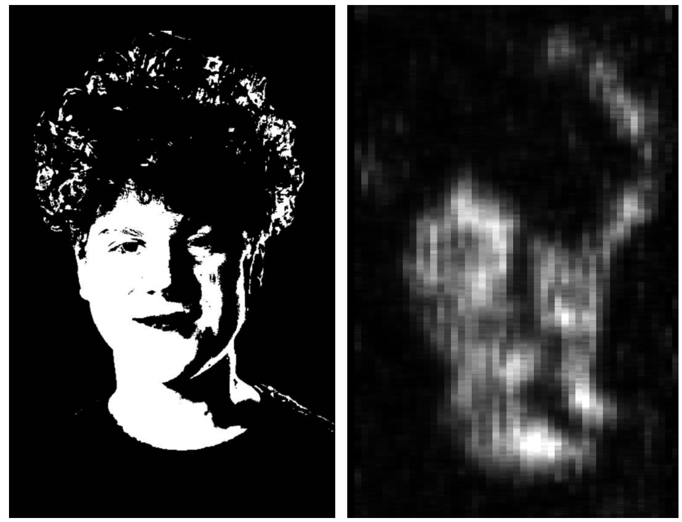

Fig. 1: Capturing and processing brainwaves causes the human eye itself to function as a photographic camera.

We can photograph such a sensor's ability to sense, using a process we refer to as "metavision" or "metaveillance" (i.e. the sensing of sensors and the sensing of their capacity to sense) [17].

For example, we have constructed a number of robotic mechanisms, including swarms of drones [18], as well as delta and cartesian 3D plotters that map out the capacity of sensors to sense. See Fig 3 where we photograph a smart street light's capacity to sense, by using a moving light source arranged so that its light output increases in proportion to a camera's ability to sense it.

In a similar way, we can also photograph automobiles along with their capacity to sense. Such photographs (metaveillographs) are useful because they provide us with insight regarding the sensory capacity of these devices, which is especially valuable when lives are at stake (e.g. self-driving cars, and having photographic evidence to verify that the automotive product was in good order when it left the assembly line) [19]. Judges and juries appreciate photographic evidence, and photographic evidence like that of Fig. 3 can serve a useful purpose in verifying the integrity of vision systems.

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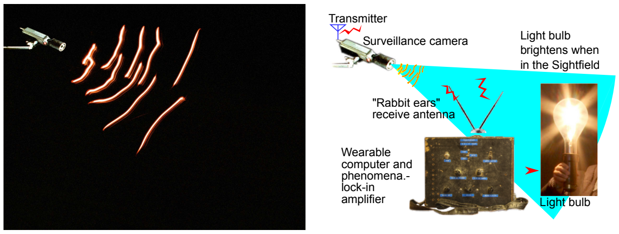


(a) (b)

Fig. 2: (a) Metaveillography, where a long-exposure photograph is captured of a light bulb being waved back-and-forth in front of a surveillance camera. Picture ©1975 S. Mann. (b) The experimental setup. A television receiver is implemented in a wearable computer system with lock-in amplifier to pick up even extremely weak television signals, amplify them, and feed them to a light bulb. The light bulb is set to always be at least slightly illuminated. When it comes into the field-of-view of the camera, it goes to full-on, due to video feedback. This allows us to see a camera's capacity to see. This sensing of sensors, and sensing of their capacity to sense, is called metaveillance [17]. Note the delayed response between when the light bulb enters the camera's field of view, and when it reaches full output. There is also a delayed "desponse" between when the light bulb exits the camera's field of view and it desponds. This is the phenomena of hysteresis (delayed response and delayed desponse) that is captured as the light source moves alternately left and right.
*Response time is the time delay on the rising edge of a stimulus, whereas "desponse" time is the time delay on the falling edge of a stimulus.

B. Meta-sensing of human vision

Mann et. al. [20] and Janzen et. al. [21] have previously photographed human vision, e.g. using photography as a medium of display for data captured through an eye test. The subject was asked to report on what is seen while a visual stimulus was presented by the experimenter.

In a recent abstract (the ACM WearSys 2019 Keynote, [12]) we very briefly described how the human visual system could be investigated directly, from nature itself, i.e. without asking the subject any questions about what is visible. The resulting "ayinograph™" can thus be regarded as evidence rather than testimony. Our method consists of monitoring the brain's response to a flickering visual stimulus, and plotting or photographing the magnitude of the response to the visual stimuli in different parts of the visual field using Steady State Visual Evoked Potentials (SSVEPs). For example, a flickering computer display was moved back and forth horizontally (or vertically, or both) across and beyond the visual field of view of a human observer, while EEG was monitored using a portable EEG headband called Muse™(manufactured by Interaxon™). The magnitude of the brain's response to the flickering stimulus at the same frequency was used to change the colour and luminance of an RGB LED light that was attached to the moving computer display. Long exposure

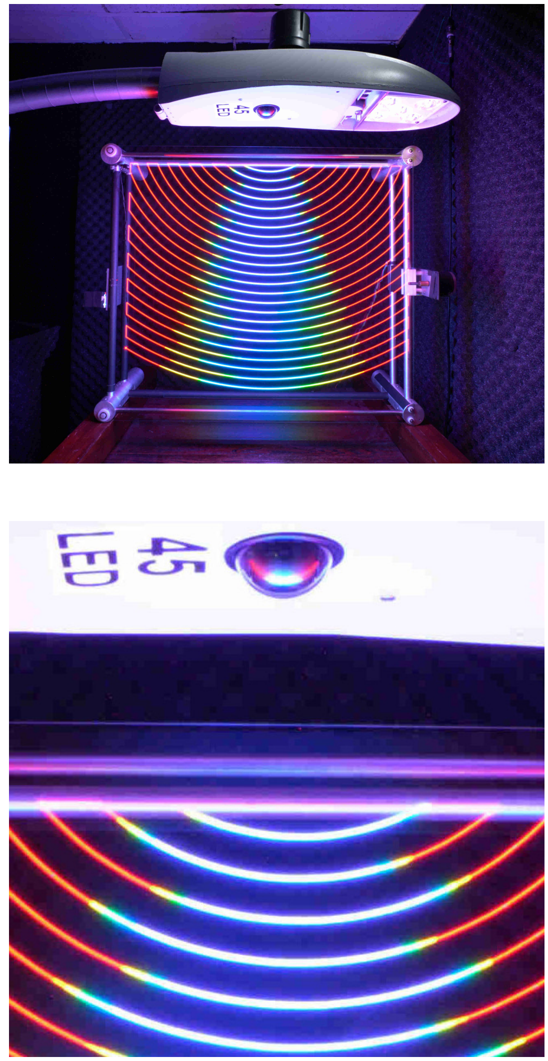


Fig. 3: Top: Long-exposure photograph of a sensor's ability to sense. Here is a photograph of a smart city LED streetlight. Like many smart city streetlights, it has a camera in it. Beneath the streetlight, we have placed a robotic mechanism that moves a light source in circular arcs. The light source is connected to an amplifier that receives input from the streetlight's vision (i.e. its capacity to sense), establishing a feedback loop as was done in Fig 2 [17]. The light source is an RGB LED with voltage to color converter, such that red is the background (bias) color (like the dull red glow of an incandescent light bulb of Fig 2 at very low voltage), green is for medium veillance, and blue is for strong veillance. Bottom: closeup showing the first six sweeps. The first sweep is a counterclockwise sweep nearest the camera. The 6th sweep is a clockwise sweep. Note the slight hysteresis (as explained in Fig 2).

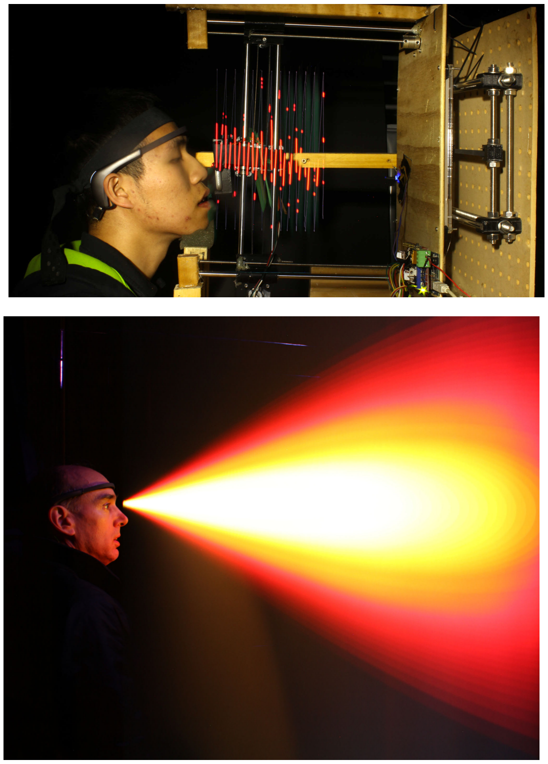


Fig. 4: Top: Metaveillography of a subject captured with mechanical prototype. Here, stepper motors move a brain-modulated light source through space. The bright red color of the RGB LED shows areas where the EEG picked up a strong SSVEP signal. The observer focuses on a single point directly ahead, and lets the smartphone move in and out of their peripheral vision. The long-exposure photograph shows only a narrow beam of sight approximately equal to the height of the phone. Bottom: Another subject's interpolated metaveillograph. Sparsely sampled SSVEP data is interpolated to make the high-resolution image [12].

photography was used to integrate this image over time for direct photography of the receptive field properties of the human visual system. In this paper we build upon this work. See for example Fig 4.

II. Eye is a camera

Previous work has been done to capture a person's vision from the exact same perspective as the human eye itself. This was done either from one eye, such as the wearer's right eye (see Fig 5) or both eyes (in the case of a stereo vision system).

We begin with a series of studies in photographing a human's capacity to see, i.e. meta-vision, which we believe may be useful for diagnosing and understanding vision, health care, eye testing, vision testing, and at the very least, a new form of visual art.

For this we created a 3D plotter which held a smartphone. The smartphone presents a set of four squares alternating between light colours and black at a fixed frequency such as

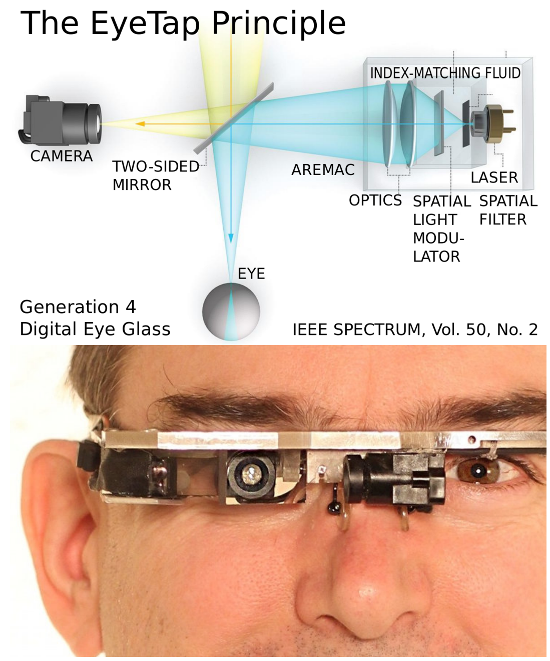


Fig. 5: The EyeTap Principle uses a camera and 45-degree mirror or beamsplitter to capture exactly the same viewpoint as the human eye. If we look into the eye of the wearer, it looks as though the eye is made of glass (camera lens) because we're seeing a reflection of the left-facing camera sitting on the nose bridge. IEEE Spectrum, used with permission.

12 Hz. The observer's head is fixed by a chin rest as well as a headrest on a high chair back. The observer looks at the smartphone's display located initially 4cm from the eye. The display is then moved slowly vertically with the plotter, going up and down at 5mm/sec, and retreating further from the participant on each pass, at 1/10th that rate (0.5mm/sec), traveling a distance of up to 21cm. This has the effect of rastering a slice of visual space in a vertical plane coming out from the face of the participant.

While this is occurring the observer is wearing a portable, wearable, EEG system (Muse™by Interaxon™), which is modified with one or more additional EEG electrodes secured in a 3D printed holder and attached to a flexible headband holding it over the occipital lobe. Specifically the center electrode is placed at location Oz (with others, optionally, at locations O1 and O2). The SSVEP is collected by measuring the power spectra of the resultant EEG signal over time. The power spectra are computed with a windowed FFT (Fast Fourier transform) with a window size of 10 seconds. The ratio of 12 Hz power to power in the rest of the frequency bands is then estimated, and used to modify the colour of the flickering checkerboard pattern, as well as an LED attached the plotter itself, facing orthogonal to the line of sight of the observer. The LED faces directly toward a camera that takes a long-exposure photograph of the person's face (side-view), their right eye (though both eyes are sensed), and the moving light source. The LED colour is changed from blue to red in proportion to

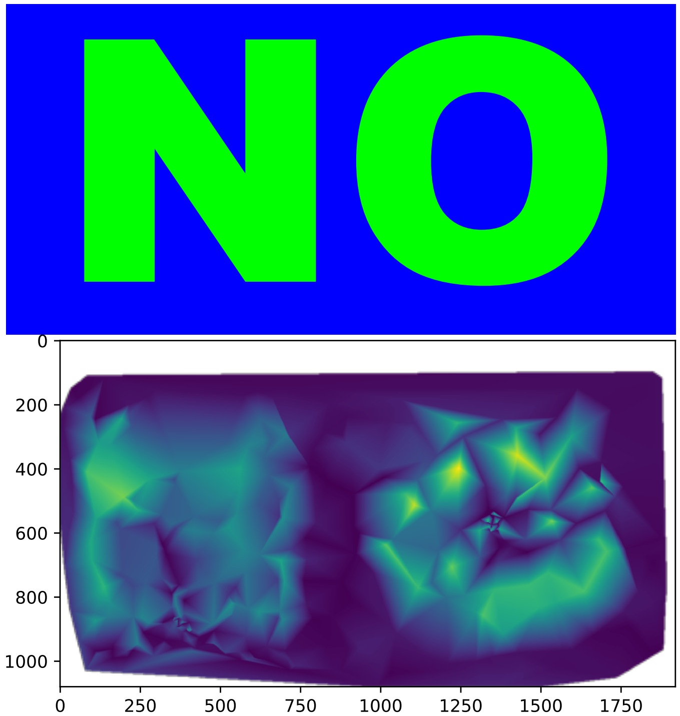


Fig. 6: The first sessions in which an image was reconstructed from recordings of brainwaves. The power of the flickering frequency in the EEG data at each point of the eyes' movements on the screen was captured. For every location the eyes looked, a color was added proportional to the coincident power of the flickering frequency (akin the the pixel value of an image). Darker areas of the image provide lower response, and lighter areas of the image provide higher response of the SSVEP (Steady State Visual Evoked Potential). Large SSVEP power was observed when the individual was looking at light colored objects such as the letters, and low SSVEP power was observed when the individual was looking at the darker (less flicker amplitude) background. The word "NO" was visibly reconstructed from mind's eye, based on SSVEP amplitude of EEG signal at each eye location during viewing of a flickering image of the word "NO". The image was interpolated in 2D to create a rough visualization of image in view of the observer. While blurry, this is the first ever reconstruction of a visual image from human brainwave activity captured with simple dry surface electrodes and using a simple commercially available EEG headband.

the relative power of 12 Hz activity compared to the rest of the spectra. This creates a way to visualize the useful field of view of the human visual system as shown in top of Fig 4.

We have established that the eye can function as a camera. By projecting the image to the side and collecting it with long exposure photography, we can photograph the observer's visual field. When the observer used overt attention to track the phone with their eyes, the effect created a broad cone of vision. However, when the observer fixated on a point directly ahead, and covertly attended to the moving smartphone display screen in the periphery, the photographed visual field appeared much narrower. Therefore we think of this visualization being related to a person's visual attention, or consciousness of the space around them. Other results from these experiments are detailed in [22].

III. Pictures from the "Mind's Eye"

Initially we created a flickering visual stimulus on the screen with contours created by non flickering black areas. We spelled the word "NO" as flickering subject matter. The observer was tasked with rastering their eyes horizontally and vertically across the flickering stimulus in a prescribed uniform raster-scan pattern, identical to the raster-scan of a progressively scanned television image. The observer's eye movements and location of fixation were tracked with a Tobii™desktop eye tracker which was pre-calibrated. The observer's EEG was recorded with a Muse headset, with an auxiliary Oz electrode providing high quality EEG data sampled at 256 Hz. See Fig. 6.

For every location to which the eyes moved, an estimate of the SSVEP magnitude was made from the EEG by performing a windowed FFT (10 second window) and computing the relative power of 12 Hz activity compared to the rest of the spectra. The more flickering light that entered the eye at that fixation location, the stronger the SSVEP magnitude was. We predicted that this modulation in SSVEP was a function of the subject matter's light level for each position of the raster scan. Thus lighter areas of the image produce higher SSVEP and darker areas lower SSVEP. This information was combined with the eye tracking data to recreate an image of what the participant was observing. See Fig. 6.

In some experiments we eliminated the need for the eye tracker, by simply displaying a cursor that moved along the subject matter in the prescribed pattern, to guide the person where to look. However, even in this case, the eye tracker is useful as it allows us to detect saccades, blinking, or other anomalies to be filtered out or down-weighted.

Although the unstructured eye-tracking based scanning approach successfully captures large patterns, it fails to capture fine details. A list of some of the problems with the previous approach:

1) eye-tracking is only accurate to within a few centimeters
2) consecutive rasters (without breaks for the subject) lead to fatigue
3) an SSVEP response is elicited not only when a person looks directly at a flashing point, but also (to a lesser degree) when there is flashing in their peripheral vision, thereby decreasing the resolution of the output image.

To address these issues, a new process was devised in which a cursor would slide across the target image. The cursor's shape, size, speed, closeness to face, colour, frequency of flashing, and brightness were optimized for maximal response and response reliability.

In this approach, the subject follows a white dot in the center of a square cursor as it slides from the left side of the image

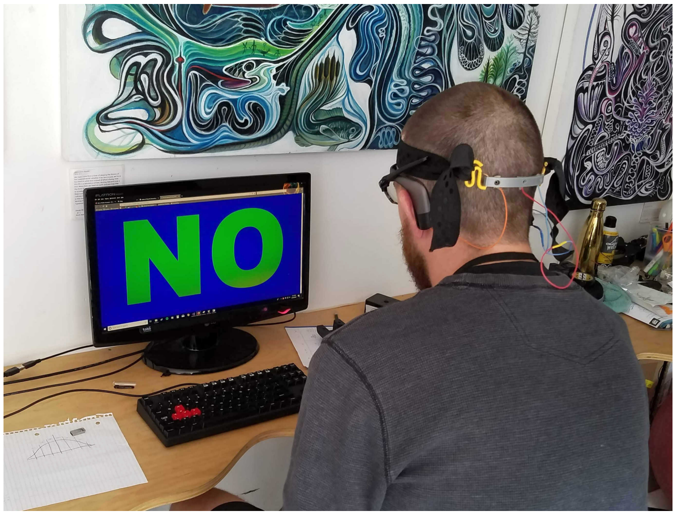


Fig. 7: Experimental setup with observer viewing a displayed image. Here the image is a simple picture of the word "NO" displayed on a dark background. (the image is flickering at 12 Hz).

to the right. When the square is over a non-black part of the image, it flashes bright yellow and blue at 15Hz, which is faster than most alpha waves, and an improvement over our previous 12Hz stimulus from our own study on the optimal stimulus, as well as results from previous literature in VEP [23], [24].

As the subject concentrates on the moving square, EEG data is recorded. The image is produced with the following methodology:

1) For each position, the power spectral density is computed over a 1700-sample window (256 samples/second * 6.67 seconds, the time it takes the cursor to pass over a point).
2) Harmonics of the fundamental VEP frequency are present in VEP response [23], so we include the 30 Hz values in our power estimate, and divide them by the power over the 14 to 50 Hz frequency domain to filter common-mode noise.
3) Due to scan lines overlapping, pixel measurements are composed of measurements in multiple vertical locations. They are combined with a linear model of human vision in the center of focus and near periphery:

$$f(x) = 2x + x_1 + x_{-1} + \frac{x_2 + x_{-2}}{2} \tag{1}$$

Where x is a given pixel value, x_1 and x_2 are pixel values at the same index above that row, x_{-1} and x_{-2} are pixel values in the same index below that row.

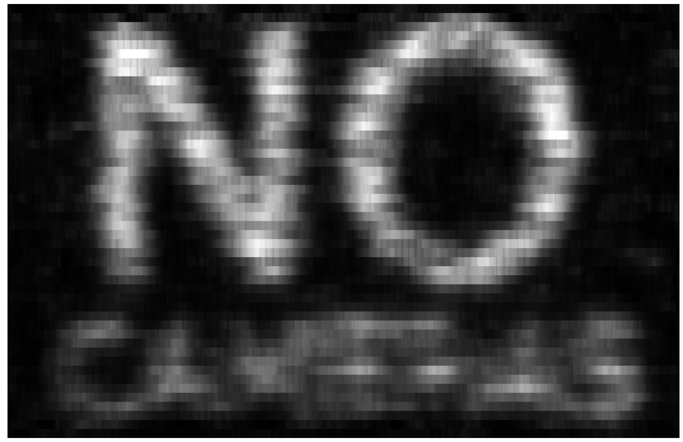
Utilizing this technique, we took a mind's eye image a ”No Cameras” sign. It has been observed [25] that establishments often use surveillance recording devices while at the same time banning patrons from taking pictures or recording video. This hypocrisy embodies a lack of integrity [26], resulting in an incomplete truth (i.e. a half-truth) [27]. To demonstrate the absurdity of such rules, we have taken an image of a ”No Cameras” sign without the use of any camera other than the human eye itself, thus blurring the distinction between seeing, remembering, and recording. Capturing an image using the human eye as a camera (by only reading bio-signals) means that we are recording data that already belongs to us. The result of this demonstration shows the absurdity of the ”No Cameras” rules, as the only way to enforce such a concept would be to ban us from entering the establishment with our brains! While the owners of such establishments may be used to leaving their brains at home, this is something that we, the authors, do not want to be compelled to do!

Continuing this research, a similar method was applied on an image of a human face. The image flashes at 15 Hz, and the test subject follows 48 rasters across the screen. The image is displayed horizontally during trials, and is then rotated 90 degrees clockwise post trial. White and black is used as opposed to yellow and blue to allow for a stronger contrast between facial features. The interpolation method used is identical to that of Fig 8b. After interpolation, data is multiplied by a factor of 2 to increase image brightness. See Fig. 1.

This technique proved extremely promising and thus it was adapted and expanded upon in order to capture ”real-world” images using the human eye as a camera. To recreate rastering in the real world, a mechanical apparatus was built that could move a light source through space at a specific location and speed. This apparatus consisted of two tripods setup 6 feet apart, each with multiple pipe mounts spaced incrementally along the vertical length of the tripod. A pipe with the attached light source was attached horizontally between these tripods, at varying heights, depending on which scan line was being captured. Each scan line was then captured by sliding the light source along the pipe at a steady rate, as controlled by a mechanical pulley system and a human operator utilizing a metronome for timing. The light source was then shone on the object that was to be photographed (see Fig. 10 to see a snapshot of the experimental process). The participant would then watch as the apparatus drew scan lines over the object of interest. See Fig. 11, a result of this method.

Continuing on the work presented in the IEEE GEM (Games, Entertainment and Media) Conference [22] taking images of real-world objects, we modified a pair of shutter glasses (traditionally used for viewing stereoscopic video in 3D displays) to induce SSVEP in a portable, wearable way. Taking photos in public poses a unique challenge, in that the photographer has very little recourse to control the scene, and must instead adapt to it. In particular, where our closed-door tests allowed us to draw a pointer that our gaze could follow to scan the scene of interest (e.g. with a data projector, or pixels on a screen), in public the apparatus had to be completely self-contained. This requirement was especially important within the art gallery where we obtained Fig. 12b, where any changes to the environment are unacceptable.

(a)



(b)

Fig. 8: (a) The 100px x 100px flashing yellow and blue square slides across ”NO CAMERAS”. Each scan line of the raster takes approximately 106 seconds. 48 overlapping scan lines make up the entire image. (b) The image obtained from capturing a participant’s EEG data while looking at ”NO CAMERAS”.

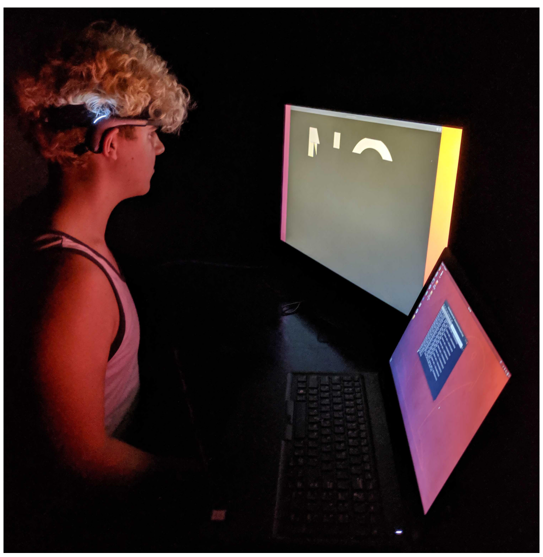
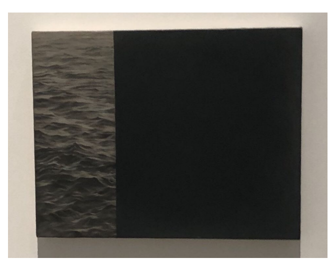


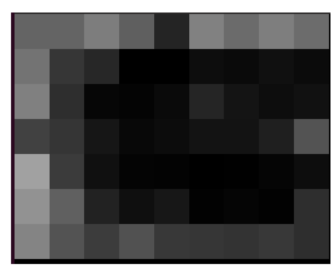
Fig. 9: The setup of the display, control computer (running Ubuntu™GNU/Linux operating system), Muse™EEG system, and participant for the ”NO CAMERAS” imaging trials.

Fig. 10: Process shot of how a picture of the human form was captured using the human eye as a camera.

Fig. 11: Left: Individual being imaged by participant. Right: Output from EEG.



(a) Reference image: work by Vija Celmens, part of the “Untitled (Ocean)” series



(b) The image of 12a obtained from the photographer’s EEG data.

Fig. 12

To this end, we moved all features of the test apparatus into the wearable computer. We occluded most of the view on our shutter glasses so the photographer could only focus on the spot directly in front of their gaze, to emulate the fine spatial control of a pointer. Then, to avoid unpredictable timing and positioning with rastering, we subdivided the scene into discrete rectangular chunks and fixated on each at a time to obtain pixels of the image. To obtain the image in Fig. 12b, the photographer fixated on each chunk for 8 seconds.

IV. Future Directions

We obtained a compelling set of results. We will continue to work to maximize the resolution, speed, and usefulness of these techniques. Here, we also present some further possible applications.

Equipment: One limitation is the use of an LCD monitor, which has irregular pixel onset time with respect to each refresh cycle, which reduces the spectral purity of the stimulus and decreasing our signal to noise ratio. In our future research we will use an improved monitor that can flicker more reliably such as a CRT (Cathode Ray Tube) which we modify to operate in vector graphics rather than raster graphics (akin to a cathode-ray oscillograph). Finally, another limitation is the use of a low cost portable EEG system with dry electrode connections. In our follow up research we will utilize a better EEG system that can record from more channels, at a faster sampling rate, and with a better signal to noise ratio.

Signal Processing: A number of potential signal processing schemes were tested and we have imagined a number of potential improvements to these schemes. We realize that some eye movements are quite quick and will not linger at the location long enough to entrain the SSVEP in the EEG. Here we corrected this by using a low pass 1.5 Hz 6th order Butterworth digital filter on the eye movement X and Y data prior to plotting. This minimizes the large eye movements but does not remove their influence all together. A future scheme will use a weighting based on the speed of eye movements, to maximize the influence of slow movements and reduce this source of error. Further, during blinking (which shuts the eye-camera and creates an electrical artifact in the EEG), this same reduced weight will be used, whereas here we ignored this complexity. Further improvements include using VEP based on the wavelet or chirplet transform [28], [29].

Imaging light vs. the mind - Simple visual illusions create the precept of contours that are non-veridical, they are all in the mind. Recording of neurons and EEG has shown that these illusions are associated with activation as if there is a real stimulus there. We predict that this technique could be used to visualize the percept of a stimulus instead of the stimulus itself. That is, if we present a visual illusion with an artificial contour perceived by the observer, we predict that the reconstructed image would also contain that illusory contour. Additionally, we may be able to record images that have a human element of relevancy. This might allow us to, for example, capture a picture with emphasis on objects the person deems relevant. Objects that a person deems relevant will show up more clearly in the picture, so that we will have a new artistic and scientific "window" into human vision.

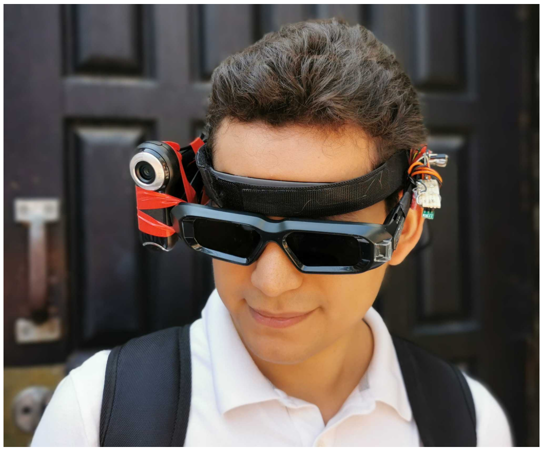


Fig. 13: SSVEPVMP apparatus.

Health Applications: We believe that the veillance images we are collecting are more related to the spotlight of attention than they are to the physical input of light to the eye. We found that when observers fixate on a single point and ignore the flickering light in their visual field, the veillance field is narrowed. However, when they track the flickering object itself, the veillance field becomes wider. Concretely, this methodology presents new opportunities for diagnosing and understanding vision, e.g. the vision test of the future. This will be useful because it goes beyond simply an eye test, and includes important elements of brain function. This could have far-reaching implications for health care, and will allow us to better understand the brain and mental health. We also propose that this could represent a useful predictive biomarker of attention issues associated with ADHD and aging, and thus a potential target for intervention.

A future direction of this research is the application of visual focus metrics in wearable computing. We have already begun to explore this through a new custom WearComp system, the SSVEPVMP (Steady State Visually Evoked Potentials Visual Memory Prosthetic). The SSVEPVMP consists of shutter glasses, EEG headset, head-worn camera, head-worn microphone, and a central processor (Nvidia Jetson™ or Raspberry Pi™ 4). While the user goes about their day, their world is mediated to flicker at 15 Hz. Then, we measure the user's SSVEP response to predict attention to events seen in everyday life. When the user's visual environment is of little importance, no (or very weak) SSVEP response is measured. When the user's visual stimulus is interesting and engaging, there is a high SSVEP response. This system has been tested to successfully predict events that were of importance to the cyborg user. See Fig. 14

V. Conclusion

We proposed a method of visualizing the eye's gaze using synchronized EEG data with SSVEP. By mapping brain wave response to a 12 Hz or 15 Hz flashing light stimulus, we've

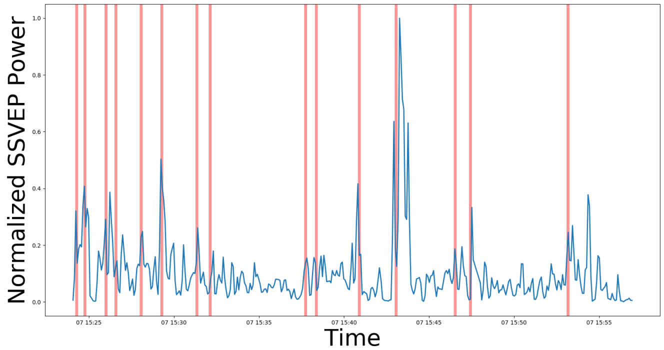


Fig. 14: We collected the SSVEP response of an individual wearing the SSVEPVMP WearComp for 30 minutes. During this time, we also recorded interesting visual events as indicated by the user. We then predicted the points of interest by collecting the times of high SSVEP response. This figure shows a graph of the normalized SSVEP power (blue) over 30 minutes. The red bands are interesting events that occurred during these 30 minutes, which were indicated by the user. In our initial tests we have seen an 89% hit rate on these interesting events.

successfully displayed images seen by the visual cortex. We hope to further advance this technique for metavision of the brain, and are working on applying the technology to commercial and medical applications.

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