A Systematic Review on Visual Fatigue Induced by Tiny Screens (Smartphones)

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Abstract. Smartphones are the friendly gadgets with emerging technology in a current-generation which made everything accessible with a single touch. They occupied huge space in our daily life, the continuous utilization of smartphone in our everyday life leads to affect the focus, attention and create functional impairments to the users. It is required to understand what are the prevalence, symptoms and factors of smartphone addiction and how it affects the individual health. Also, what are the techniques available to analyse the visual fatigue caused by smartphone? Detailed search of scientific articles from the various database for the past ten years with selected keywords visual fatigue, eye activity, usage duration, smartphone addiction. Due to the rising trend of addiction to smartphone, visual fatigue has become a negative concept, and scientists have mostly focused on its harmful applications. With authors knowledge, no studies related to visual fatigue were found in India. The excessive utilization of smartphone can cause visual and musculoskeletal disorders also damage one’s interpersonal skills.

1. Introduction
Smartphones are evolving at a great pace. It has changed the way we used to live, from play to payment; it is capable of doing them all. At present globally, there are more than 1 billion smartphone utilizers, which has improved our way of living with various technologies like access to the latest news, keeping connected and many. Most of us are pretty attached to our phones. Studying, travelling, playing, sleeping, eating we carry it everywhere we go and leaving it behind is not an option for us. Often people are found to spend more time with a smartphone than family and friends. In the current scenario, the most of the smartphone is equipped with larger display screen, internet, greater connectivity options, and a virtual assistant like Siri or Google, GPS capability, capturing and storing high-definition pictures and videos, voice recognition and many others [1]. In 2020, it is observed that the total numbers of smartphone users globally are 3.5 billion, which indicates that about 45.12% of the total world population own an individual smartphone each [2]. Whereas in India, approximately 400 million people utilize smartphone and they are the second largest smartphone utilizer. It is predicted that the number of smartphone utilizers would double by the year 2022 with a 12.9% compound annual growth rate [3]. Staring continuously at the smartphone screen leads to specific health issues like migraine, dark circles under eyes, weakening of eyesight, head and neck pain, it messes with our brain as well, and literally leads to visual, muscle and mental fatigue [4]. The discomfort caused by any kind of digital medium referred to as digital eye strain. Also, the blue light technology behind smartphone screens leads to increase the fatigue levels causing disrupting sleep.
patterns, feeling of weakness, blurred or reduced vision, eye pain, headache, reduce the melatonin hormone and many other health issues. It is observed that more blue light is absorbed by young adults than adults, because of prolonged smartphone utilization, maintaining the shorter distance between smartphone and eyes, utilizing improper illumination [5]. Excessive smartphone utilization leads to addiction, which causes maladaptive dependency on a smartphone, behavioural changes including, mood modification, tolerance, reinstatement, anxiety, depression [6]. Technology or smartphone acceptance, engagement, attachment, addiction, and its continuous or excessive utilization damages one’s psychological well-being. An assessment tool is proposed to understand their level of addiction in order to reduce digital eye strain [7]. Generally, Digital eye strain symptoms are of two types internal and external symptoms. Accommodation or vergence, ametropia problems considered as internal, and dry eyes considered as externa [8].

2. Methodology
The methodology for our literature search was (i) find the appropriate keyword(s), the keywords are “Visual Fatigue”, “Eye activity”, “Usage duration”, “Smartphone addiction”; (ii) collect papers from literature databases namely Google Scholar, SCOPUS and ISI from scientific search engines namely PUBMED, IEEE and Science Direct; (iii) sorting of papers to recent ten years from 2011-2020; (iv) quick scan to the identify the articles by understanding the titles with a matching principle; (v) thorough check of the identified articles with abstract reading, to select which are suitable to the research; and (vi) with detailed procedure of analysing and understanding the selected articles full text. All the gathered data resources have been reviewed for this research work from available published research works.

3. Results and Discussions
This article reviews forty recently published articles on what are the reasons behind the visual fatigue induced by smartphone or the digital medium, and techniques to measure. The following paragraphs summaries as reasons of visual fatigue (Section 3.1), techniques available to measure visual fatigue levels (Section 3.2). The available techniques are utilizing eye-trackers, biomedical instrumentation, camera and subjective data.

3.1. Reasons behind Visual Fatigue due to Smartphone
3.1.1. Blue Light Technology behind Smartphone. Our eyes are persistently taking in different types of light—its majority blue light from various digital screens. Blue light is also a part of the visible light spectrum which have a shorter wavelength of range 380 to 500 nanometres and highest energy. Sunlight is the primary source of blue light, whereas the other sources of blue light are tablet, smartphones, computer monitors, LED televisions and compact fluorescent light (CFL) bulbs. Generally, people start staring at smartphones before the sun rises, and utilize various digital medium whole day for various work practices. Later get back home and stare at the TV and end the day by looking at the smartphone. And people are not aware what is the light emitted from a smartphone, how it could affect human health? The studies noted that users spend an average of seven hours a day looking at those screens and that even kids were affected [9]. The utilization of smartphone causes people being exposed to blue light frequently, and the eye’s lens and cornea cannot reflect or resist it. It is toxic as if eyes are exposed to blue light on the retinal area for a longer duration, it will slowly kill photoreceptor cells which cause eye cancer. The continuous exposure of it could interrupt sleep and affects the body to create melatonin and contribute to digital eye strain. Sarah L. Chellappa, et al., [10] investigated on various sleep structure and brain activity of smartphone users, by conducting an experiment with 30 subjects of age group (20-31 years) for 2hours duration under three different light exposures of polychromatic light (2500K, 3000K and 6000K). The subjects should sleep under dim light conditions for 1.5hours, then under complete darkness for 2 hours and under CFL bulbs of 2500K for another 2 hours finally again under dim-light for another 45 minutes. The same procedure continued for the other light conditions of 3000K and 6000K. They measured the quality of sleep...
utilizing a vitaport-3 digital recorder which comprises of one electrocardiogram, one electromyogram, two electrooculogram, eight electro-encephalogram and acquires polysomnographic recordings. They observed that sleep was significantly affected for the subjects under 2-hour 6000 K light than under 2500 K and 3000 K. C. Martyn Beaven, et al., [11] compared the difference between the effects of blue light and caffeine. The experiment was conducted on 21 subjects of non-athletes between 22 and 30 years of age, and they considered four conditions with the combination of either under blue-light or white for 1 hour and either no caffeine or 240mg of caffeine. They measured the subject’s alertness condition with Karolinska sleepiness scale after the four conditions. They came to an inference that the alertness and addiction level after taking 240mg of caffeine is the same as the exposure of blue light for 1 hour. Also, the overexposure of blue light and caffeine has a very severe effect which causes various psycho-physiological effects. Liese Exelmans, et al., [12] studied the correlation between sleep quality and mobile phones usage for 844 adults of 18-94 years old. They measured insomnia by Bergen insomnia scale (BIS), fatigue assessment scale (FAS) and Pittsburgh sleep quality index (PSQI). They observed that 60% of the subjects were taking their mobile phones inside the bedroom and utilizing for texting, calling and other applications. Also, the relationship between sleep time and mobile phone at bedtime utilization and fatigue are significantly affected by the age of the subject. They concluded that sleep quality negatively correlated with the bedtime smartphone usage in adults. Jung-Yoon Heo, et al., [13] examined the effect of smartphone utilization with and without blue-light with 22 subjects. An experiment is conducted on each subject for 150 minutes from 7.30 to 10.00 PM with both normal and under blue-light condition. Various parameters including body temperature, serum melatonin and cortisol levels are tested, before, during and after the experimentation for both the lighting condition. They utilized various fatigue and sleepiness scale for assessment of subject’s condition. They drew an inference that exposure of blue-light lead to increase in body temperature, commission to error, serum cortisol and melatonin levels and reduction in sleepiness. Maja Kopper, et al., [14] analysed difference between reading from the paper and the computer monitor. Four different experiments performed to access pros and cons associated with reading from a computer screen (1) with same proofreading speed, (2) longer duration, (3) reduction in brightness of the screen and (4) positioning the screen similar to the paper with same inclination and distances, what is the digital eye-strain associated under different circumstances. They observed that from above all conditions expect positioning similar to paper, the other conditions would rise digital eye-strain. Experts and researchers have studied the widespread of mobile device, and its excessive utilization can physically harm to users. The blue light from smartphone and tablet screens can damage the retina. Also, some smartphone companies are adding blue-light filters to the screens, which is a good idea, but how far those filters can resist the emission of blue light.

3.1.2. How 3D display causes Fatigue. In the real world, we have learned far away objects and near objects require us to focus far and near; our pupil size changes to adjust for proper focal length. This concept does not work when viewing stereoscopic or 3D displays; eyes have to be focussed at the focal length of the screen. The disparity between focal length and parallax observed between eyes confuses the brain, which has learned to focus at the different distance objects with different focal length to make the vision clear. Many people get headaches or blurred vision while viewing stereoscopic 3D images or videos. Jung-Hoon Lee, et al., [15] conducted a subjective evaluation to identify the differences in each subject while watching stereoscopic videos or images. The authors considered genetic relationship with visual fatigue, age and gender as main factors and examined them. Analysis was conducted on 294 subjects of 105 female subjects and a group of 57 subjects of teenage, a group of 206 subjects of 20’s and remaining above 30 years old. They rate their level of fatigue based on questionnaire data which comprises of nausea, eye-strain, headache, ophthalmalgia and dizziness. They observed headache, ophthalmalgia and dizziness are the frequent symptoms of visual fatigue. They conclude that at 95% confidence levels, almost 7% of subjects cannot continue watching because of severe fatigue levels and 36% of subjects experienced serious issues while watching stereoscopic images or videos. They also observed no significant difference between
genders; also, teenagers tend to have more fatigue than 20-30 age group subjects. Zhiyu Qian, et al., [16] proposed a method to measure visual fatigue while watching stereoscopic images utilizing electroencephalogram (EEG). They experimented on eight male subjects of 20-26 years age group; they considered four stereoscopic videos of 137 seconds duration each with 60 seconds duration of relaxation before and after each video. They obtained blink signal from EEG data by utilizing Butterworth filter of order 4, from which they calculated eyelid closure time, and they obtained the percentage of closure of eyes (PERCLOS), average blink time and blink response. Chunxiao Chen, et al., [17] studied on fatigue due to stereoscopic videos and evaluated utilizing EEG. They experimented on 25 subjects of 20-24 years old out of 11 female subjects under two conditions while watching 3DTV and 2DTV and attached an EEG to each subject and analysed the data. They proposed a new model to calculate the visual fatigue due to 3DTV utilizing power spectral entropy and gravity frequency and achieved higher stability and accuracy rates. They observed watching 3DTV for longer durations significantly leads to physiological and psychophysiological effects, which can also affect the central nervous system. J. Antonio Aznar-Casanova, et al., [18] examined visual fatigue induced due to watching 3D movies and two models were proposed (i) based on visual direction includes oculomotor imbalance and (ii) viewing distance includes vergence distance and focal distance to predict visual fatigue. Fifteen subjects of age 19-28 years old were examined, and every subject underwent a medical check-up of eyes to know whether they have any vision issues. The subjects classified as three groups of wearing a base-out prism, wearing lens and normal vision. The results supported a mixed model based on both viewing distance and visual direction for better accuracy and efficiency in the prediction of visual fatigue due to 3D movies. Jinwook Choi, et al., [19] proposed a smart camera for shooting a stereo video by considering content-based factors and camera-based factors in order to reduce fatigue levels of eyes. Content-based factors include depth gradient, brightness difference, temporal mean, temporal and spatial complexity, whereas camera-based factors include centre position, rotation angle, focal length, baseline distance. They performed disparity estimation and geometrical distortion analysis to reduce geometrical distortion between the left and right eye, which causes visual fatigue. They also performed a subjective test to validate their objective data and obtained 82% correlation between both the data.

3.2. Measures available to identify Visual Fatigue levels

3.2.1. Eye Tracker. An eye tracker is a technology identifies the state of being of eyes. It utilizes the high-resolution cameras and infra-red technology to track the gaze direction and pupil centre. It measures the eye activity, eye size, eye movement, and position. Toshiyuki Hosokawa, et al., [20] developed a portable fatigue meter which works on measuring the critical flicker fusion frequency. This study was one of the early studies noticed in the year 1997 to measure fatigue caused by the digital medium with an inexpensive system. This meter even lightweight, small and portable which can be carried in everyone’s pocket. They experimented on 11 male subjects of different age groups with different illuminations and different distance between computer and eyes and observed the variation in pupil diameters and point of convergence. They observed flicker frequency does not differ much, however, there were significant changes in point of convergence in less illumination environments; also, when illumination intensity increases significantly there was a decrease in pupil diameter. Xiaowei Shi, et al., [21] designed a system smart eye pro5.6 to measure visual fatigue induced due to the video display terminal (VDT) work. The sensors are incorporated on the measuring equipment to record the change in pupil diameter, blinking frequency, eyelid opening or closing and its time, eye movement. A total of 25 subjects of 24-26 years old are experimented and also gone through subjective assessment for more validate results. The results revealed that VDT workers experienced higher fatigue levels; there exists a positive correlation between eyelid opening and pupil diameter after excessive VDT utilization. The pupil diameter and blink frequency changes with an increase in utilization of VDT. Sunu Wibirama, et al., [22] examined the effect of screen size utilizing eye-tracking data. They conducted a subjective assessment to identify the state of the subject while utilizing the smartphone. They experimented on 16 subjects of 19-40 years old and asked to play
‘Fruit Ninja’ game in both Apple iPhone 5 of 4-inch screen size and Google Nexus 7 of 7-inch screen size smartphones. They observed portability in space and time, type of application and screen size were correlated with addiction factors of the smartphone. They concluded that when compared with small screen size smartphone with big screen size have more significant experience of immersion. Bon-Yeop Koo, et al., [23] determined the change in pupil diameter and fatigue levels while watching videos under different environments like viewing conditions such as different display screens and different illumination intensity. One hundred eight subjects have experimented, and questionnaire assessment was conducted before and after the experimentation. The subjects were asked to watch two 30-minute videos one with higher illumination intensity the other with the moderate illumination levels in two LED TV of 55 inches one with radius of curvature and flat one at a distance of 3 meters from the screen. The results revealed that pupil diameter had negative correlation with the viewing time, whereas fatigue levels had positive correlation. Yan Wang, et al., [24] proposed two models for eye-fatigue assessment utilizing eye blink rate and eye movement. An experiment was conducted for 25 subjects between 20-35 years age for video watching on each subject. They observed in a span of about 54 minutes the eyes of each subject turned from entirely relaxed state to fatigue state. Chin-Jung Chao, et al., [25] studied on display technologies, duration of utilization and task complexity of smartphone and its effect on the human eye. They experimented on 36 subjects and asked them to assemble the hard disk and the motor by looking at the virtue parts from the 3D display, and determined blink rate utilizing critical fusion frequency tester. They also conducted a subjective assessment to know eye symptoms and measure visual fatigue. The results revealed that task complexity and duration of usage significantly affect the visual fatigue levels. Sungryul Park, et al., [26] analysed on how task duration and display curvature effect the performance of subjects in terms of proofreading, visual comfort levels. They experimented on ten subjects with a 27-inch curved display of different radii 4000R, 2000R, 1140R and 600R with a distance of 600mm between the screen and the eye for 1 hour. They observed the higher proof-reading speed with 600R screen when compared with other screens and subjects experience more fatigue levels and mental workload after the 15 minutes of proof-reading. Hanui Yu, et al., [27] examined how the luminance ratio or illumination intensity of tablet screen affects the fatigue for prolonged duration utilization. They experimented with four different luminance ratios of ambient to tablet surface luminance at 45 and 15 cd/m² of 1:9, 1:6, 1:3 and 1:1. They observed subjects experience more difficulty for text reading in luminance ratio of 1:6 and 1:9. They observed that there exist a significant difference in fatigue levels of the eye while utilizing 1:1 and 1:9 luminous ratios.

3.2.2. Biomedical Instrumentation. The Electroencephalogram (EEG) and Electrooculogram (EOG) are the most reliable and expensive systems for measuring eye data. The EEG measures the electrical activity in the brain, which gives the output in terms of frequency. Based on the frequency levels, the data can be classified as either they are feeling dizziness or relaxed or stressed. Based on the frequency, the fatigue levels can be analysed. An EOG is obtained through the potential difference generated by eye movements. The voltage difference between the retina and the cornea is measured. EOG relies on three factors: the voltage difference, noise, and offset. EOG can measure the electrical activity in eye, which measures the saccade length, horizontal movement, vertical movement, blink rate, percentage closure of eyes, eye movement, fixation duration, and so on. Maria Haeez, et al., [28] studied the frequency attributes of EEG for addicted and non-addicted smartphone game player to identify the initial signs of addiction for games through psychophysiological signals. They designed a wearable EEG system to identify the addiction levels and also visual fatigue induced due to the addiction or excessive utilization of smartphone. The subjective assessment is conducted on all 25 subjects to identify the psychological state of each subject. Time-domain and frequency domain analysis was performed to identify the correlation of addiction. They observed a distinct variation in alpha and theta frequencies between addicts and non-addicts. Chao Zhang, et al., [29] proposed an algorithm to determine the heart rate and blink frequency simultaneously utilizing independent component analysis. They collect the cardiac signals and blink signals at the same time under different
operations or environments. Conducted experiment on 21 subjects and captured three videos of each subject in LG G3 and iPhone 6 to record the blink rate and PHILIPS DB12 - pulse oximeter was attached to finger of each subject simultaneously to measure cardiac activity. They concluded that the change in blink rate significantly alters the heart rate. Mohammed H. Alhaag, et al., [30] investigated the effects of watching 3D and 2D displays based on the viewing time and viewing distance. They considered two conditions either watching from 6H or 3H, where H is viewing display screen height. They utilized electromyogram (EMG) to determine the visual fatigue of eyes through muscle activity from orbicularis oculi (OO) which defined in terms of the percentage of maximum voluntary contraction (MVC). They experimented on 20 subjects from 25-30 years old and none of them with any kind of vision problems. All the subjects have gone through the subjective assessment to get the visual discomfort score. They obtained results as subjects experienced more discomfort while watching 3D screens from short viewing distance; also, 3D screens will cause more fatigue while watching for a longer duration. Vytautas Abromavicuis, et al., [31] identified the set of features for prediction of 3D images visual comfort level. They examined on 28 subjects with 120 3D images visual comfort level by EEG, pupillometric and gaze data. They analysed six different time frames to measure four features EE band activity, focus points disparity level, pupil size dynamics and number of focus points. They obtained results as subjects experienced more discomfort while watching 3D screens from short viewing distance; also, 3D screens will cause more fatigue while watching for a longer duration.

3.2.3. Camera. Computer vision technology is a field of multiple disciplines how computers can gain high-level understanding by training with specific data from digital images or videos. The objective is to automate a task that the human can perform. Computer vision technology is the process of analysing, processing, acquiring, understanding digital images, and executing high-dimensional information from the real world to regenerate symbolic or numerical data. Computer vision technology is now helping healthcare industries by accurately classify conditions and illness by reducing inaccurate diagnoses and saving patients. An-Chao Tsai, et al., [32] developed an eye fatigue measuring system based on the camera. They examine the fatigue levels based on the state of the eye like dark circles, blinking frequency. As dark circles indicate illness or less sleep which indicates long-term fatigue and reduction in blink rate indicates, eyes need eyes were tired and requires rest which indicates short-term fatigue. They utilized OpenCV to detect face and extract the facial features and more specifically, the eye region. They performed infraorbital region and eye region segmentation to identify the dark circles and blink rate. The results obtained are if the blink rate is less than the normal blink rate is considered as short-term fatigue. Xinyi Sun, et al., [33] proposed a robust system to locate and detect the position of eyes, and identify the fatigue levels. They utilized Gabor transformation based on adaptive threshold and gray-level integration projection which divides the image into two segments based on gray features (i) background and (ii) foreground. By applying filters and normalisation techniques, they locate the position of eyes. Based on PERCLOS, the fatigue level is determined, which includes degree and time of opening or closing of eyes. They obtained results as if PERCLOS is larger than 0.4 is considered as a subject is in fatigue state, if PERCLOS is between 0.1 and 0.4 is considered as moderate fatigue levels and if PERCLOS is less than 0.1 is considered as no fatigue. Rui Huang, et al., [34] designed a visual fatigue detection technique based on neural networks and developed a Fatigue detection neural network system. They calculated the fatigue levels of the eye based on blink frequency and PERCLOS. In this system, they capture the video of the eye and identified its fatigue levels. The blink frequency of the normal condition is about 15-30 blinks per minute if the number of blinks reduces to 8 per minute is considered as moderate fatigue and beyond if it reduces to 4 blinks per minute is considered as severe fatigue. Similarly, if PERCLOS is ~0.05 is normal fatigue level, if PERCLOS is ~0.24 considered moderate fatigue level, and if PERCLOS is ~0.914 is considered as high fatigue levels.

3.2.4. Subjective Assessment. In subjective assessment, they collect the questionnaire data of each subject either web-based or pen and paper-based to assess the state of each subject without any
physical examination. The subjective analysis completely based on their state of being, judgement, emotions, point of view, interpretations and personal opinions. The collected data can be filtered based on questions and answers, respondent status and time, once the survey is finished results can be exported for further use or analysis. Leon Straker, et al., [35] conducted a subjective assessment and performed statistical analysis to understand how smartphone technology influences the school children health in terms of visual disorders and musculoskeletal disorders. Hanui Yu, et al., [36] examined the correlation between readability and luminance of the tablet screen. They consider three conditions of luminous of minimal, optimal and ambient luminous, and conducted the subjective analysis. Siao Hui Toh, et al., [37] conducted subjective analysis among Singapore adolescents and correlate how smartphone device causes visual health and musculoskeletal disorders. Seong-Soo Cha, et al., [38] analysed the prevalence and factors for the smartphone addiction in middle school children through questionnaire data. Beatriz Antona, et al., [39] investigated the symptoms associated with the visual fatigue caused by smartphone due to improper lighting conditions while reading. Jihhyeon Yi, et al., [40] examined how display curvature affects the smartphone holding posture or usability through subjective assessment. Shih-Miao Huang [41] studied how font style and size affects the readability on smartphones for traditional Chinese characters. Siao Hui Toh, et al., [42] studied how smartphone utilization pattern and duration leads to visual and musculoskeletal symptoms and disorders.

4. Conclusion
Smartphones are the friendly gadgets with emerging technology in a current-generation which made everything accessible with a single touch. They occupied huge space in our daily life, which is capable of handling many operations. As every coin have two sides similarly, the cons of the smartphone are the excessive utilization leads to various eye-related and musculoskeletal disorders. Nevertheless, there are very few studies noticed to analyse or identify the level of severity due to excessive smartphone utilization. Also, the studies regarding health issues caused by smartphone are virtually zero in India, which is the second-highest smartphone utilizer among other nations. Further validation techniques are required to make data and results more reliable. The methods available to measure the fatigue levels are highly expensive; still further studies are needed to reduce the cost of the measurement and make it portable.

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