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## **VISIO-VESTIBULAR INTERACTION IN HUMANS: CHANGES IN THE VESTIBULAR RESPONSE FOLLOWING VISUAL STIMULI OF DIFFERENT COLORS**

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### **INTRODUCTION**

Neuroscience studies indicate the presence of pathways from the visual-processing brain regions to the central and peripheral vestibular apparatus [1], [2]. These pathways can enable a visual stimulation to induce a vestibular response change [3]–[5]. For example, there have been extensive applications of color therapy (exposure to light of different colors) to compensate for vestibular related deficiencies [6].

In a cat study, diverse inhibitory-excitatory vestibular responses were obtained from vestibular units following exposure to flashes of varying intensities and duration [4]. In another study, investigating color perception in a macaque monkey brain regions there was activation of cortical and subcortical areas linked to the vestibular including posterior inferior temporal cortex, PITd (in superior temporal sulcus) and TEO (temporo-occipital in inferior temporal areas) [7]. However, there is no similar study measuring a direct vestibular peripheral response in humans.

Using functional MRI (fMRI), color centers in the human visual brain were reported to be cortical areas V4 (the right fusiform gyrus), superior parietal lobe, precuneus, and the right hippocampus [8]. These brain areas have some direct and indirect connections to the vestibular processing regions of the brain [1], [9]. In this study, the responsiveness of the human

vestibular periphery to various colors was assessed using a new technology called Electrovestibulography (EVestG) [10], which is an objective method of noninvasively measuring vestibular response.

### **VISUAL-VESTIBULAR INTERACTION**

Photons of light striking the retina cause chemical changes in the pigments of the photoreceptor [11]. These changes produce electrical potentials, which are carried through optic nerves and reach optic tract through optic chiasm. From optic tract, there are projections to the lateral geniculate nucleus (LGN), superior colliculus, pretectum of midbrain and suprachiasmatic nucleus of the hypothalamus [12]. These regions send fibers to visual-processing areas of the brain including striate (V1) and extrastriate cortices (V2, V3, V4, MT) [13]. From these cortices, electrical signals reach to superior colliculus through the inferotemporal cortex. There are neural connections between the superior colliculus and vestibular nuclei (VN) [14]. The VN sends projections to the efferent vestibular system, which then sends efferent fibers to the vestibular periphery (afferents and type II hair cells) of the semicircular canals and otolith organs (utricle and saccule). Neural activities of the hair cells, vestibular nerve and VN can be recorded using EVestG technology described in the following section.



Figure 1: From left to right; Ear electrode, electrode placement, and subject connections [10].

## EVestG TECHNOLOGY

EVestG was first introduced in [10] as an objective method for assessing the central and peripheral vestibular system. In this technology, static and dynamic vestibular responses are recorded noninvasively and painlessly by two electrodes inserted into external ears. A hydraulic chair provides passive whole-body tilts as stimuli for dynamic vestibular response. Passive vestibular response is recorded while the chair is in stationary position. The electrodes are soft cotton wool tips soaked in a mixture of saline and conductive gel to reduce interface impedance. In each ear, one electrode is placed close to the eardrum and one electrode on earlobe for differential recording, while the common electrode is placed on the forehead of participants to reduce the common environmental noises and other biological artifacts (e.g. EEG, EOG, EMG). After preparing and connecting the electrodes, participants sit in the hydraulic chair in an anechoic chamber (<30 dB), where recording is performed [10].

## METHODOLOGY

Thirteen subjects including five males participated in this pilot study (age:  $27.5 \pm 4.9$  SD). Individuals were given an oral explanation of the procedure prior to electrode attachment. In this study, we did not use any of the dynamic stimuli (the tilts). Participants sat in the chair in the anechoic chamber without undergoing any tilts. A simple virtual reality (VR) environment consisting of a solid background was generated using Unity Game Engine. Participants were immersed in VR by wearing a head mounted display (Oculus Rift, Development Kit 2) connected to a laptop (EUROCOM Sky X4, NVIDIA GTX 970M, G-Sync Technology). A sequence of colors (Black, White, Black, Blue, Black, Green, Black, Red, Black) were shown, when the participant

pushed a start button located on the armrest of the chair (Fig. 2). For each color, the respective red, green and blue (RGB) value was set to 255 and the two others set to zero (the intensity of RGB colors are summarized in table 1). Duration of each color exposure was 30 seconds; thus, the recording lasted for 270 seconds. Presenting black background in between other colors was chosen to remove the image aftereffect.

## SIGNAL ANALYSIS

The recorded vestibular responses were fed into an algorithm called the neural event extraction routine (NEER) algorithm [10]. The NEER algorithm is a part of the EVestG technology which produces two outputs [10], [15]: 1) the average field potential (FP), and 2) time interval between detected FPs. The FP refers to the extracellular potential produced as a result of the almost simultaneous firing of many vestibuloacoustic predominantly vestibular fibers. Features extracted from the FP can be used as comparison criteria for diagnostic purposes [15]–[17]. Practically, the average time gap between each detected FP is approximately 3.3 milliseconds [15]. Knowing that the frequency of the spontaneous efferent



Figure 2: EVestG recording procedure during exposure to different colors

vestibular activities is between 10 to 50 Hz, another useful feature can be extracted from the time interval signal (NEER algorithm output), called the 33-Histogram interval [20]. In this case, the gap between each 33 detected field potentials are calculated (10 Hz is equivalent to 100 msec; thus  $100/3.3 \text{ msec}=33$ ) This 33-Histogram interval corresponds to the lower range of the potentially modulating efferent input effect on afferent spontaneous vestibular activity [18].

## RESULTS

Figure 3 shows the average of the 33-Histogram intervals for all participants. Based on the diagram, a range of vestibular responses was obtained following exposure to light of different colors. The largest difference corresponded to the black and red histograms ( $p < 0.1$  for both ears) with the black color having the shortest average interval. However, it should be noted that the intensity and wavelength were confounding variables. To address this issue, two scenarios needed to be considered and investigated; 1) fixed intensity-different wavelengths, 2) fixed wavelength-different intensities.

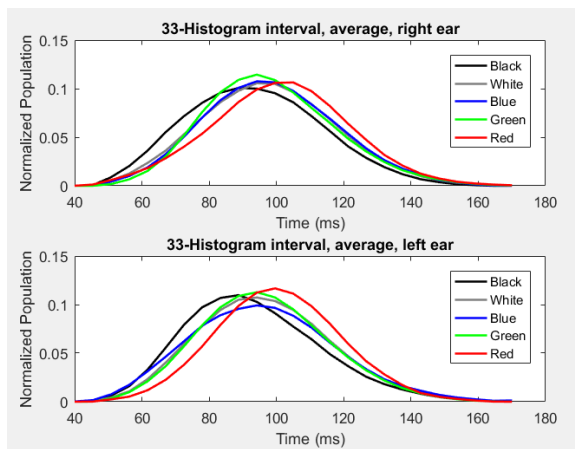


Figure 3: Average 33-Histogram interval for different colors

The fixed wavelength-different intensities scenario was examined for one female subject. Using a photometer (DT-1309 / Wide Range

<sup>1</sup> 1Lux=one lumen per square meter

Professional Light Meter), a blue color screen with different intensities was applied (Blue1=15.4, Blue2=13.1, Blue3=11, Blue4=10.1 Lux<sup>1</sup>). The duration of each specific intensity was 30 seconds with the black in between of each two colors. The time segment 20-25 seconds after blue onset was analyzed to remove the image aftereffect and transient responses. As it can be seen in Fig. 4, the histogram's peak shifted to the right as the intensity of the blue color decreased, implying the vestibular response to blue color of lower intensities had longer intervals.

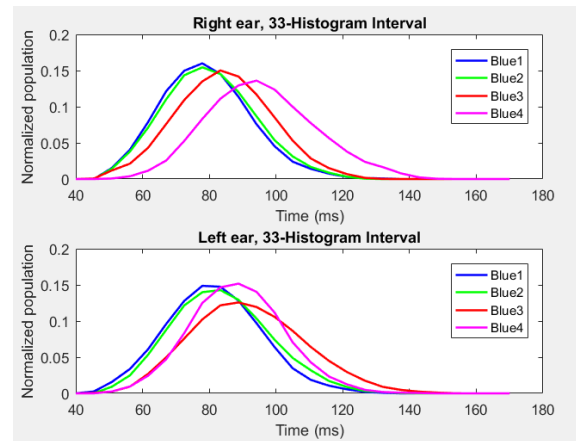


Figure 4: The effect of different intensities on 33-Histogram interval for the blue color

## DISCUSSION AND CONCLUSION

The sequence of color distributions from left to right being black-blue/green-red is difficult to interpret given the confounding wavelength and intensity variables. Exposure to light (any color) causes photoreceptors to secrete less neurotransmitter compared to darkness [1], i.e. the photoreceptor circuitry is most active in darkness; as shown in Fig. 3, the response to black color showed the shortest intervals. However, the results shown in Fig. 4 suggest that not only colors can bring about differing vestibular responses, but also brightness level has an effect on the vestibular apparatus.

We also tested the fixed wavelength-different intensities scenario, where different brightness levels were considered for the blue color. Vestibular activities change proportional

to brightness levels presented within the well-lit photopic vision range (>3 Lux, cone vision is dominant [19]). Indeed, by increasing the intensity, the number of detected vestibular firings increased (histogram shifted towards shorter time intervals, Fig. 4), and vice versa.

We also studied two other midrange brightness levels (i.e. close to the mesopic light levels range [19]) in which both cones and rods are activated. Those blue color screens with intensities of 7.4 and 6.4 Lux resulted in increased vestibular activity. The lowest intensity levels (scotopic range, primarily rods) vestibular activity was also decreased.

Although our results are encouraging it should be noted that the fixed wavelength-different intensities scenario was investigated only for the blue color in one participant. The effect of red and green colors with different intensities as well as the fixed intensity-different wavelengths scenario still needs to be fully examined. Our results raise many questions such as: Does the color order or intensities order or representation affect the histogram response? How do changes in pupillary size and retinal light adaptation following an exposure to different colors and intensities affect the vestibular response? Is vestibular response more sensitive to wavelength or intensity? how do the physiological/emotional effects of colors on individuals change the vestibular response? These are questions for future research in a more controlled study and in a much larger sample size.

Table 1: Color intensities measured through photometer.

Color	Intensity (Lux)
White	83.2
Green	47.7
Red	25.1
Blue	18.9
Black	1.9

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