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Research Article

Evaluating the User Physical Stresses Associated with Watching 3D and 2D Displays over Extended Time Using Heart Rate Variability, Galvanic Skin Resistance, and Performance Measure

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This paper compares the effects of viewing videos with 2D and 3D displays with regard to the viewing distance ($3H$ vs. $6H$, where H is the height of the screen) and viewing time to determine the physical stresses in terms of heart rate variability, galvanic skin resistance (GSR), and performance of the viewer (percent of correct responses). Twenty healthy male university students with a mean age ± standard deviation of 27.7 ± 2.53 years participated in this study as volunteers. None had color blindness, and all had normal vision acuity. Display type by viewing distance interaction had a significant effect on most of the heart rate variability measures and associated with watching time for the GSR responses. The results concluded that viewing the 3D display from a short viewing distance produced significantly high physical stresses compared to viewing the 2D display from the same short viewing distance. However, the 3D display seemed to impart lower physical stress than the 2D display at long viewing distances. The findings of this study indicate that physical stresses appeared significant at close viewing distance after watching a 3D display for 50 min and increased with continued watching time. In addition, viewer performance was higher for the 3D compared to 2D display type.

1. Introduction

The use of stereoscopic 3D display has been associated with a myriad of visual fatigue symptoms such as nausea, fatigue, eyestrain, malaise, and headache [1]. These symptoms were observed to have a higher rate of incidence within existing populations. The American Optometric Association (1995) performed a survey that discussed the occurrence of these symptoms in at least a quarter of individuals who played 3D video games or watched 3D films [1, 2]. Such results were corroborated by informal online surveys conducted by http://HomeTheater.com that highlighted the presence of visual fatigue symptoms in 53% of individuals who extensively viewed 3D content [1, 3].

Additional independent research that revolved around the use of observational studies and public surveys reported that 25–50% of 3D viewers experienced eyestrain and other fatigue symptoms [2–5]. A current large-scale study with appropriate experimental controls discussed that the actual incidence rate of these symptoms was still relatively high even though it was less than previously believed [4, 6]. In particular, 3D viewing was seen to be a causal factor for eyestrain and headache occurrence in 14% of 3D viewers. Furthermore, the study noted that an additional 8% of the 3D viewers expressed discomfort that arose either as a result of the 3D glasses or due to the nocebo effect in the form of negative presumptions regarding 3D viewing [4, 6].

The visual fatigue linked with 3D displays has been affected by the viewing time and distance [7–9]. The guidelines for video displays [7] defined the watching distance as an essential environmental condition in which the discomfort due to negative and positive conflicts in the binocular disparity depends strongly on it [10]. In addition, the degree of visual fatigue might be increased due to the prolonged viewing of a 3D display [8, 11]. According to the American Optometric Association, using of visual systems for a long time causes inefficient visual processing functions and leads to visual fatigue [2].

Several studies have been conducted to evaluate visual fatigue by using subjective ratings and physiological evaluation methods. Kennedy et al. [12] developed a Simulator Sickness Questionnaire (SSQ), and Kuze and Ukai [13] established a questionnaire to evaluate subjectively the visual fatigue caused by watching movies, TV programs, and video games. Lambooij et al. [8] recommended that to evaluate stereoscopic visual fatigue subjectively, the questionnaire should include the items summarized in Sheedy et al.'s questionnaires [14]. In addition, numerous studies have been carried out to evaluate visual fatigue using electroencephalogram (EEG) features in 3D display environment [15–27]. Other objective methods include electrocardiography (ECG) and galvanic skin resistance (GSR) in a 3D display environment [28–41]. Wang et al. [42] used a questionnaire and optometric indicators comprising fusion range as well as accommodation convergence/accommodation (AC/A) ratio to investigate relationship between visual fatigue and viewers' phoria for viewing autostereoscopic 3D displays. Wang et al. [43] investigated the binocular fusion range for a polarized 3D display. Recently, Alhaag and Ramadan [44] used electromyography (EMG) responses to investigate the effects of the display type on visual fatigue.

The ECG is a graphic recording of electrical activity of the heart during the cardiac cycle. General characteristics of the ECG signal are heart rate variability, heart rate, and interbeat interval (RR). The emotional state of the individual affects the heart rate, or pulse per minute, which easily differentiates between different emotions of individuals. Heart rate variability is assumed as a measure of autonomic nervous system activity based on the assumption that visual fatigue is associated with the increase of autonomic nervous system. Park et al. [35] assessed the effects of viewing 3DTV in young and elderly subjects using ECG. Results of Park et al. [34] showed that the average RR was decreased significantly for watching 3D visuals as opposed to 2D visuals, and the variation in the low-frequency/high-frequency (LF/HF) rhythm ratio was increased significantly when watching 3D visuals. The 3D visuals generate higher fatigue and stress in the elderly than the young subjects. Park et al. [37] used heart rhythm and autonomic balance to evaluate 3D visual fatigue. They found that viewing 3D rather than 2D video destabilizes the heart rhythm and increases heart rate, as well as induces a shift in autonomic balance, mainly due to increased activation of sympathetic nerves. Moreover, the autonomic balance was significantly different between the 2D and 3D groups.

Chen et al. [40] used a spectral analysis of heart rate variability (HRV) and subjective physiological measures to identify if individuals would be subject to fatigue, weakness, and any other discomfort factors after viewing a 3D video. They found a decrease in parasympathetic nervous activities of the participants after viewing a 3D video, which indicated that viewing a 3D video would render people uncomfortable and tired. In addition, there were insignificant differences in the sympathetic and parasympathetic nerve activities prior and following viewing a 2D video. Thus, they suggested that HRV measure could be an objective indicator for visual fatigue during viewing of 3D videos.

An alternative method that measures a sympathetic nervous system function is galvanic skin resistance (GSR) [45]. The GSR is a variation in the electrical properties of the human skin caused by an interaction between the individual's psychological state and environmental actions [46]. When an individual is aroused or excited, the moisture levels in the skin change, causing changes in its electrical conductance. This phenomenon occurs because sweat glands are regulated by the sympathetic nervous system, and this variation in conductance can be an indirect measure of mental activity [46]. GSR is a nonintrusive quickly captured physiological signal mostly used for assessment of the actual state of the user, mainly for mental stress, arousal level, attention, emotional state, and anxiety [47–49]. As mental stress increases, variations in the electrical conductance of the skin are identified by GSR sensors. Kim et al. [33] recommended that GSR be utilized to evaluate visual fatigue in participants watching 3D and 2D displays.

Previous researchers that studied the physiological responses to watching display images compared measures recorded in pre- and postwatching periods to determine reliable measurement methods for visual fatigue. Hence, the physiological responses that occurred when the display was watched for an extended time were neglected. This study investigated the effects of the display type, viewing distance, and viewing time on the physical stress based on HRV and GSR. In addition, the performance of the viewer was measured by evaluating the number of correct answers to certain questions in a questionnaire related to the films that were watched.

2. Methods

2.1. Participants. The participants in the current study are the same as those used in the previous studies [27, 44]. Twenty healthy male university students with a mean ± SD age of 27.7 ± 2.53 years participated in this study as volunteers (more details on the participant's characteristics are available in Alhaag and Ramadan [44]). A written informed consent form approved by the Human Participants Review Board of the university was completed by each participant prior to participation in the experiment. All participants had normal vision acuity, and none had any medical history. All participants were instructed to have a full night of rest and avoid cigarettes and caffeine in the preceding 6 h.

2.2. Instruments. The instruments used in this study are the same as those used in the previous studies [27, 44], which included a commercial 50-in LG 3D Smart TV (50LF650T) with passive 3D glasses. In addition, an 8-channel Biomonitor ME6000 (Mega Electronics Ltd., Kuopio, Finland), with one channel for ECG recording; sensor-CASSY (Leybolo Didactic GMBH, Germany); skin resistance box (Leybolo Didactic GMBH, Germany); a Snellen chart; GPM Vernier calipers; and measuring tape were used. The ECG signals were recorded using Mega Win 3.0.1 (Mega Electronics Ltd., Kuopio, Finland) at a sampling rate of 1000 Hz, and a

CASSY Lab (Leybolo Didactic GMBH, Germany) was used to amplify and record the GSR sampling data at a sampling rate of 100 Hz. Additional materials used include 70% isopropyl alcohol swabs, cotton squares, bandages, and Ag/AgCl solid adhesive pregelled electrodes for ECG (Ambu A/S, Denmark). In addition, Kubios HRV software v2.2 (University of Western Finland, Finland) was employed to compute the HRV.

2.3. Experimental Setting. The experiment setup and specifications of the LG 3D smart TV adopted to conduct the current study are the same as those used in the previous studies (for more details, please see Ramadan et al. [27] and Alhaag and Ramadan [44]). Commercial movies in both 2D and 3D mode were displayed on a LG 3D Smart TV (50LF650T) using passive-row interlaced technology. The LG TV has the capability of changing from 2D to 3D mode and vice versa. The LG TV was positioned at a table height of 0.96 m with the center of the display height of 1.29 m from the lab floor. The viewing distances were 1.95 or 3.90 m ($3H$ or $6H$). The reason for selecting three ($3H$) or six ($6H$) times the display height was recommended by the International Telecommunication Union (ITU) standards [50]. The back distance from the screen to the wall was set at 0.12 m. Black sheets were pasted on the wall surrounding the TV to eliminate any disturbance to the participant's surrounding.

All experiments were conducted in the Human Factors Lab with an average dry-bulb temperature and relative humidity of 23.8°C and 30.6%, respectively. The experimental zone was ensured to have no vibrations or strong odors during the test. Lighting conditions were maintained constant for all sessions. The environmental luminance at the screen center was approximately 250 lux. The participants were asked to be seated in front of the display center and maintain their eyes' position constant across all sessions at viewing distances of 1.95 or 3.90 meters.

2.4. Experimental Design. Four independent variables were considered: two involved repeated measures and the remaining two were binary variables. Thus, the mixed design (i.e., $A \times B \times (C \times D \times S)$) was used to represent the experiment. The two independent binary variables were (A) the display type (2D vs. 3D) and (B) viewing distance ($3H$ vs. $6H$). The two independent variables based on repeated measures were (C) movies (Avengers, Jurassic World, San Andreas, and Godzilla) and (D) viewing time (pretest, T10, T20, T30, T40, T50, T60, and posttest). This experiment examined the influence of the viewing distance and display type in a repeated experiment based on the session time. Thus, it was a $2 \times 2 \times 4 \times 8$ design. Each of the (A) and (B) $= 2 \times 2 = 4$ display-distance conditions contained $S = 5$ participants, and each participant watched all four movies. All physiological measurements were measured continuously: pretest (3 min prior to executing the experiment), T10 (first 10 min period), T20 (second 10 min period), T30 (third 10 min period), T40 (fourth 10 min period), T50 (fifth 10 min period), T60 (sixth and last 10 min period), and posttest (3 min period after watching videos). In addition, pairwise comparisons were used to investigate the source of any significant effects regarding the time factor.

2.5. Task Performance. The performance of the viewer was measured by evaluating the number of correct answers to certain questions in a questionnaire related to the films that were watched. These questions were related to the actions in and views on what occurred in the movie and are represented in percent of correct responses.

2.6. Physiological Measures

2.6.1. Heart Rate Variability. HRV is assumed as a measure of autonomic nervous system activity based on the assumption that visual fatigue can increase autonomic nervous system activity. Therefore, it is likely possible to measure visual fatigue by measuring HRV. Chen et al. [40] showed that HRV could be an objective physiological indicator for visual fatigue during watching 3D movies. In this study, HRV is used as an indicator to measure physical stress, which was adopted from Markov et al. [51]. The time domain measures of HRV used in this study include the average of RR intervals (RR), the corresponding average heart rate (HR), the standard deviation of normal RR intervals (SDNN), the root mean square of successive differences in RR intervals (RMSSD), number of successive intervals differing more than 50 ms (NN50), and the percentage rate of times a successive RR interval was greater than the previous interval by >50 ms (pNN50). The SDNN reveals the overall HRV for both sympathetic and parasympathetic influences [51], while RMSSD can be used as a measure of short-term variability [52]. In addition, the pNN50 and RMSSD are indicators corresponding to parasympathetic neural regulation of the heart [51].

HRV frequency domain measures were further investigated, which were low frequency (LF = 0.04–0.15 Hz), very low frequency (VLF = 0–0.04 Hz), high frequency (HF = 0.15–0.4 Hz), and finally total power (TP = 0–0.4 Hz). The sum power was deemed to be an indicator for the comprehensive autonomic activity [51]. Also, it was found that the vagal nerve activity influenced the HF band's power spectrum, while the sympathetic nerve activity influenced the LF band's power spectrum [51]. In addition, the sympathetic-parasympathetic balance was deemed to be indicated by the absolute power ratio in the LF and HF bands (LF/HF) [52]. The components of the frequency domain were computed in terms of relative values (%) and absolute units (ms^2).

2.6.2. Galvanic Skin Resistance (GSR). GSR is a method of capturing the autonomic nerve response as a feature of the sweat gland function to measure the electrical resistance of the skin. Higher GSR levels recorded during stressful tasks indicate higher levels of stress [53, 54]. Kim et al. [33] recommended that GSR can be utilized to evaluate physical stresses in participants watching 3D and 2D displays.

In this work, the electrical conductance of the skin was measured by attaching Velcro strip electrodes to the tips of the participants' index and ring fingers. To reduce errors in the GSR measurement and compare within and between individuals during experiments, GSC was standardized as a percentage change from baseline (%ΔGSR) [55, 56]. This baseline value is defined as the difference between the maximum GSR value recorded during the most arousing period and the minimum GSR value recorded during the resting period in a room environment. All physiological data was measured and recorded continuously during the one-hour test with 10 min interval averages calculated, with the exception of the period prior to initiation of the experiment (pre-5 min period) and the last 3 min (post).

2.7. Statistical Analysis. A four-way mixed repeated ANOVA was implemented to examine the time, films, display type, and viewing distance effect on response variables (hear rate variability and GSR). In addition, univariate ANOVA was performed to study the effect of display type and viewing distance on ratings of correct answers. Finally, pairwise comparisons were used to investigate the source of any significant effects. Statistical analysis was achieved using SPSS Version 23. It is worth noting that ANOVA requires that certain assumptions be met, including homogeneity of variance in the data, normality, and continuous data (not dichotomous). In addition, not only the statistical significance is calculated but also the effect size based on the partial eta-squared value (η^2). Partial eta-squared indicates the variance percentage in the dependent variables attributable to particular independent variables [57].

2.8. Experimental Protocol. The experimental protocol of this study is the same protocol used in the previous studies [27, 44]. Participants were introduced and welcomed to the experimental room. Each participant was required to come to the lab four times on different days for approximately 2 h each time. This allowed the physical stress associated with the four watched films to be evaluated on separate days without interference from the other movies. The interval time between visits was at least 48 h. During the preexperiment session (first visit), each participant was briefed regarding the objective of the study and experimental procedure as well as the time required for each visit. Then, the participants were given the opportunity to ask any questions regarding the study. They were informed of their right to cease participation in the experiment at any time. Then, each participant was given a consent form to read and sign and a demographic questionnaire to complete. Visual acuity and color blindness tests were conducted.

On execution of the experimental sessions, the participants were prepared to place electrodes on their skin for ECG and GSR sensors. For a comparative evaluation of the visual fatigue, the twenty participants were randomly allocated to one of the following four conditions:

(i) Condition 1: view the four videos in 3D from a distance of 1.95 m (3D3*H*)

(ii) Condition 2: view the four videos in 3D from a distance of 3.90 m (3D6*H*)

(iii) Condition 3: view the four videos in 2D from a distance of 1.95 m (2D3*H*)

(iv) Condition 4: view the four videos in 2D from a distance of 3.90 m (2D6*H*)

The four films were watched randomly by each participant. None of the participants was allowed to participate under more than one condition to avoid bias and the learning effect. In other words, if a subject watched the same film under more than one condition, he may become drowsy or bored, which could affect the HRV and GSR (i.e., response variables). Participants who watched the 3D movies wore passive 3D glasses with lenses containing circular-polarizing filters.

The ECG and GSR signals were recorded for 3 min (pretest). The participant then watched the assigned movie from the designated distance in the assigned mode (2D or 3D) for 1 h while the ECG and GSR signals were recorded for 60 min (this was later divided into six 10 min sessions). After the participant finished watching the movie, the ECG and GSR signals were recorded continuously for another 3 min (posttest). Finally, the participant answered the movie perception questionnaire to evaluate participant comprehension. The right wrist, upper right forearm (distal to the elbow), and the upper left forearm (distal to the elbow) were selected for ECG electrode placements. The selected skin positions were cleaned using 70% isopropyl alcohol swabs. The Ag/AgCl pregelled electrodes were placed in prepared positions. The red ECG clip was attached to the electrode tab on the upper left forearm (distal to elbow). The yellow and black clips were attached to electrode tabs on the upper right forearm (distal to the elbow) and the right wrist, respectively. The three ECG leads were connected to 1-ch ECG preamplifier for ME 6000. The 1-ch ECG preamplifier was connected to ch-3 and ch-4 of the ME 6000. The participant was asked to be seated in a relaxed position on a chair, resting his forearm on the arms of the chair or his legs, as shown in Figure 1.

3. Results

3.1. Performance Measure. The performance of the viewer was measured at the end of each video in terms of correct answers to the questions presented in a questionnaire related to the film. Results indicated that display type had a significant effect on the performance of the viewer, $F(1, 64) = 24.82$, $p < 0.0001$, $\eta^2 = 0.213$. For the 3D display, the participant's performance (88.3% (15.7%)) was significantly higher than the performance with the 2D display (70% (20%)) regardless of the distance, as shown in Figure 2.

3.2. Heart Rate Variability Analysis. It was seen that there was a general pattern noted with regard to all the cardiovascular measures, through which the difference between the viewing distances and the displays was observed. Although there were individual differences between the study participants, it was noted that the results proved to be valid for every participant. Additionally, the results obtained for a few of the cardiovascular measures were seen to depend on

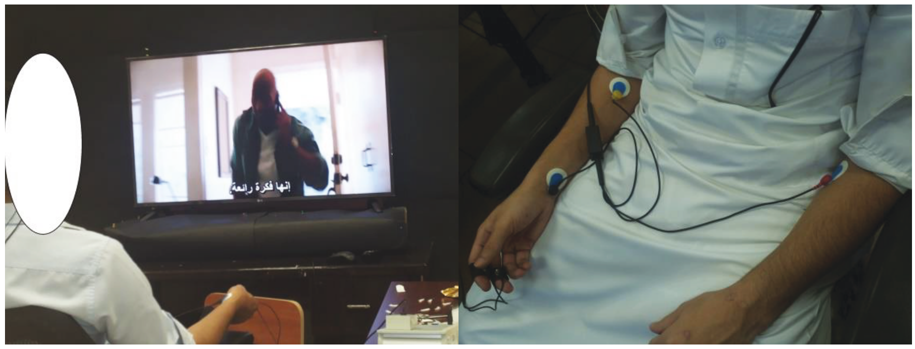

Figure 1: Experimental setup and electrode placement.

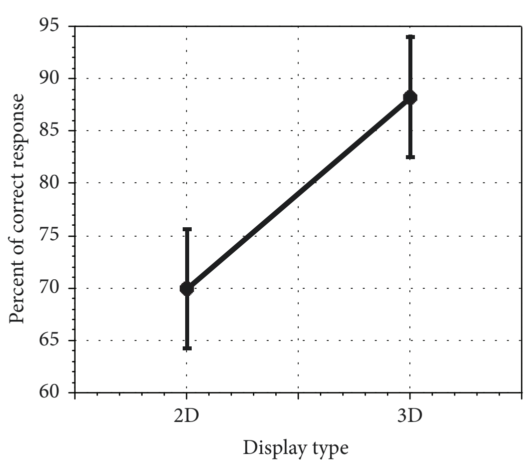

Figure 2: Effect of display type on performance of the viewers.

the type of display and the distance. It was seen that the other cardiovascular measures depended strongly on interactions. These results have been illustrated in Table 1.

3.2.1. Time Domain Measures. A time domain comparison of the different cardiovascular measures was made between the viewing distance and the type of display. This comparison was inclusive of STDHR, RR, NN50, HR, RMSSD, pNN50, and SDRR parameters. Significant differences were noted between the 3D and 2D type of display within the HR measure. The HR was significantly higher (approximately 7 bpm) for the 3D than the 2D display experiments. This held true for films in excess of one hour. It can be concluded that watching films with 3D display, under highly monotonous conditions, is more demanding than the 2D display. In addition, significant differences between viewing displays at near and far distances can be detected only in the HR itself ($p < 0.0001$). The HR was significantly higher (approximately 3 bpm) while watching films from a great distance ($6H$) than from near distance ($3H$).

Significant interactions between display type and viewing distance can be detected in the rest time domain measures. For 3D display, no significant changes in the STDHR, RR, SDRR, RMSSD, NN50, and pNN50 were observed regardless of distance. For 2D display, however, significant decreases in the STDHR, RR, SDRR, RMSSD, NN50, and pNN50 values approximately 21%, 6.6%, 37.7%, 50%, 238%, and 240%, respectively, were observed when the participates switch watching films from near ($3H$) to far distance ($6H$), $p < 0.001$ for all measures.

3.2.2. Frequency Domain Measures. As shown in Table 1, a significant interaction effect between display type and viewing distance was found for the HF power band, $p < 0.0001$. In addition, there was a significant display type effect on the HRV parameters (VLF and LF/HF absolute power). Neither the display type nor the viewing distance factor had an effect on the LF power. The measured VLF power showed a significant decrement when participants watched a 3D display compared to a 2D display, $p < 0.047$. The circadian effect was noted to be equal for both far and near viewing distances, which was revealed by the VLF parameter. Thus, there existed no variation in the band power of the VLF. Trutschel et al. [58] showed that VLF power was not appropriate with regard to workload discrimination; it nevertheless demonstrated the impact of the circadian effect on the performance and fatigue data. The LF/HF ratio band specifically demonstrated a significant decrease with regard to those participants that viewed the 3D display as compared to the participants that viewed the 2D display ($p < 0.043$). The HF parameter illustrated the effect of respiration on the heart that played a vital function in the strenuous near viewing of the 3D display.

3.3. Galvanic Skin Resistance. The results show that both the main variables had significant effect on GSR, display type ($F(1{,}128) = 66.35$, $p < 0.0001$, $\eta^2 = 0.341$), and viewing distance ($F(1{,}128) = 37.13$, $p < 0.0001$, $\eta^2 = 0.225$). In addition, the display type by session interaction and viewing distance by session interaction had significant effects on GSR, ($F(7{,}128) = 14.88$, $p < 0.0001$, $\eta^2 = 0.449$), ($F(7{,}128) = 21.71$, $p < 0.0001$, $\eta^2 = 0.543$), respectively. Finally, the display type by viewing distance by session interaction had a significant effect on GSR, ($F(7{,}128) = 53.99$, $p < 0.0001$, $\eta^2 = 0.747$).

The simple effect technique [59] was used to analyze the three-way interaction. As shown in Figure 3(a), it can be concluded that both display types (2D and 3D) follow the same trends with time. However, after 50 minutes of watching, there is a significant increase in the %ΔGSR for participants watching the 3D display compared to those

Table 1: Means (standard deviations) of heart rate variability measures in the study.

Parameters	Study variables				p (η^2)		
Display type	2D display		3D display				
Viewing distance	3*H*	6*H*	3*H*	6*H*	Display type (η^2)	Distance (η^2)	Interaction (η^2)
HR (bpm)	74.110 (0.523)	76.132 (0.385)	81.156 (0.326)	79.134 (0.372)	0.0001 (0.487)[a]	0.0001 (0.240)[b]	0.062 (0.027)
STDHR (bpm)	5.67 (0.194)	7.8 (0.14)	4.64 (0.15)	4.89 (0.16)	0.075 (0.025)[a]	0.002 (0.071)[b]	0.001 (0.077)[c]
RR (ms)	850.5 (7.8)	797.3 (6.5)	754.8 (4.9)	738.7 (4.2)	0.0001 (0.541)[a]	0.0001 (0.299)[b]	0.007 (0.055)[c]
SDRR (ms)	62.1 (2.1)	45.6 (1.4)	41.7 (1.1)	41.9 (0.9)	0.0001 (0.343)[a]	0.0001 (0.293)[b]	0.0001 (0.167)[c]
RMSSD (ms)	45.2 (2.6)	30.0 (1.4)	27.6 (0.8)	29.0 (1.3)	0.0001(0.188)[a]	0.0001 (0.137)[b]	0.0001 (0.172)[c]
NN50	88.0 (6.5)	26.5 (2.6)	34.5 (3.0)	24.1 (2.4)	0.0001 (0.256)[a]	0.0001 (0.399)[b]	0.0001 (0.280)[c]
pNN50 (%)	17.347 (1.2)	5.3 (0.6)	5.9 (0.5)	4.1 (0.4)	0.0001 (0.343)[a]	0.0001 (0.454)[b]	0.0001 (0.336)[c]
HF (ms^2)	884.3 (144.8)	316.3 (28.3)	284.0 (17.6)	371.7 (48.3)	0.001 (0.087)[a]	0.002 (0.070)[b]	0.0001 (0.128)[c]
LF (ms^2)	1805.5 (63.2)	590.2 (34.0)	674.3 (53.5)	513.6 (30.0)	0.171 (0.015)	0.140 (0.017)	0.205 (0.013)
VLF (ms^2)	1640.5 (554.1)		889.8 (40.4)		0.047 (0.031)[a]	0.174 (0.014)	0.118 (0.019)
LF/HF	3.203 (0.182)		2.817 (0.122)		0.043 (0.031)[a]	0.682 (0.001)	0.892 (0.000)

HR: mean heart rate; STDHR: standard deviation of instantaneous heart rate; RR: mean of RR intervals; SDRR: standard deviation of RR intervals; RMSSD: square root of the mean squared differences between successive RR intervals; NN50: number of successive RR interval pairs that differ more than 50 ms; pNN50: NN50 divided by the total number of RR intervals; HF: absolute power of the high-frequency band, 0.15–0.40 Hz; LF: absolute power of the low-frequency band, 0.04–0.15 Hz; VLF: absolute power of the very low-frequency band, 0–0.04 Hz; LF/HF: ratio of LF to HF band powers. [a]Significant difference between the two display types; [b]significant differences between the two viewing distances; [c]significant difference of the interaction; η^2 effect size.

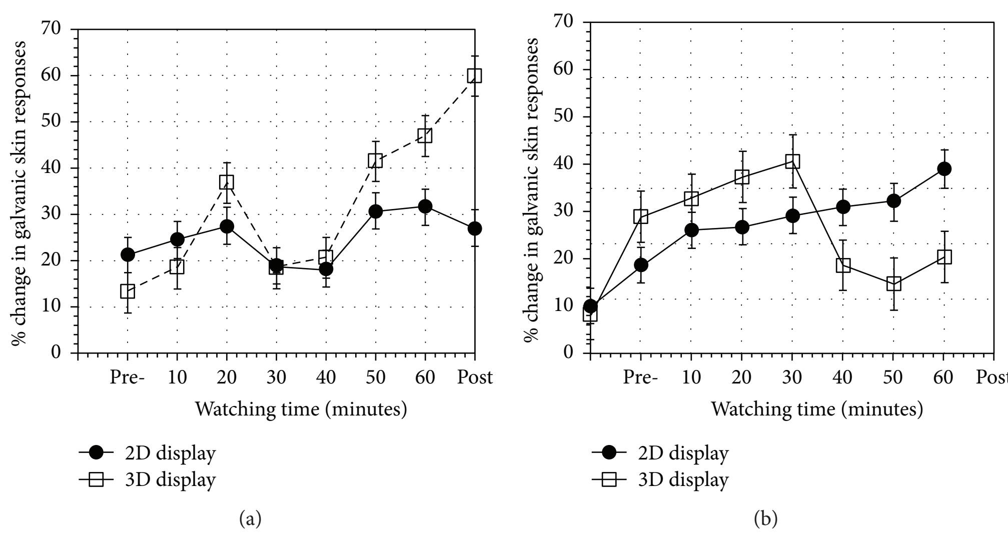

Figure 3: Display type by viewing distance by watching time interaction on percentage changes in the GSR. (a) Short viewing distance (3*H*: 1.95 m); (b) long viewing distance (6*H*: 3.9 m).

watching the 2D display. In addition, as shown Figure 3(b), for the 3D display, the %ΔGSR increased steeply during the first 40 min and then decreased significantly until the end of experimental time. However, in the case of the 2D display, the %ΔGSR was increasing slightly steady to the end of the experiment. Based on a pairwise comparison, there were significant differences between the two display types in different sessions. Participants watching the 3D display exhibited less %ΔGSR after 50 min compared to those watching the 2D display.

4. Discussion

In this study, performance (percent of correct responses), HRV, and GSR were used to evaluate the effect of watching films on 2D and 3D displays from different viewing distances (3*H* vs. 6*H*) over a viewing time of 60 min on the physical stress of the individual. Participants who watched videos on the 3D display exhibited a higher performance (percent of correct responses) than those who watched on the 2D display, regardless of the viewing distance (short or long). Based on this study, the heart rate (beats per minute) of the participants was investigated during the watching of different films on 2D and 3D displays over sixty minutes from a long and a short viewing distance. Hence, it has been found that the heart rate increased significantly when the participant was watching the 3D display. The heart rate increased slightly from the preview over the first twenty minutes (session 3) and remained stable to fifty minutes (session 5); then, it increased slightly again from session five until the end of the film. Furthermore, it has been found that watching the 3D display from a short viewing distance contributes to increasing the heart rate to 81.16 bpm, whereas it contributes to a decrease in heart rate to 74.110 bpm for the 2D display. For the long viewing distance ($6H$), there is no statistically significant effect of display type on the heart rate; however, the 3D display contributes to increasing the heart rate. Moreover, when the viewing distance is changed from $3H$ to $6H$, the heart rate increased for the 2D display type, whereas it decreased for the 3D display type.

The reasons for the increasing heart rate associated with watching a 3D display from a short distance may be due to the excitement and appeal of as well as immersion in the 3D display. This result agrees with that of Åkerstedt et al. [60] wherein they state that visual fatigue could result from immersion in work. Furthermore, this result is consistent with Park et al. [37] who showed that viewing 3D rather than 2D video destabilizes the heart rhythm and increases the heart rate. They further showed that the visual fatigue caused by viewing 3D video is related to these changes in the heart rhythm. This is because the vagal nerve endings in the heart can transfer signal changes in the heart rhythm and blood pressure to the brain. This situation leads to emotional stress and reduced cognitive and reactive functions [37, 61–64]. The reasons for the increasing heart rate while watching a 2D display from a long distance may be due to alertness and difficulty in focusing, which in turn leads to decreased cognitive capacity of participants for processing visual information regarding increased cognitive load [37, 65].

The RR was significantly lower for watching 3D as opposed to 2D visuals, and the variation in LF/HF ratio decreased significantly for 3D visuals. Park et al. [37] found that viewing 3D rather than 2D video destabilizes the heart rhythm and increases the heart rate, and viewing 3D rather than 2D video induced a shift in autonomic balance, mainly due to increased activation of the sympathetic nerves. In addition, the autonomic balance was found to be significantly different between the 2D and 3D groups. Sakamoto et al. [39] studied the effect of watching a 3DTV video on physiological and subjective measurements of the TV viewer's emotional state. They showed that heart rate and HRV (LF/HF) increased in almost all participants who gave high scores for "comfortable," "like," and "relaxed"; however, this was not the case for "sensation of involvement." The reason for the increasing HR and LF/HF with a high score is because some participants may have fallen asleep. Park et al. [34] studied the effect of 3D visual fatigue on the autonomic nervous system using cardiac responses, namely, RMS-SD (root mean squared successive difference), SDNN (standard deviation of RR intervals), and HF/LF ratios extracted from the measured PPG (photoplethysmogram) after viewing the 3D display. The results indicated that after the subjects viewed the 3D display, responses in the sympathetic nervous system and parasympathetic nervous system were activated and deactivated, respectively, compared to those before viewing the 3D. They found that the HF/LF ratio, Ln (LF), and Ln (HF) after 3D viewing reduced significantly relative to those before the viewing. Park et al. [34] revealed that visual fatigue caused by watching 3D adversely affected the autonomic nervous system and accordingly increased activation of the sympathetic nerve resulting in decreased HRV; the results of this study are in agreement.

In terms of physical stress, the percentage change in the GSR increased significantly while watching videos on 3D displays and with increasing watching time when compared with the 2D displays when participants watched from a short viewing distance. This result is consistent with the study by Kim et al. [33], in which the authors showed that the patterns of GSR increased significantly while watching 3D compared to 2D videos. This result is concluded because the activation of the sympathetic nervous system was higher in the 3D than in the 2D case, which has a negative effect on cognitive function. However, the percentage change in GSR increased insignificantly while watching videos on 3D displays until a watching time of 40 min from a far viewing distance, when compared to watching the same videos on 2D displays. However, after 50 min of watching videos, the percentage change in GSR decreased significantly for the 3D display and with increasing watching time to the end of session when compared to watching the same videos on 2D displays.

The result of the current study is in agreement with the results of the previous studies reported by Ramadan et al. [27] and Alhaag and Ramadan [44]. In the previous studies [27, 44] and the present study, different measures were used to quantify different types of symptoms. Ramadan et al. [27] used electroencephalogram (EEG) relative beta power and alpha/beta power of EEG to assess human visual system and brain activity. While Alhaag and Ramadan [44] quantified visual fatigue associated with the display type, viewing time and distances using electromyography (EMG) in terms of the percentage of maximum voluntary contraction (%MVC) of the orbicularis oculi (OO) muscle activity and subjective visual discomfort score. Ramadan et al. [27] found that the decrease in relative beta power of the EEG and the increase in the alpha/beta ratio from the start until the end of the viewing session were significantly higher when watching the 3D display. They showed that viewing 3DTV has different influences on the brain as compared against watching 2DTV. Ramadan et al. [27] found that watching 2DTV from short viewing distances and watching 3DTV from longer viewing distances relaxed the brain, while watching 3D display from short viewing distances requires participants to utilize more cognitive loads for processing three-dimensional information leading to cause visual fatigue due to decrease in the cognitive capacity of the participants for processing visual information. Moreover, watching 2D displays from long distances increases the cognitive load because of low level of attentional focusing ability and regulates occipital lobe required by the brain to process the information.

In the other articles, Alhaag and Ramadan [44] showed that watching the 3D display from a short viewing distance produced significantly high muscle contraction compared to watching the 2D display from a short viewing distance. When the viewing distance was increased from 1.95 m to 3.90 m, the muscle fatigue of the orbicularis oculi (OO) muscle decreased in the 3D display case whereas it increased insignificantly in the 2D display case. In addition, there was approximately the same level of muscle fatigue when watching videos in 2D or 3D from a long viewing distance (3.90 m). The onset of visual fatigue appears in 30 minutes and 50 minutes of watching 3D display at short and long distances, respectively. They concluded that the OO muscle activity of the participants while watching the 3D display from a long distance ($6H$) did not change over the viewing time, which means that viewing the 3D display from a long viewing distance is safer than viewing a 2D display.

The present study focused on quantified physical stress associated with watching display type from different distances over an extended period based on HRV, GSR, and performance (percent of correct responses). It was found that watching 3D display from a short viewing distance contributes to increase physical stress, as compared to 2D display. For the long viewing distance ($6H$), there is no physical stress associated with display type (2D and 3D displays have same effect at long distance). Moreover, when the viewing distance is changed from $3H$ to $6H$, the physical stress increased for the 2D display type, whereas it decreased for the 3D display type. The results suggested that to reduce the physical stress, the 2D display must be watched from a short viewing distance or the 3D display from a long distance. It also noted that the onset of physical stress based on HRV and GSR measures appeared after 50 minutes of watching. From the comparison between the previous studies [27, 44] and the current study, it has been noted that watching a 2D display from a short distance and watching a 3D display from a long distance have less effect on physical stress, brain activity, visual fatigue, and eye muscle fatigue (orbicularis oculi (OO) muscle) which is turned to the safe condition for watching 2D and 3D displays. Despite the authors' repeated attempts to recruit females by distributing flyers and pamphlets in the girls' section, only male participants were recruited for the study.

5. Conclusion

The data analysis strongly suggests that HR variability and GSR are the best measures to distinguish between watching films on 2D and 3D displays from near and far viewing distances. Consistent variation in HR demonstrated that continual film viewing using 3D display is relatively more strenuous than watching films using 2D displays. Conversely, it was seen that HRV is relatively superior in measuring the physical stress condition.

Conflicts of Interest

The authors declare no conflict of interest.

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