Doctoral Thesis

Curved Displays, Empirical Horopters, and Ergonomic Design Guidelines

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Graduate School of UNIST

2018

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A dissertation
submitted to the Graduate School of UNIST
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Sungryul Park

12. 26. 2017

Approved by

Advisor

Prof. Gyouhyung Kyung

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This certifies that the thesis/dissertation of Sungryul Park is approved.

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ABSTRACT

Visual display products should be comprehensively evaluated from the perspectives of productivity, safety, and well-being. Curved display products are known to provide advantages. Although previous studies found that curved displays increase visual task performance, reduce visual fatigue, and improve the watching experience, these studies did not comprehensively examine the effects of display curvature. Moreover, they used low-fidelity curved screens that may not effectively reflect actual curved displays. The purpose of this thesis was to develop ergonomic design guidelines for determining appropriate display curvatures, considering the productivity, safety, and well-being of visual display terminal (VDT) users. Two studies on monitors and one study on TVs were conducted for this goal. In Study 1, the effects of the display curvature, display zone, and task duration on visual task performance and visual fatigue during a visual search task on a 50-inch multi-monitor were investigated. In Study 2, the effects of the display curvature and task duration on visual task performance, visual fatigue, and user satisfaction during a proofreading task on a 27-inch monitor were investigated, and the associations between ergonomic evaluation elements were then examined. Prediction models of visual fatigue and user satisfaction were subsequently developed. In Study 3, the effects of the display curvature, viewing distance, and lateral viewing position on presence, visual comfort, and user satisfaction during a TV watching task on a 55-inch TV were examined, and the importance of six viewing experience elements affecting user satisfaction was revealed. Finally, ergonomic design guidelines for curved displays were suggested. Based on the results of studies 1 and 2, an appropriate rest-break time was recommended, taking into account visual task performance and visual fatigue.

Study 1 examined the effects of the display curvature (400 R, 600 R, 1200 R, and flat), display zone (five zones), and task duration (15 and 30 min) on legibility and visual fatigue. A total of 27 participants completed two sets of 15-minute visual search tasks with each curvature setting. The 600 R and 1200 R settings yielded better results compared to the flat setup regarding legibility and perceived visual fatigue. Relative to the corresponding center zone, the outermost zones of the 1200 R and flat settings showed a decrease of 8%–37% in legibility, whereas those

of the flat environment showed an increase of 26%–45% in perceived visual fatigue. Across curvatures, legibility decreased by 2%–8%, whereas perceived visual fatigue increased by 22% during the second task set. The two task sets showed an increase of 102% in the eye complaint score and a decrease of 0.3 Hz in the critical fusion frequency, both of which indicated a rise in visual fatigue. To sum up, a curvature of around 600 R, central display zones, and frequent breaks were recommended to improve legibility and reduce visual fatigue.

Study 2 examined the effects of the display curvature and task duration on proofreading performance, visual discomfort, visual fatigue, mental workload, and user satisfaction. Fifty individuals completed four 15-min proofreading tasks at a particular curvature setting. Five display curvatures (600 R, 1140 R, 2000 R, 4000 R and flat) and five task durations (0, 15, 30, 45, and 60 min) were incorporated. The mean proofreading speed at its highest when the display curvature radius was equal to the viewing distance (600 R). Across curvatures, speed-accuracy tradeoffs occurred with proofreading, as indicated by an increase of 15.5% in its mean speed and a decrease of 22.3% in its mean accuracy over one hour. Meanwhile, the mean perceived visual discomfort, subjective visual fatigue, and mental workload increased, by 54%, 74%, and 24% respectively, during the first 15-min of proofreading. A decrease of 0.4 Hz in the mean critical fusion frequency during the first 15 min and a reduction in the mean blink frequency also indicated increases in visual fatigue and mental workload. The mean user satisfaction decreased by 11% until 45 min. A segmented regression model, in which perceived visual discomfort was used as a predictor, attributed 51% of the variability to visual fatigue. To sum up, a curvature of 600 R was recommended for speedy proofreading. Moreover, the breakpoint was observed be flexible, depending on VDT task types. These findings can contribute to determining ergonomic display curvatures and scheduling interim breaks for speedy but less visually fatiguing proofreading.

Study 3 examined the effects of the display curvature, viewing distance, and lateral viewing position on the TV watching experience. The watching experience was assessed regarding the spatial presence, engagement, ecological validity, negative effects, visual comfort, image quality, and display satisfaction. Four display curvatures (2.3 m, 4 m, 6 m, and flat), two viewing distances (2.3 m and 4 m), and five lateral viewing positions (0 cm, 35 cm, 70 cm, 105 cm, and 140 cm) were evaluated. Seven pairs of individuals per curvature watched ten 5 min videos together, each time at a different viewing distance and lateral viewing position. Spatial presence and engagement increased when the display curvature approached the given viewing distance. Regardless of display curvature and viewing distance and TV watching experience factors, except negative effects, were degraded at more lateral viewing positions. Engagement could effectively explain the display satisfaction. These findings can contribute to enhancing TV watching experiences by recommending specific levels of display curvatures, viewing distances, and lateral viewing positions, as well as providing information on the relative importance of each watching experience element.

This work suggested ergonomic design guidelines for curved displays. In Study 1, a curvature of approximately 600 R, central display zone, and frequent breaks were proposed to improve legibility and reduce visual fatigue during visual search tasks at the viewing distance of 500 mm. In Study 2, a curvature radius of 600 R and a minimum 15-minute break interval were proposed for a speedy proofreading task, at the viewing distance of 600 mm. In Study 3, a display radius of curvature similar to the viewing distance was recommended to improve the viewing experience. These results support that a curved display is ergonomically more beneficial when the display curvature approaches the empirical horopter. A relatively short 15-minute rest-time interval was suggested, considering the decrease of task accuracy and the increase of visual fatigue in studies 1 and 2. Two regression models were selected in Study 2 regarding predictive accuracy. They accounted for 70.4% of subjective visual fatigue variability and 60.2% of user satisfaction variability. Although this work was performed using relatively higher-fidelity mock-ups than previous studies, it is necessary to verify the findings with actual curved display products in the future. Furthermore, various tasks (e.g., word processing, graphics design, and gaming) and personal characteristics (e.g., presbyopia, gender, visual acuity, and product experience) should be considered to generalize the results of this thesis. These results can contribute to determining the ergonomic display curvature in consideration of productivity, safety, and well-being, and prioritizing elements of the visual fatigue and user satisfaction resulting from VDT work.

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Chapter 1. Introduction

1.1. Background

Since the introduction of curved display products (e.g., monitors, TVs, smartphones, and smart watches) in the market, there has been a variety of comparative studies between curved and flat displays. Curved displays are expected to provide benefits such as the improvement of visual task performance, the reduction of visual fatigue, the expansion of design freedom, immersive experience, grip comfort, screen privacy, and glare reduction (Raymond, 2013). Such benefits should be considered during the process of product design and development, while further efforts should be made to define the additional usefulness of curved displays to enhance their competitiveness. Also, it is necessary to examine whether existing visual ergonomic standards (e.g., AS3590.1, AS3590.2, ISO9241-303, ANSI/HFES 100, EU90/270/EEC) initially developed for flat and convex displays, such as cathode-ray tube (CRT), are still applicable on curved (concave) displays.

The International Ergonomics Association recommends that new display products should be comprehensively evaluated regarding three aspects; productivity, safety, and well-being. Productivity on visual displays could be mainly evaluated through visual task performance (Kong et al., 2011; Lin et al., 2013; Lin et al., 2008; Lin et al., 2009; Oetjen and Ziefle, 2009; Piepenbrock et al., 2013). Improved productivity on curved displays is expected as curved displays have been known to provide higher legibility compared flat displays. Safety on visual displays can be assessed through visual fatigue. Although prolonged VDT tasks often cause visual fatigue, the positive aspects of curved displays, such as uniform viewing angle and distance, the improvement of image distortion, and a low glare, are expected to reduce visual fatigue. The well-being relating to visual displays can be appraised through users' watching experience. A higher level of presence is expected as curved displays are likely to provide a physically immersive watching environment (Lombard et al., 2000).

It is necessary to develop more practical guidelines for the actual product development, referring to the contributions and limitations of previous studies. Recently, several studies have been conducted to identify the effects of curved displays compared to flat displays in various aspects. Three limitations were found from the previous literature on curved displays (figure 1.1). Firstly, static visual stimuli, such as images printed on paper, were used in experiments. Further study is needed to include dynamic visual stimuli to reflect the actual use of visual display products. Secondly, simple and segmented curvatures were applied for experiments such as comparing curved and flat displays and applying manually adjusted display curvature levels. Thirdly, several studies assessed a limited amount of evaluation factors. However, new display products need to be comprehensively evaluated regarding productivity, safety, and well-being, and most of the previous studies considered only one or two evaluation factors per study.

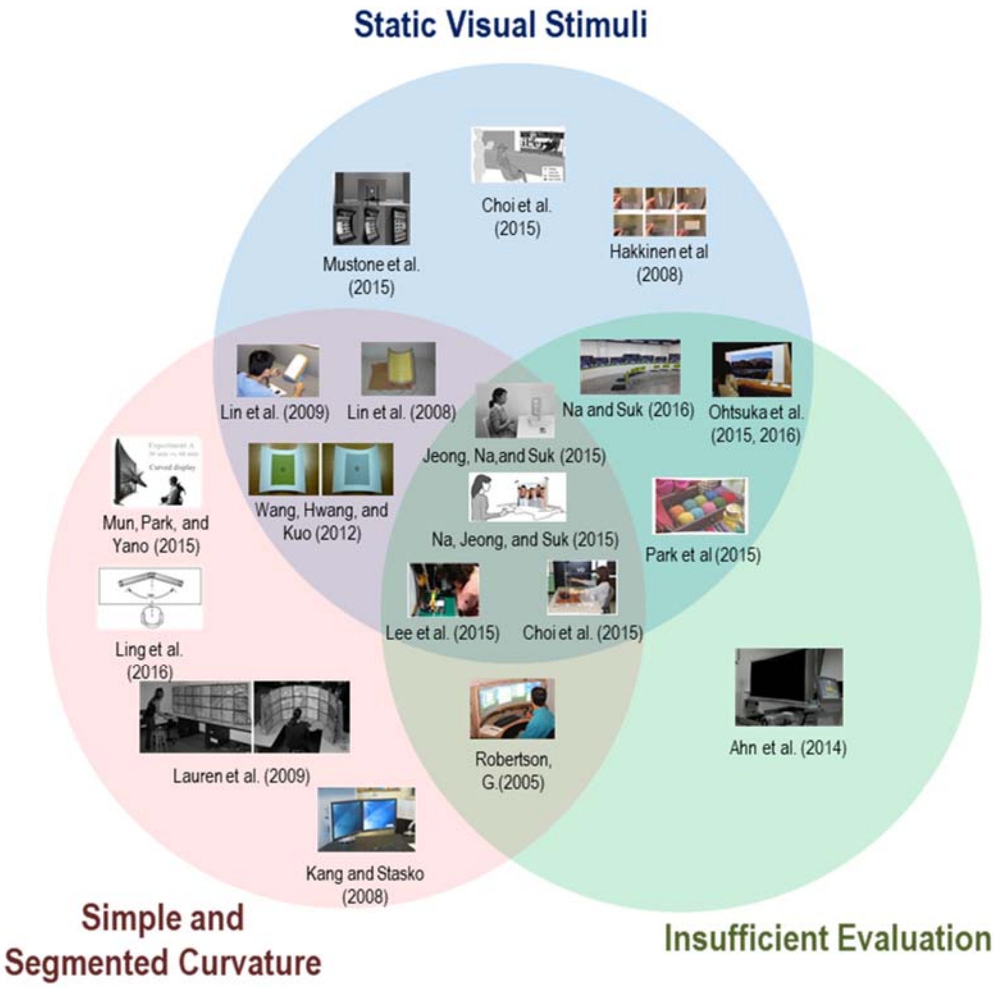

Figure 1.1 Three limitations of previous studies on curved displays

Table 1.1 List of previous studies that compared curved displays and flat displays

Authors	Display size	Display curvature	Task	Task duration	Viewing distance	Dependent variables		
						Productivity	Safety	Well-being
Lee and Kim (2016)	35" (3440 x 1440)	1000 R, 2000 R, 3000 R, 4000 R, flat	Six VDT tasks chasing, finding, reading	30 min	700 mm		Subjective ocular symptoms, near point of accommodation, near point of convergence, pupil size, saccadic movement	
Luo et al. (2016)	34"	3000 R and flat	Visual search task	55 min	400 mm		Subjective visual discomfort, convergence and accommodative Functions, saccadic movement	
Na and Suk (2016)	55", 65", 75"	1000 R, 2000 R, 3000 R, 4000 R, 5000 R, flat	Watching image (54 stimuli)		2500 mm			Aesthetic appeal, visual comfort, usability
Ohtsuka et al. (2016)	80" and 40”	2500 R and flat	Watching stimuli (Still, Blind, Motion)		2500 mm (ex 1&2) 700 mm (ex. 3)	Stabilometry (Normalized path length and path length change rate)		
Choi et al. (2015)	27” screen	Manually adjusted	Finding preferred curvature		600 mm			Optimal curvature
Choi et al. (2015)	65"	4200 R and flat	Visual search, visual attention, watching video	20 min	2000 mm	Visual performance (fixation count and duration)		Visual comfort, aesthetic appeal, novelty, gaze
Lee et al. (2015)					250 -800 mm			Perceived crease
Mun et al. (2015)	55" TV	5000 R and flat	Watching 3D	30 min and 60 min	2000 mm (ex1) and 5000 mm (ex2)		Subjective visual fatigue, EEG, EOG	Realness and engagement

Continued

Authors	Display size	Display curvature	Task	Task duration	Viewing distance	Dependent variables		
						Productivity	Safety	Well-being
Mustonen et al. (2015)	4.5" display	±100 R, ±50 R, flat	Target detection (ex1, 2) threshold letter search time (ex3)		450 mm	Sensitivity and accuracy of target detection		
Na, Jeong, and Suk (2015)	23" and 27"	Flat ~2000 R (adjustable)	Watching image and reading newspaper	20 min	600 mm			Preference and visual comfort,
Ohtsuka et al. (2015)	80" screen	2500 R ~ flat	Watching images		0 H ~ 2 H			Naturalness, range of view, visibility
Park et al. (2015)	65" TV, 86" and 120" screen	3000 R, 4000 R, 5000 R, 6600 R, 7000 R, flat	Watching images		3500 mm			Perceived distortion, preference
Ahn et al. (2014)	55"	5000 R, flat	Watching video	12 min	3400 mm		Subjective visual fatigue, physical fatigue	Immersion, satisfaction
Wang et al. (2012)	E-ink, A4 (printed)	±100 R and flat	Pointing the direction of Landolt-C gap		1500 mm	Accuracy and minimal separable visual angle		
Lin et al. (2009)	A4 (printed)	±100 R and flat	Letter search task (pseudo text)		500 mm	Speed and accuracy	Subjective visual fatigue, CFF	
Häkkinen, Kawai, et al. (2008)	5.8" printed plastic	±80 R, ±60 R, flat	Reading		Preferred			Subjective reading legibility
Wang et al. (2007)	A4 (printed)	±100 R and flat	Visual searching task		600 mm	Percentage of correct		Preference

1.2. Objective and Specific Aims

The objective of this dissertation was to determine ergonomic display curvatures regarding VDT workers' productivity, visual safety, and well-being, in order to develop ergonomic design guidelines. To achieve this, three experiments were conducted. The specific aims are as follows:

(1) Investigate the effects of the display curvature, display zone, and task duration on legibility (visual search speed and accuracy) and visual fatigue (Chapter 3 on 50" multi-monitors).

(2) Investigate the influence of display curvature and task duration on productivity (proofreading speed and accuracy), safety (visual discomfort, visual fatigue, and mental workload), and well-being (user satisfaction) (Chapter 4 on 27" monitors).

(3) Identify the speed-accuracy trade-off during proofreading tasks (Chapter 4 on 27" monitors).

(4) Determine the degree to which display curvature, task duration, distortion ratio, and their interactions affect the variability of proofreading speed and accuracy, visual discomfort, subjective visual fatigue, CFF, blink duration, blink frequency, pupil diameter, mental workload, and user satisfaction (Chapter 4 on 27" monitors).

(5) Examine the association between proofreading speed and accuracy, visual discomfort, subjective visual fatigue, CFF, blink duration, blink frequency, pupil diameter, mental workload, and user satisfaction (Chapter 4 on 27" monitors).

(6) Identify the relationship between visual discomfort and subjective visual fatigue (Chapter 4 on 27" monitors).

(7) Develop prediction models for visual discomfort, subjective visual fatigue, mental workload, and user satisfaction using display and task characteristics (display curvature, task duration, distortion ratio, and their interactions), objective measures (proofreading speed, accuracy, CFF, blink duration, blink frequency, pupil diameters), and demographic characteristics (gender, age, visual acuity, and eye conditions) (Chapter 4 on 27" monitors).

(8) Determine the degree to which composite variables composed of dependent variables affect the subjective visual fatigue and user satisfaction (Chapter 4 on 27" monitors).

(9) Investigate the influence of display curvature, viewing distance, and lateral viewing position on a sense of presence and watching experience (Chapter 5 on 55" TVs).

(10) Determine the degree to which display curvature, viewing distance, and lateral viewing position affect the variability of spatial presence, engagement, ecological validity, negative effects, visual comfort, image quality, and display satisfaction (Chapter 5 on 55" TVs).

(11) Determine the degree to which six watching experience elements (spatial presence, engagement, ecological validity, negative effects, visual comfort, and image quality) affect the display satisfaction (Chapter 5 on 55" TVs).

(12) Determine the degree to which three composite measures composed of six watching experience elements (spatial presence, engagement, ecological validity, negative effects, visual comfort, and image quality) affect the display satisfaction (Chapter 5 on 55" TVs).

1.3. Scope

A flowchart of the current research is shown in figure 1.2.

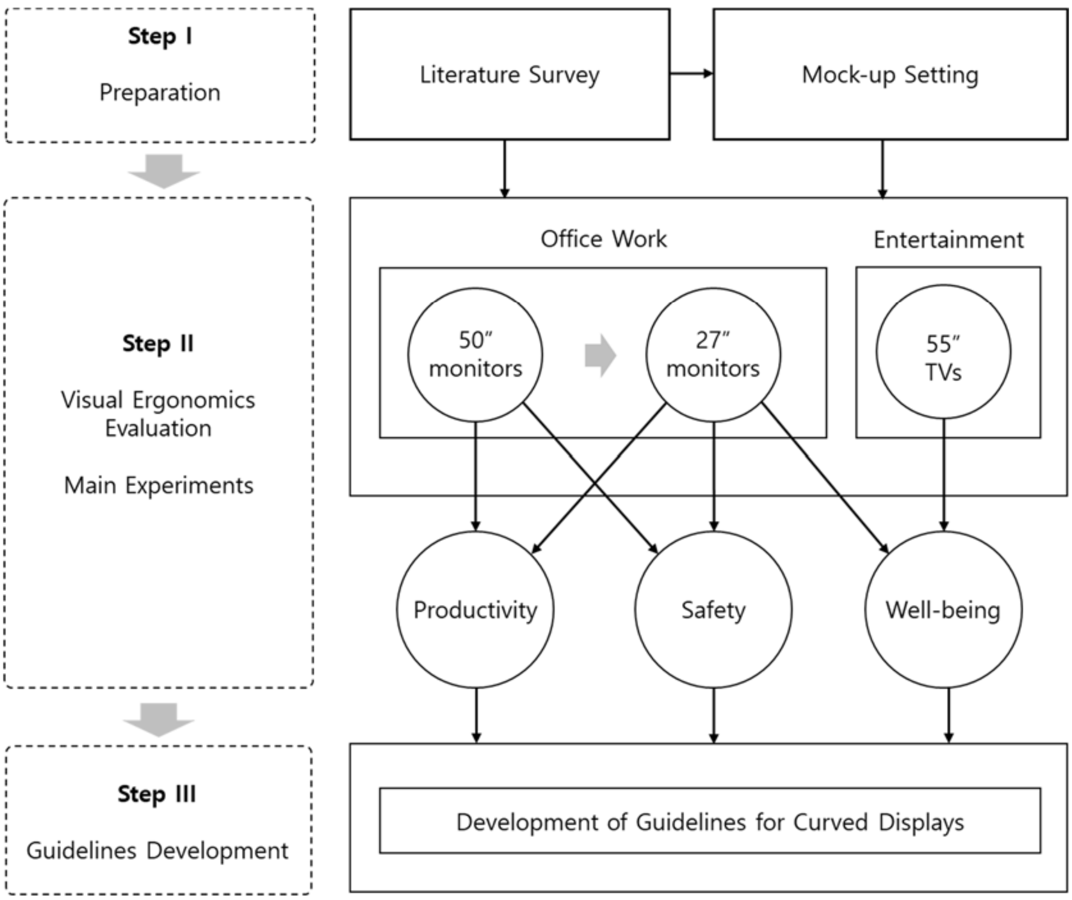

Figure 1.2 Flow chart of the current research

In general, three aspects; physical environment, an individual's visual ability, and work task, should be considered to perform a visual ergonomic evaluation. The scope of this thesis is explained from these three perspectives (Figure 1.3): 1) the physical environment - display curvature, display size, visual distance, geometrical viewing position, and experimental evironment; 2) work tasks - types of tasks for different display products, and task duration; and 3) the individual's visual ability - visual acuity, age, color blindness, eye correction surgery, and dominant eyes.

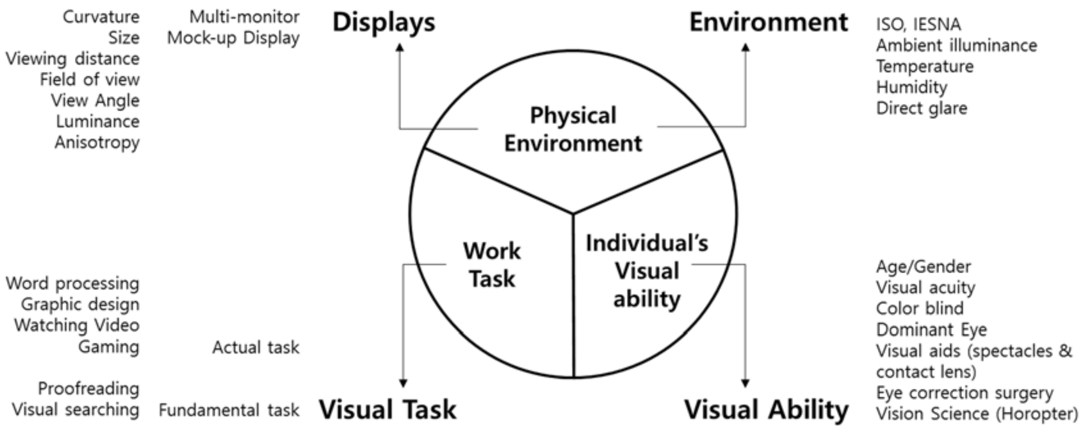

Figure 1.3 Visual ergonomic research factors for the evaluation of the visual display

For the physical environment, three types of curved displays, 50" multi-monitors (1220 mm width × 382 mm height, corresponding to 24" dual monitors with 1136 mm width × 438 mm height), 27" curved monitors (603 mm width × 346 mm height), and 55" curved TVs (1218 mm width × 685 mm height), were used. In this study, office work and entertainment were chosen. Concerning the display size, the 50" monitor was selected, corresponding to previous studies (Hoffmann et al., 2008; Lee et al., 2012). In the case of the 27" monitor and 55" TV, products already released in the market were referred to. Mock-up displays were developed to manipulate display curvatures. The 50" multi-monitors consist of five 17" flat linking display panels, while the 27" curved monitors (603 mm × 346 mm) were composed of a rear screen, beam projector, and image distortion correcting software. The 55" curved TVs (1218 mm × 685 mm) consisted of a curved a Styrofoam screen, a beam projector, and image distortion correction software. The levels of display curvature were determined considering the viewing distance in the experiment, the curvature of the curved display products, and the effective field of view (FoV). Flat displays were included as a control condition. Experimental environments, such as ambient illuminance and temperature, were determined by referring to ISO and IESNA standards. Regarding the work task, the visual tasks used in this work are basic tasks (visual searching task on 50" monitors and proofreading task on 27” monitors) and entertainment task (watching videos on 55” TVs). In the aspect of an individual’s visual ability, younger individuals in their 20s participated in this study. All participants had a visual acuity of 0.8 or higher, no color blindness, and did not wear visual aids, such as spectacles or contact lenses. They were instructed not to perform visually demanding tasks from the day before the experiment. Those with glasses were excluded from the recruitment to prevent the effects of the occlusion of vision and the distortion of visual stimuli (Kim et al., 2003; Lee and Chung, 2012).

In the current research, all experiments for each specific objective were designed by reviewing related studies and standards. The main experiments were conducted after verifying experimental protocols via pilot studies. All experiments, which were approved by the UNIST IRB (institutional review board), were performed in a controlled laboratory environment. The outline of the experiments on the 50” multi-monitors, 27” curved monitors, and 55” curved TVs are shown in figure 1.4.

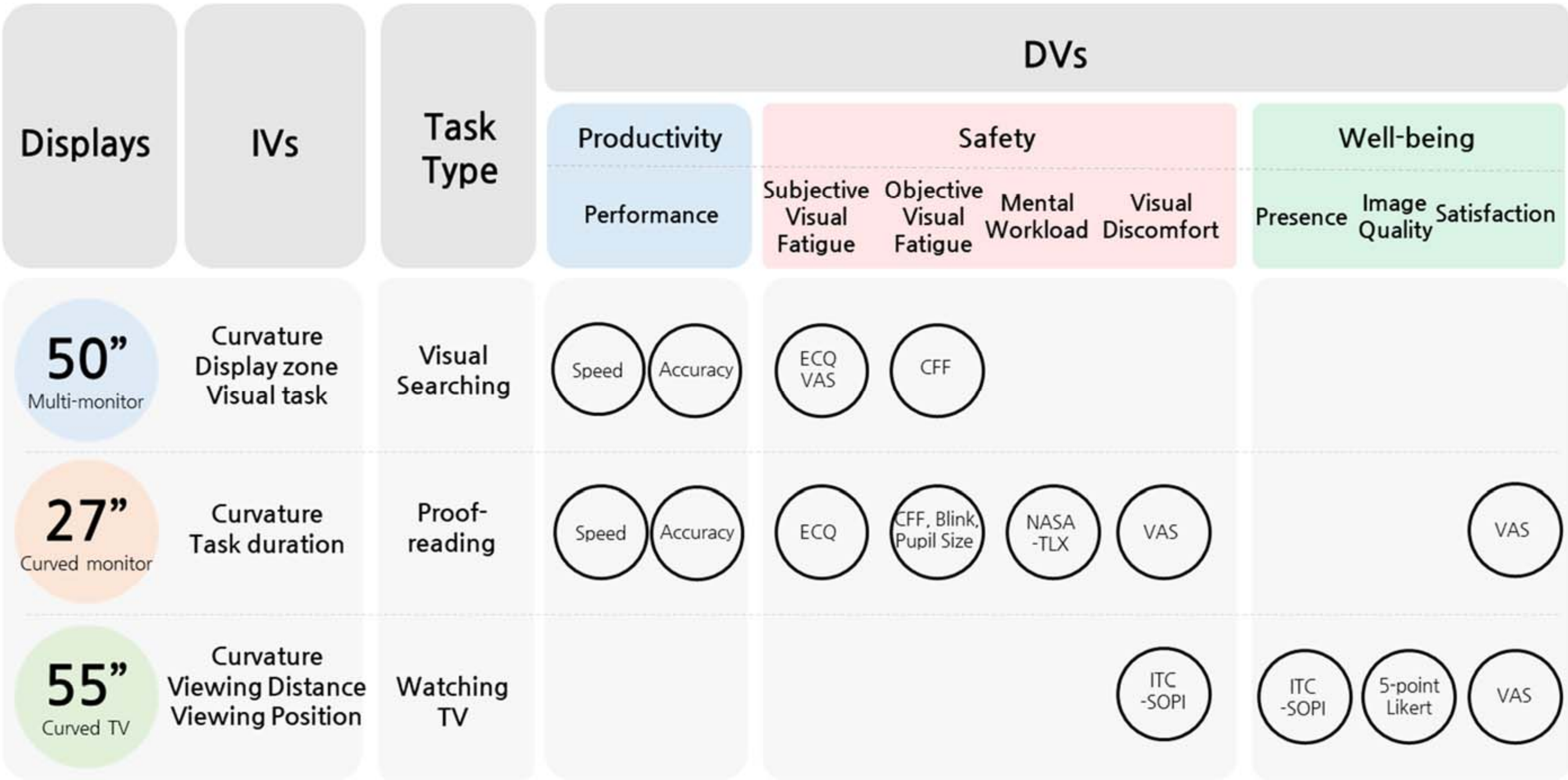

Figure 1.4 Outline of experiments on 50” multi-monitors, 27” curved monitors, and 55” curved TVs

1.4. Dissertation Outline

The current study is composed of six chapters. An appropriate curvature was explored by analyzing changes in productivity, safety, and well-being during visual tasks on curved display products. Regression models were developed to explain the significance of the display curvature, task duration, viewing distance, and viewing position on ergonomic evaluation elements in a study on a 27” monitor (chapter 4) and a study on 55 ” TV (chapter 5), respectively.

Chapter 1 discusses the overall concepts, evaluation factors and methods, and significance and limitations of previous studies.

Chapter 2 summarizes the literature review. It explains the basic knowledge of display factors, human vision, and visual ergonomic evaluation indicators.

Chapter 3 presents a study investigating the effects of the display curvature, display zone, and task duration on legibility and visual fatigue during visual searching tasks using a 50” multi-monitor.

Chapter 4, with an improvement to the experimental limitations of the 50” multi-monitor study, describes a study investigating the effects of the display curvature and task duration on the user’s productivity, safety, and well-being in proofreading tasks on a 27” curved monitor.

Chapter 5 presents a study investigating the effects of display curvature, viewing distance, and viewing position on a user’s watching experience during video watching tasks with a 55” curved TV.

Chapter 6 summarizes major findings, and suggests ergonomic design guidelines for curved displays and explains the limitations of this thesis and further studies.

Chapter 2. Literature review

2.1. General Overview of Visual Displays

2.1.1. Display curvature

A curvature of displays is an inherent property of curved displays comparing to flat displays. The curvature of a display is determined by measuring the radius (R) when the curve is perfectly circular. Although previous studies on display curvature have considered various tasks, display sizes, and display forms, the observed curvature effects are not consistent. Display curvature can have positive as well as negative impacts depending on the type of VDT work and the working environment.

Display curvature can provide some advantages in terms of visual task performance, visual fatigue, preference, and satisfaction comparing to flat displays (Czerwinski et al., 2003; Häkkinen, Pölönen, et al., 2008; Na et al., 2015; Na, Jeong, and Suk, 2015; Park et al., 2017). Using a 7 cm to 13 cm plastic mock-up display, Häkkinen et al. (2008) examined the effects of display curvature (0, ±60 R, and ±80 R) and curvature direction (horizontal/vertical) on legibility. They found that neither vertically convex displays nor vertically concave displays affected legibility significantly, whereas horizontally concave displays (60R and 80R) that were set parallel to the text reading direction improved legibility. Czerwinski et al. (2003) and Robertson et al. (2005) compared computer task performance on a 42” curved display and a 15” flat display and observed faster performance, higher satisfaction, and higher preference with the curved display.

However, some studies argued that the display curvature does not affect users (Lin et al., 2008; Lin et al., 2009; Wang et al., 2012; Wang et al., 2007). Wang et al. (2012) studied the effects of display curvature (0, ±100 R), age (20–29 years and 60–69 years), and ambient illuminance (50 lx) on visual task performance. No significant effect of display curvature was observed for the younger group, whereas the older group showed better performance under three treatment settings: 50 lx and ±100 R curvature, and 500 lx and flat or ±100 R curvature. Lin et al. (2009) examined the effects of display curvature (0, ±100 R), surface coating film (three types), and ambient illuminance (200, 1500, and 8000 lx) on legibility and visual fatigue, but they did not observe any significant effects due to curvature. Wang et al. (2007) examined the impact of display curvature (0, flat; 100 R, concave; ±100 R, convex), text/background color combination, and ambient illuminance on task performance and user preference during visual searching task using A4-size paper. They found that display curvature and ambient brightness did not affect task performance significantly; the flat setting was the most preferred setting, while the 100 R (concave) setting was the least preferred setting. By contrast, negative impacts of curved displays have shown in some studies. Mustonen et al. (2015) found that a smaller display curvature (±50 mm) reduced visual processing speeds during a visual search task on 4.5” displays with five curvature settings (0, ±50 R, and ±100 R) at a visual distance of 45 cm. In the study by Ohtsuka et al. (2015), a negative shape after effect was reported for 80” 2500 R and 1500 R curved display settings.

Some studies determined ergonomic display curvature. When display curvature approaches a given viewing distance, TV viewers' preference regarding aesthetics and comfort increases and perceived image distortion decreases (Choi et al., 2015; Na and Suk, 2016). In the study by Choi et al. (2015), the proper viewing distance for using a 27” monitor at a standard viewing distance of 600 mm was 560.9 mm. In the study by Na and Suk (2016), the aesthetic appeal and visual comfort at a viewing distance of 2500 mm were better with a curved display than a flat display. Also, a display curvature of 2000 R was most preferred for 55”, and a curvature range of 2000 R–3000 R was appropriate for 65” and 75” displays. In the study by Choi et al. (2015), the mean aesthetics and comfort at a viewing distance of 2000mm increased by 319% and 151% on a 65" 4200 R curved TV compared to a 65" flat TV. In the study by Na, Jeong, and Suk (2015), a 633 R display curvature was associated with higher preference and lower visual discomfort for a reading task on a 23" curved monitor at a viewing distance of 600 mm, and more than 85% of the participants perceived image distortion when the display curvature was smaller than 600 mm.

2.1.2. Lateral viewing position

Lateral deviation of a viewing position, which directly affects viewing angle and FoV, can affect watching experience. Indeed, the perceived display image becomes trapezoidally more distorted at a more lateral viewing position (Todd et al., 2007). Especially, in consideration of the actual context, a multi-viewer condition is more common for TV watching. In Korea, the ratio of households with two or more members was 73% (Korea, 2015); similarly, that rate was 70% in the USA (Vespa et al., 2013). Previous studies on curved TV, however, evaluated only the watching experience of the viewer-centered in front of a TV (Choi et al., 2015; Choi et al., 2015; Jeong et al., 2015; Mun et al., 2015; Na, Jeong, and Suk, 2015; Ohtsuka et al., 2015; Ohtsuka et al., 2016; Park et al., 2015). The effect of lateral viewing position on the TV watching experience should thus be considered to better take into account the actual TV watching context.

2.1.3. Field of view

Field of view (FoV) refers to the range of the angle subtended by a frontal display. The human horizontal and vertical binocular FoVs are approximately 200° and 135° respectively (Arthur, 2000). Display curvature influences FoV, for example, the FoV increases when the curvature radius approaches the viewing distance, and it decreases when the display curvature is more planar or more curved than the viewing distance. The outer zones of a display with a wide horizontal FoV require excessive eye/head rotations (Table 2.1).

Table 2.1 Recommended horizontal FoV, range of motion, and corresponding display zone

Recommendation and range of motion
10°–20° [Easy word recognition by Hatada et al. (1980)]
≤30° [Effective visual field by Hatada et al. (1980)]
70° [Maximum eye rotation by Tilley et al. (2002)]
90° [Easy head rotation by Tilley et al. (2002)]
120° [Maximal head rotation by Tilley et al. (2002)]
124° [Binocular horizontal vision by Tilley et al. (2002)]
160° (Maximum eye rotation + easy head rotation)
190° (Maximum eye and head rotation)

The horizontal FoV for displays of the same size can be calculated for various curvature levels (Figure 2.1).

$$\alpha = \frac{W}{R} \tag{1}$$

$$W1 = R \times \sin\left[\frac{W}{2R}\right] \tag{2}$$

$$W2 = VD \times \frac{R \times \sin\left[\frac{W}{2R}\right]}{VD - R + R \times \cos\left[\frac{W}{2R}\right]} \tag{3}$$

$$A1 = R - R \times \cos\left[\frac{W}{2R}\right] \tag{4}$$

$$A2 = VD - R + R \times \cos\left[\frac{W}{2R}\right] \tag{5}$$

$$A3 = R \times \cos\left[\frac{W}{2R}\right] \tag{6}$$

$$Y = \tan^{-1}\left[\frac{R \times \sin\left[\frac{W}{2R}\right]}{VD - R + R \times \cos\left[\frac{W}{2R}\right]}\right] \tag{7}$$

$$D = \frac{R \times \sin\left[\frac{W}{2R}\right]}{\sin Y} \tag{8}$$

The horizontal field of view is

$$\text{FoV (curved)} = 2 \times \tan^{-1}\left[\frac{R \times \sin\left[\frac{W}{2R}\right]}{VD - R + R \times \cos\left[\frac{W}{2R}\right]}\right] \tag{9}$$

$$\text{FoV (flat)} = 2 \times \tan^{-1}\left[\frac{W}{2 \times VD}\right] \tag{10}$$

where, W means width of the display, R means radius of a curvature, VD means viewing distance from the user's eye to the center of the display.

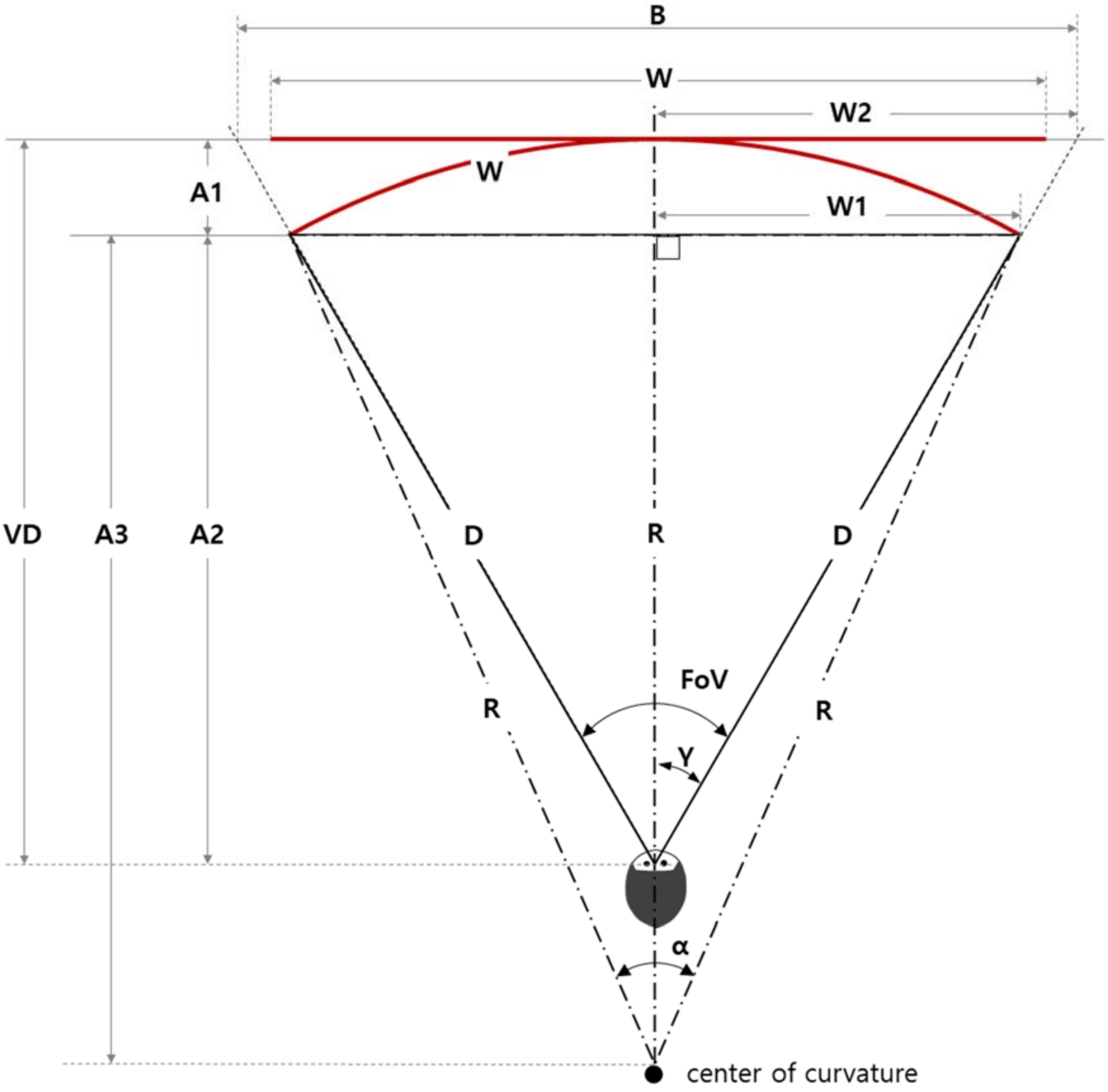

Figure 2.1 Geometry based on the horizontal field of view (FoV). Plan views of the viewer and display. α: central angle of an arc, D: viewing distance from the user eye to the left and right edge of the display. Red lines describe curved and flat display

2.1.4. Viewing angle

In this study, the term viewing angle (VA) is defined as the angular extent between the perpendicular line to the tangent of the display surface and the line of sight (Figure 2.2). The viewing angle is known to affect visual task performance (Bezerianos and Isenberg, 2012; Wigdor et al., 2007). When the horizontal viewing angle increases, the visual stimuli on display become distorted (Cai and Li, 2013) and anisotropy of the display increases (Oetjen and Ziefle, 2009).

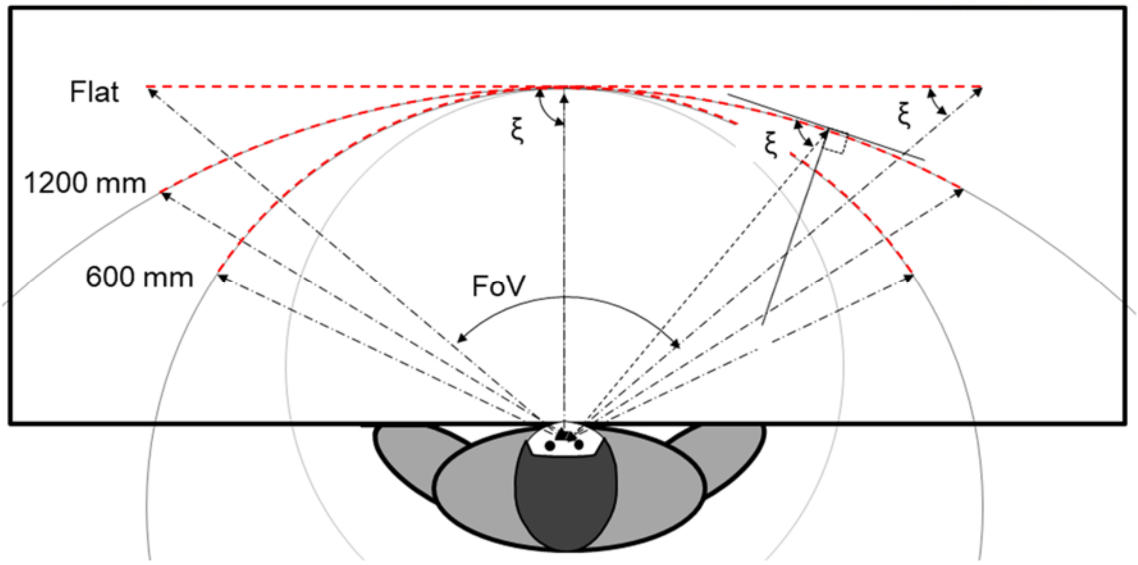

Figure 2.2 Examples of viewing angle (VA; |90° – ξ|) and field of view (FoV)

2.1.5. Anisotropy

Anisotropy is known as a specific phenomenon in which users can sense rays of light at an extended viewing angular position from an LCD screen, as the amount of light emitted depends on the direction (Oetjen and Ziefle, 2004). In other words, in a psychophysical view, the luminance on the surface of a display differs depending on the viewing angle. Anisotropy has a negative influence on visual discrimination speed (Gröger et al., 2005; Gröger et al., 2003; Hollands et al., 2001; Hollands et al., 2002; Oetjen and Ziefle, 2007, 2009; Oetjen et al., 2005).

2.2. Human Vision (binocular vision)

“The binocular vision is the coordination of both eyes to achieve a simultaneous vision state, a single image is perceived by the binocular fusion of two slightly dissimilar images depicted in each eye” - Zhang (2016) -

2.2.1. Binocular disparity

The human sees slightly different images of an object through the left and right eyes as the two eyes are horizontally separated, this is related to binocular disparity. Although the retina receives two-dimensional images, our brain uses binocular disparity and the retinal images to perceive stereopsis. There are two types of disparities according to the orientations of the disparity:

horizontal and vertical disparity. The horizontal disparity (P) of a given point in space (x) is described by Zhang (2016), as a function of the lateral distance between the left and right eyes divided by target distance (Figure 2.3):

$$P = 2 \times \ \tan^{-1}\left[\frac{a}{b}\right] \ \times k \qquad (11)$$

where, 'a' denotes half of the inter-pupil distance, 'd' is the distance between the visual stimuli and the nodal points in eyes, and 'k' is a conversion factor depending on 'P' (e.g., degree, prism diopters) (Benjamin, 2006).

The relative disparity is defined as the depth interval between two object points in angular units. Horizontal relative disparity (D) is calculated as the difference of parallax angles (P1 and P2), corresponding to two points (x and y) in geometric space (Figure 2.3):

$$D = P1 \ - \ P3 \qquad (12)$$

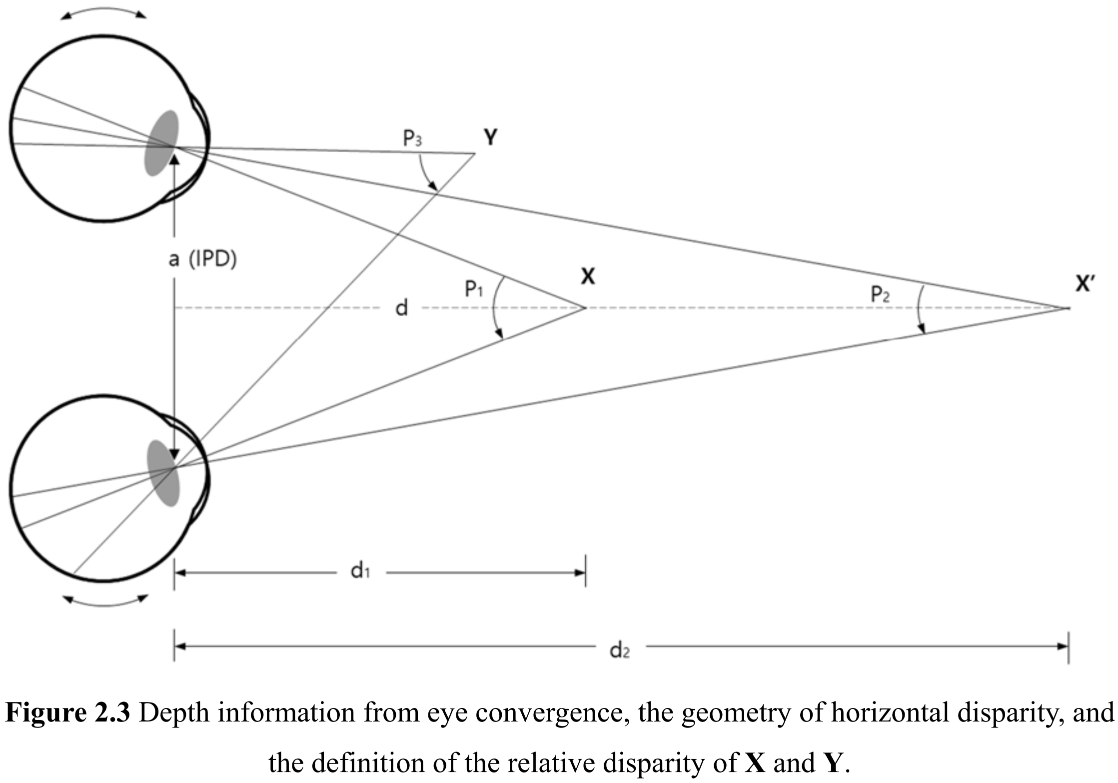

Figure 2.3 Depth information from eye convergence, the geometry of horizontal disparity, and the definition of the relative disparity of **X** and **Y**.

2.2.2. Ocular information

Accommodation and convergence of our eyes are primary physical responses during a visual task that assist the visual system to see the target more clearly. Focusing the lens (accommodation) and manipulating the angle between the two eyes' line of sight (convergence) are fundamental functions for depth perception (Palmer, 1999). Accommodation occurs when the eye's muscles are bending the lens to focus the image at the retina; convergence occurs when the eyes are horizontally rotated to aim at the target so that the images of both eyes are directed onto the fovea. Convergence is the extent to which the two eyes are turned inward (towards each other) to fixate an object (Palmer, 1999). Both of these require muscles in the eyes to work. It is assumed that this function can cause muscle fatigue, just as other muscles in the body tire (Megaw, 1995).

2.2.3.1. Horopter

Horopter is defined as "the set of environmental points that simulate corresponding points on the two retinae." The theoretical horopter is defined "geometrically by projecting pairs of corresponding retinal points outward through the nodal point of the eye" (Palmer, 1999) and describes the locus of all object points in space that are imaged on the two corresponding retinal elements at a given fixation distance (Figure 2.4). A single vision can be achieved with the objects located along the line with the same angles at the two eyes as the fixation lines (Howard, I.P., Alhazen's neglected discoveries of visual phenomena. PERCEPTION-LONDON-, 1996. 25: p. 1203-1218).

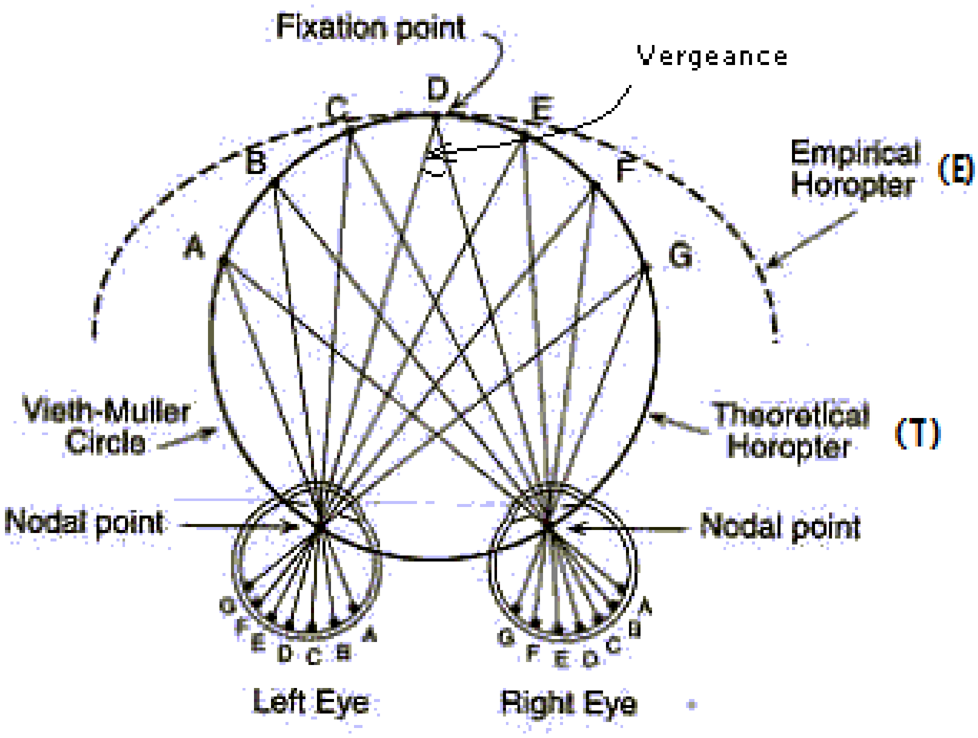

Figure 2.4 The horopter in the horizontal plane. The theoretical horopter in the horizontal plane of the eyes is a circle (Veith-Muller circle). The empirical horopter (dashed line) is slightly behind the theoretical horopter as indicated (Palmer (1999), p.208).

Empirical horopter (Lambooij et al., 2009) can explain the advantage of curved displays. Objects that form single-vision images on the retina without visual accommodation lie on a more planar line, i.e., the empirical horopter, than a geometrically defined curve, i.e., the theoretical horopter (Ogle, 1950; Shipley and Rawlings, 1970). Visual stimuli on curved displays are relatively closer to the empirical horopter than on the flat condition unless curvature is excessive. As Wheatstone (1838) observed, the empirical horopter was much planar compared to the theoretical horopter. At a neighboring point, empirical horopter is close to the Vieth–Miller circle (the Hering–Hillebrand deviation). At a fixed distance of 6 m, the horopter is close to the frontal plane, and if the fixation point is larger than 6 m, the horopter is away from the frontal line (Parkin, 2015) (Figure 2.5).

Barfield and Furness (1995) introduced five types of empirical horopters, according to the measurement methods; the nonius horopter (i.e., the longitudinal horopter), the equidistance horopter, the apparent fronto-parallel plane horopter, the singleness of vision horopter (i.e., the fusion horopter) and the stereoacuity horopter. To determine the nonius horopter, the subject binocularly fixates a target and views the upper half of a vertical rod positioned off to one side of the fixation target through one eye and another eye on the lower half of the rod. The subject then aligns the upper and lower part of the rod to be collinear. The equidistance horopter is defined as a locus of eccentrical points which are perceived as the same distance compared to the binocularly fixated point by the observer. The apparent fronto-parallel plane horopter is defined as a locus of eccentrical points which are perceived to be located on the same frontoparallel plane as the target. Both are related to humans' spatial perception. The singleness of vision horopter is defined as the variation of the distance that an eccentrically located stimulus is no longer perceived as a single object compared to a binocularly fixated target. The stereoacuity horopter is determined by measuring the smallest detectable depth between two nodal points located at the same retinal eccentricity. The five horopter concepts only take account of the horizontal plane. Helmholtz (1925) defined the empirical vertical horopter as a tilted straight line that passes from a point near the ground level, and lies directly below the subject's eyes, through the binocular fixation point.

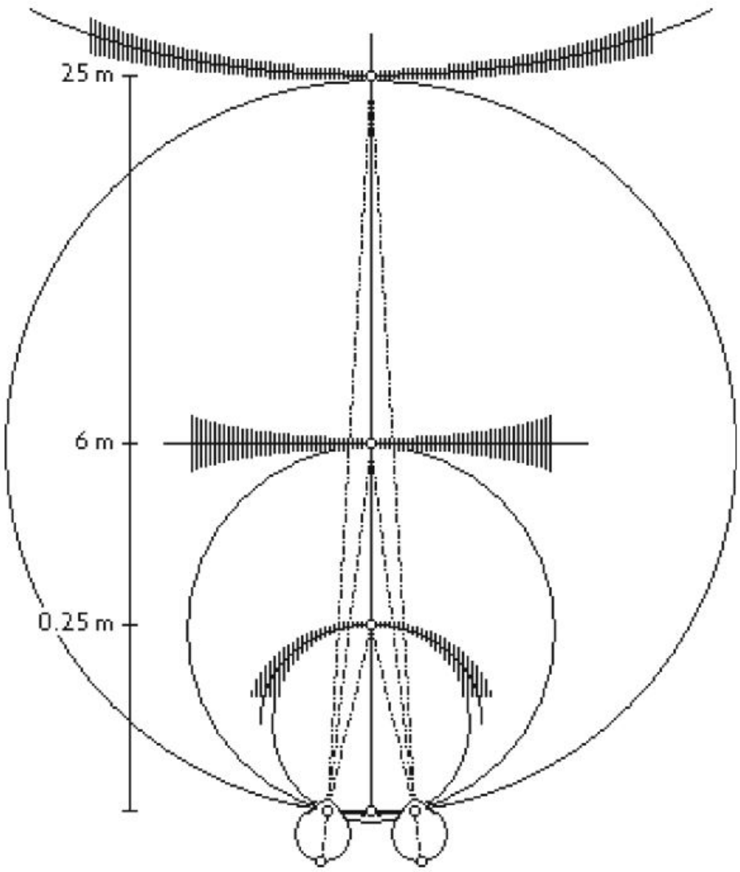

Figure 2.5 Vieth–Muller circle, empirical horizontal horopter, and Panum's fusional area for three different fixations (not to scale). When fixation distance is about 6m, the horopter is close to the frontal plane [Parkin (2015); chapter 12, p. 214]

2.3. Visual Ergonomics

The IEA defined visual ergonomics as "the multidisciplinary science concerned with understanding human visual processes and the interactions between humans and other elements of a system." Visual ergonomics aims to improve users' well-being and system performance with related theories, knowledge, and methods (Toomingas, 2014). To evaluate new display products, three visual ergonomic aspects, namely productivity, safety, and well-being should be considered.

2.3.1. Productivity Indicators

2.3.1.1. Visual task performance

Visual task performance (speed and accuracy) is an essential indicator of productivity assessment (Häkkinen et al., 2008; Hall and Hanna, 2004; Na et al., 2015; Oetjen and Ziefle, 2007, 2009; Ojanpää and Näsänen, 2003; Piepenbrock et al., 2013). In the evaluation of the visual task performance, it is necessary to examine the effect on speed-accuracy tradeoff. About VDT tasks, the accuracy is more important than the speed of the task, and at the same level of speed, more accurate work will be preferred regarding the overall task performance.

Legibility is a widely used ergonomic criterion for display evaluation (Kong et al., 2011; Lin et al., 2013; Lin et al., 2009; Lin et al., 2008; Oetjen and Ziefle, 2009; Piepenbrock et al., 2013). Determinants of legibility include letter size, font type and thickness, letter and line spacing, color contrast, viewing distance, and ambient illumination (Bernard et al., 2003; Hwang et al., 1997; ISO, 2011; Lee and Kim, 2007; Sanders and McCormick, 1993; Vartabedian, 1971; Wickens et al., 2004). Measures for legibility depend on the characteristics of the visual tasks considered. When long sentences are used for legibility studies, text reading speed and accuracy in finding target words in paragraphs are usually used (Hall and Hanna, 2004; Hill and Scharff, 1997; Lin, 2003; Lin et al., 2013; Ling and Van Schaik, 2002; Shieh and Lin, 2000), and when images, letters, or numbers are presented for a short time, visual stimulus recall rate and perceptional ease are typically used (Al-Harkan and Ramadan, 2005; Lin, 2003; Shieh and Lin, 2000).

An appropriate display curvature is likely to provide better legibility as it optically reduces image distortion (e.g., regarding image size and shape, particularly toward the lateral ends) and indirect glare. Legibility measures include reaction time and accuracy associated with finding target words in paragraphs (Hall and Hanna, 2004; Hill and Scharff, 1997; Lin et al., 2013; Ling and Van

Schaik, 2002; Ojanpää and Näsänen, 2003). Visual stimulus recall rate and perceptual ease (Al-Harkan and Ramadan, 2005; Lin, 2003; Shieh and Lin, 2000), and physiological correlates of legibility (Yeh et al., 2013).

Proofreading is a fundamental skill for reading and writing (Chromik, 2002; Enos, 2010). Proofreading methods are categorized into comparison and non-comparison (Anderson, 1990). Comparison proofreading is a direct comparison between a dead copy (original version) and a live copy. For non-comparison proofreading, there is no dead copy, or the dead copy is used for reference only (Chan and Ng, 2012). Among the major daily office task categories (search, analyze, create, process, manage, and meeting), proofreading for the analysis was considered as a high cognitive demand task (Kalvelage and Dorneich, 2016).

The stored knowledge and attentional resources of the proofreader can affect proofreading performance (Shafto, 2015). Noncontextual errors (in one word) are easier to proofread than contextual errors (in words and sentences) (Hacker et al., 1994; Plumb et al., 1994). Detecting noncontextual errors is automatically processed, whereas contextual errors are attentionally demanding and are more susceptible to surrounding noise such as sound (Weinstein, 1977).

Proofreading is influenced by display factors and visual environment. Proofreading performance (time and accuracy) increased as the line spacing of Chinese text increased and was better in the horizontal than in vertical text direction (Chan and Ng, 2012). Proofreading accuracy on a paper sheet (210 mm width × 297 mm length) was higher in illumination of 800 lx than in 70 lx (Mayr et al., 2013). Proofreading task performance was better on 24” positive polarity display (dark text on bright background) than negative polarity, and subjects’ pupil size was smaller with positive polarity display (Piepenbrock et al., 2014a)

2.3.2. Safety indicators

2.3.2.1. Visual discomfort and visual fatigue

Regarding safety, visual discomfort and visual fatigue are important factors that are widely used to evaluate visual displays. Visual discomfort is a subjective feeling, while visual fatigue can be objectively explained with performance degradation of the human vision system. Even though both concepts have been used interchangeably in related studies, few studies have systematically verified the relationship between the two concepts (Lambooij et al., 2009). Visual discomfort can be caused by prolonged viewing, increase in demand for visual systems, and reduced visibility such as image blur (Lambooij et al., 2009). On the other hand, visual fatigue can be triggered by visual task with either repeated contraction/relaxation of the eye muscles (Hsu and Wang, 2013) and constant focal distance (Young, 2009). Relatively similar viewing distances across a curved screen can be advantageous in the former aspect but disadvantageous in the latter point.

Various types of visual tasks for VDT operations have been used to evaluate visual fatigue. Visual fatigue has been assessed in visual tasks with low cognitive workload such as reading, searching, watching, and data entering (Saito et al., 1994; Saito et al., 1993), whereas visual fatigue due to visual tasks with the cognitive workload and visual stress have been evaluated during visual discrimination, reading, computer mouse operation, and typing tasks (Hwang et al., 1988; Kong et al., 2011; Omori et al., 2008; Sommerich et al., 2001; Wang et al., 2012).

Visual fatigue can be measured using subjective ratings, such as the visual fatigue Graphic rating scale (Cushman, 1986), eye complaint questionnaire [ECQ; (Steenstra et al., 2009)], questionnaires using seven-point scales e.g., (Li et al., 2012), Visual fatigue induced by stereoscopic images (Bando et al., 2012), and visual fatigue scale (Benedetto et al., 2013). Physiological measures, such as critical fusion frequency [CFF (Bando et al., 2012; Chi and Lin, 1998; Lin and Huang, 2013; Lin et al., 2013; Lin et al., 2009)], accommodative power (Saito et al., 1993), visual acuity, pupil diameter, ocular speed (Chi and Lin, 1998), electromyogram (EMG) of the orbicularis oculi (Nahar et al., 2011), and brain signals (Yeh et al., 2013), have been used as objective measures.

2.3.3. Well-being indicators

Regarding user well-being, the effect of display curvature on the elements of the viewing experience is important. TV watching experience comprises diverse elements. In previous studies on TV, presence (Baranowski et al., 2016; Bracken, 2005; Lee and Lee, 2006; Lombard et al., 2000; Moon, 2014), visual comfort (Chang et al., 2014; Kim et al., 2014; Lambooij et al., 2011; Nojiri et al., 2006; Park, J. et al., 2015; Tam et al., 2011; Zhang et al., 2015), image quality (Ardito et al., 1996; Bracken, 2005; Häkkinen et al., 2008), satisfaction (Zhang et al., 2015), visual fatigue (Chen et al., 2013; Lee and Park, 2009; Sakamoto et al., 2012; Zhang et al., 2015), motion sickness (Baranowski et al., 2016), empirical 3-dimensional (3D) image distortion (Kim et al., 2014), and emotional reactions (Häkkinen et al., 2008) were used to evaluate the watching experience.

2.3.3.1. Presence

Presence, which is one of the important watching experience factors on TVs, is defined as the human operator's sense of being there in a remote location (Minsky, 1980). With the advancement of display-related technologies (e.g., high-resolution contents and screens and 3D contents and screens), sense of presence while watching TV has become an important part of TV watching experience. As the screen size increases, the presence increases (Lessiter et al., 2001). For the same screen size, curved screens provide higher presence than flat ones (Ohtsuka et al., 2015). Large curved TVs, therefore, are likely to intensity watching experience.

Presence relies on external (media form and media contents) and internal (personal factors) determinants (Lessiter et al., 2001). There are three external determinants of presence. Media form factors can affect geometric distortion and brilliance (Goldmark and Dyer, 1940), and in turn, affect the watching experience. Display size (Lombard, 1995; Reeves and Nass, 1996; Tan, 2004), viewing distance (Reeves et al., 1993), and image quality (Bracken, 2005; Fukuda, 1990; Lee, 2005) belong to media form factors. Social realism, use of media conventions, and nature of task or activity belong to media content factors, and willingness to suspend disbelief, knowledge of and prior experience with medium, and personal types belong to personal factors (Heeter, 1992).

For measuring the presence, self-reporting was regarded as a fundamental method (Sheridan, 1992), and subjective verbal ratings were frequently used (Wissmath et al., 2010). Subjective questionnaires for presence include ITC-sense of presence inventory (Lessiter et al., 2001), presence questionnaire (Witmer and Singer, 1998), and Slater–Usoh–Steed questionnaire (Slater et al., 1994). Objective measures of presence include psychophysiological measures (e.g. heart rate and blood pressure), neural correlates (e.g., electroencephalograph and functional magnetic resonance imaging), behavioral measures (e.g., facial expression and postural response) and task performance measures (van Baren and IJsselsteijn, 2004).

2.3.3.2. Visual comfort

TV watching experience was also evaluated regarding visual comfort. Curved TV with appropriate curvature is expected to improve visual comfort than flat TV by providing constant focal distance and reducing image distortion. In terms of visual safety, visual comfort was evaluated in 3D, 2D flat TV, and head-mounted display (Lambooij et al., 2009; Lambooij et al., 2007; Nojiri et al., 2004; Yano et al., 2004; Yano et al., 2002), and visual discomfort in the 3D display was higher than in 2D display (Lambooij et al., 2009).

Subjective measures of visual discomfort include explorative studies (Meesters et al., 2004), visual analog scale [VAS; (Borisuit et al., 2014)] and single stimulus continuous quality evaluation (BT.500-13, 2012), and questionnaires (Sheedy, 1992a; Sheedy and McCarthy, 1994). Objective measures of presence include accommodation response (Yano et al., 2002), pupil size, dark vergence, and dark focus (Taptagaporn and Saito, 1993).

2.3.3.3. Image quality

Image quality is one of the important evaluation factors for TV watching experience (Huynh-Thu et al., 2010) because image quality is subjectively determined through comparison between the displayed image and the viewer's image impressions (Schade, 1987). Subjective measures of TV image (video) quality include single-stimulus continuous quality scale and double-stimulus continuous quality scale (Nuutinen et al., 2016). Objective image quality evaluation methods include the peak signal to noise ratio (Mittal et al., 2012) and the moving pictures quality metric (Seshadrinathan and Bovik, 2010), but these methods have limitations that do not reflect subjective judgment (Fiedler et al., 2010; Hemami and Reibman, 2010; Kim et al., 2008; Lin and Kuo, 2011).

2.3.3.4. Satisfaction

Curved display products, which have a new shape, should be evaluated for improvement in the quality of experience (QoE) compared to existing products. Satisfaction was used as one of the important evaluation factors for QoE for visual displays products. Satisfaction was lowered as the eyestrain increased during a 1.5-hour visual task on an LED display (512 mm × 256 mm) (So and Chan, 2013). Visual discomfort and visual fatigue occurred during a 1-hour viewing of 2D and 3D videos at a viewing distance of 70 cm on a 46” display, which decreased the user's satisfaction (Iatsun et al., 2015). Questionnaires and VAS are used as subjective methods to measure satisfaction on watching TV. However, from the authors’ point of view, there is still no study that comprehensively considers diverse watching experience elements or a study that explains display overall satisfaction using various watching experience elements.

2.3.4. Mental workload

Mental workload is another important factor that is closely related to visual task performance and visual fatigue (Rocha and Debert-Ribeiro, 2004). VDT tasks induce mental loads and therefore reduce the efficiency of reading tasks (Lee et al., 2011). Thus, it is necessary to verify whether the display curvature can reduce the mental workload during visual tasks. In studies on multi-monitor, it was found that rotating the displays in the direction of the user reduced the workload. Kang and Stasko (2008) demonstrated that compared to a 17" single monitor, a dual-monitor (using two 17" monitors) increased information searching speed on the Internet, reduced cognitive workload, and increased user preference. Su and Bailey (2005) recommended that a 66" multi-monitor should be located within a 45° FoV from the perspectives of subjective workload and satisfaction.

The mental workload can be measured using a subjective measurement method, NASA task load index (NASA-TLX), which is a multi-dimensional mental workload rating that contains six subconcepts: mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart, 2006). CFF (Lin, 2015; Luczak and Sobolewski, 2005), pupil size and blink (Ahlstrom and Friedman-Berg, 2006; Fong et al., 2010), PERCLOS (Halverson et al., 2012), ECG (Fallahi et al., 2016), and EEG (Kang et al., 2017) have been used as objective measures for the mental workload.

Oculomotor behavioral changes are correlated with visual task performance (Matessa, 2004; McKinley et al., 2011), and more specifically, it is known that blink duration and frequency are increased as visual task performance decreases (McIntire et al., 2014). Blink rate and duration decline as a function of higher workload (Brookings et al., 1996). The increment of mental workload reduces blink frequency (Faure et al., 2016); as an example, people blink more often during the conversation, but less often during reading than resting time.

2.3.5. Time on VDT Tasks

Working time is one of the important factors influencing VDT workers' productivity and eye safety. It is well known that prolonged VDT tasks often cause visual fatigue, which can result in headaches and task performance degradation (Sheedy, 1992a, 1992b). Numerous studies have used task duration as one of the independent variables. However, they did not significantly suggest how long a VDT worker could work without any degradation on task performance or symptoms of visual fatigue. Several international organizations are providing rest-time recommendations for VDT workers as safety issues; 1 hour (New Zealand Accident Compensations Corporation, 2010), 1 or 2 hours (OSHA, 1997), and 1 hour for high visually demanding work and 2 hours for moderate visually demanding work (National Institute for Occupational Safety and Health (NIOSH)). However, the results of previous studies, which were conducted during a wide range of task times (4 minutes to 4 hours), evaluating productivity as well as visual safety, suggest that a relatively shorter break interval is needed compared to existing guidelines (Table 2.3). Previous studies found that frequent and short break schedules were more beneficial for enhancing visual task performance and reducing visual fatigue. In previous studies, a 30-min interval was suggested considering visual task performance (Balci and Aghazadeh, 2003), a 25 min (Shieh and Chen, 1997) and 1-hour interval (Galinsky et al., 2000) were recommended to prevent visual fatigue.

Table 2.2 Visual task types and task duration in previous studies

Study	Task	Task duration (min)	Findings Decrease in CFF (Hz; Pre-/Post-task)
Luo et al. (2016)	Visual search task	55	
Lee and Kim (2016)	Combination of tasks	30	
Lin (2015)	Text entry	4–10	Up to 1.85
Mun et al. (2015)	Watching video	30	
Ahn et al. (2014)	Watching video	12	
Benedetto et al. (2013)	Reading	73	0.54–0.95
Chang et al. (2013)	Reading	17–20	2.25–3.10
Lin et al. (2013)	Searching	5–7	1.26–1.57
Hsu and Wang (2013)	Gaming	120	2.1 in total 1.2 during 0–10 min 1.1 during 50–60 min
Kwon et al. (2012)	Watching	78	
Kang et al. (2009)	Reading	51–54	1.59–2.52
Lin, P. H. et al. (2008)	Searching	10–12	1.37–1.76
Lin et al. (2008b)	Tracking	20, 60	0.4(41.1/40.7)–2.0(41.6/39.6)
Jebaraj et al. (1999)		40	
Chi and Lin (1998)		20 and 60	
Ziefle (1998)		2.5 to 3 h	
Saito *et al.* (1994)	Data entry	240	1.3 (36.6/35.3)
Gallimore and Brown (1993)		2 h	
Magnussen et al. (1992)		10 to 60	
Watten et al. (1992)		2 and 4 h	
Tyrrell and Leibowitz (1990)		Under 2 h	
Iwasaki et al. (1989)	Calculating	60	2.0 after 15 min (in red light); 1.0 after 30 min (in green and yellow lights)
Miyao et al. (1989)		1 h	
Goussard et al. (1987)		2 h	
Lunn and Banks (1986)		10	

Chapter 3. Effects of Display Curvature, Display Zone, and Task Duration on Visual Searching Task Performance and Visual Fatigue [Study 1: 50” monitors]

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3.1. Introduction

Curved displays are currently used in various display devices (e.g., smartphones, TVs, and computer monitors). The advantages of this new display technology include a high degree of design freedom, an immersive viewing experience, screen privacy, and glare reduction (Raymond, 2013). Existing display-related ergonomics standards (e.g., AS 3590.1, AS 3590.2, ISO 9241-5, ISO 9241-303, ANSI/HFES 100, and EU90/270/EEC) have been developed for flat and convex displays (e.g., LED and cathode-ray tube displays). However, it is largely unknown whether these standards are applicable to curved displays. Therefore, further investigation of display curvature is necessary from the ergonomic perspective, e.g., in terms of legibility and visual fatigue.

Legibility is a commonly used ergonomic criterion for display evaluation (Kong et al., 2011; Lin et al., 2013; Lin et al., 2008; Lin et al., 2009; Oetjen and Ziefle, 2009; Piepenbrock et al., 2013). It depends on letter size, font type and thickness, letter and line spacing, colour contrast, viewing distance, and ambient illumination (Bernard et al., 2003; Hwang et al., 1997; Lee and Kim, 2007; Sanders and McCormick, 1993; Vartabedian, 1971; Wickens et al., 2004). An appropriate display curvature is likely to provide better legibility as it optically reduces image distortion (e.g., in terms of image size and shape, especially toward the lateral ends) and indirect glare. Legibility measures include reaction time and accuracy associated with finding target words in paragraphs (Hall and Hanna, 2004; Hill and Scharff, 1997; Lin et al., 2013; Ling and Van Schaik, 2002; Ojanpää and Näsänen, 2003), visual stimulus recall rate and perceptual ease (Al-Harkan and Ramadan, 2005; Lin, 2003; Shieh and Lin, 2000), and physiological correlates of legibility (Yeh et al., 2013).

Visual fatigue is another criterion that is widely used for display evaluation. Tasks involving prolonged exposure to visual displays often cause visual fatigue, which can result in headaches and task performance degradation c In general, visual fatigue can be induced either by repeated activation/deactivation of the ocular muscles (Hsu and Wang, 2013) or by prolonged accommodative response to similar focal distances (Company, 2009). Relatively similar viewing distances across a curved screen can be advantageous in the former aspect but disadvantageous in the latter aspect. Also, distorted letters on the screen also increase visual fatigue (Lee and Chung, 2012), which can be mitigated by a curved screen. Visual fatigue under low cognitive workload is assessed in tasks such as reading, searching, watching, and entering data (Hwang et al., 1988; Kong et al., 2011; Omori et al., 2008; Sommerich et al., 2001; Wang et al., 2012), whereas visual fatigue primarily due to cognitive workload and visual stress is assessed in tasks such as visual discrimination, reading, computer mouse operation, and typing (Hwang et al., 1988; Kong et al., 2011; Omori et al., 2008; Wang et al., 2012). Visual fatigue is also evaluated using subjective ratings, such as the Visual Fatigue Graphic Rating Scale (VFGRS), Eye Complaint Questionnaire (ECQ), Visual Fatigue induced by Stereoscopic Images (VFSI), and Visual Fatigue Scale (VFS), and physiological measures, such as critical fusion frequency (CFF), accommodative power (Saito et al., 1993), visual acuity, pupil diameter, ocular speed (Chi and Lin, 1998), electromyogram (EMG) of the orbicularis oculi (Nahar et al., 2011), and brain signals (Yeh et al., 2013).

Some previous studies have examined the effects of dual- or multi-monitor settings on user behavior or performance. Grudin (2001) observed that many multi-monitor users placed primary information on the center monitor and secondary information on the side monitors. Also, multi-monitor users usually arrange their monitors in a curved array (Na, Jeong, and Suk, 2015). Kang and Stasko (2008) demonstrated that, compared to a 17" single monitor, a dual-monitor setting comprising two 17" monitors with an included angle of 160° has higher user preference, as it increases Internet search speed and reduces cognitive workload.

Although previous studies on display curvature have considered various tasks, display sizes, and/or display forms, the observed curvature effects are not consistent. Legibility and visual fatigue in the case of curved displays are often assessed using visual search tasks involving pseudo-texts (Lin et al., 2008; Wang et al., 2012; Wang et al., 2007). Czerwinski et al. (2003) and Robertson et al. (2005) compared computer task performance on a 42" curved display and a 15" flat display and observed faster performance, higher satisfaction, and higher preference in the case of the curved display. Wang et al. (2007) examined the effects of display curvature (0, flat; −100 R, concave; +100 R, convex), text/background color combination, and ambient illuminance on task performance and a user preference associated with searching for specific words printed on A4-size paper. They found that display curvature and ambient brightness did not affect task performance significantly; the flat setting was the most preferred setting, while the −100 R (concave) setting was the least preferred setting. Using a 13 cm × 7 cm plastic mock-up display, Häkkinen, Pölönen, et al. (2008) examined the effects of display curvature (0, ±60 R, and ±80 R) and curvature direction (horizontal/vertical) on legibility. They found that neither vertically convex displays nor vertically concave displays affected legibility significantly, whereas horizontally concave displays (–60 R and –80 R) set parallel to the text reading direction improved legibility. Using pseudo-texts printed on A4-size paper, Lin et al. (2009) examined the effects of display curvature (0, ±100 R), surface coating film (three types), and ambient illuminance (200, 1500, and 8000 lx) on legibility and visual fatigue, but they did not observe any significant curvature effects. Using visual stimuli printed on A4-size paper, Wang et al. (2012) studied the effects of display curvature (0, ±100 R), age (20–29 yrs and 60–69 yrs), and ambient illuminance (50, 500, 6000, and 12,000 lx) on visual task performance. No significant display curvature effects were observed for the younger group, whereas the older group showed better performance under three treatment settings: 50 lx and +100 R curvature, and 500 lx and flat or +100 R curvature. Mustonen et al. (2015) found that a smaller display curvature (±50 R) reduced visual processing speeds during a visual search task on 4.5" displays with five curvature settings (0, ±50 R, and ±100 R) at a visual distance of 45 cm.

The objective of study I is to determine ergonomic display curvatures for 50" displays by examining the effects of display curvature, display zone, and task duration on legibility and visual fatigue. Legibility was measured in terms of accuracy and speed during target searching in pseudo-texts, and visual fatigue was assessed subjectively as well as physiologically.

3.2. Methodology

3.2.1. Participants

A total of 27 college students participated in the study. Their mean (SD) age was 20.9 (1.2). The participants included 14 males (mean (SD) age = 20.9 (1.2)) and 13 females (mean (SD) age = 20.9 (1.3)). The exclusion criteria were as follows: wearing a pair of glasses, being colour blind based on the Ishihara test (Ishihara and Force, 1943; Strayer and Johnston, 2001), suffering from any ocular disease in the past six months, or having visual acuity < 0.8 (=16/20 in the Snellen fractional notation) based on the Han Chun Suk test (Kee et al., 2006). The last criterion is typically used in visual performance studies (Schega et al., 2014; Shen et al., 2009; Wu, 2011). Wearing contact lenses was allowed. The mean (Snellen notation; SD) normal or corrected-to-normal visual acuities of the participants' left and right eyes were 1.1 (22/20; 0.3) and 1.0 (20/20; 0.2), respectively. All the participants provided informed consent approved by the Institutional Review Board (IRB) at Ulsan National Institute of Science and Technology (UNIST), and were compensated for their time.

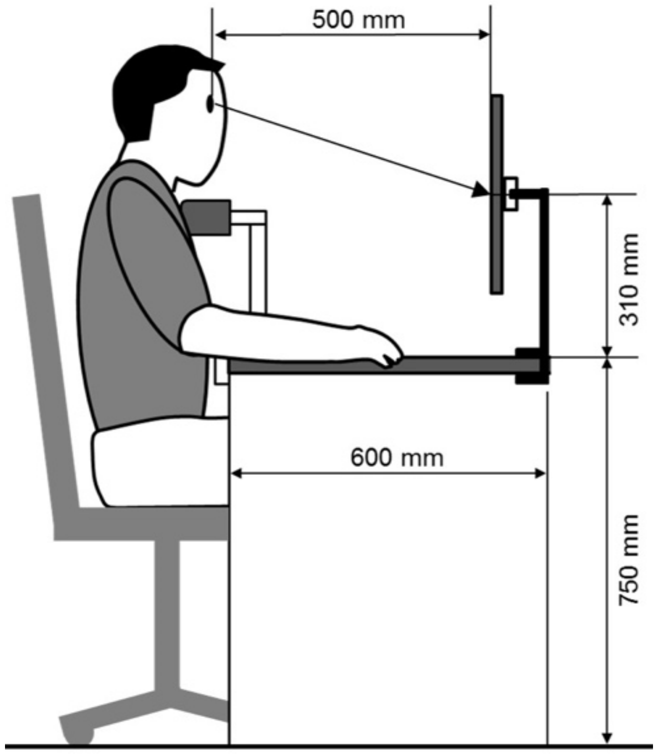
3.2.2. Experimental setting and procedure

The windows of the experimental room were covered by blackout curtains to keep out sunlight and other external light. The experimental desk and the room walls were covered with black cloth to minimize their color and reflection effects. A 50" (width × height = 1220 mm × 382 mm) experimental multi-monitor setting comprising five 244 mm × 382 mm display panels (LP171EE3, LG, Korea) was used. The size of the multi-monitor setting was similar to that of a dual-monitor setting comprising two 24" monitors (1136 mm × 438 mm). The resolution of each display panel (display zone) was 1050 × 1680 pixels. The multi-monitor curvature was adjusted to a particular setting by attaching custom brackets between the display panels. A height-adjustable chair was provided to accommodate stature variability, and a chest rest was used to facilitate neck rotation while controlling viewing distance. The horizontal viewing distance (a) to the center display (Z_3; Figure 3.1) was set to 500 mm. The 600 R curvature corresponds to the sum of the horizontal viewing distance (500 mm) and the distance from the head pivot for transversal head rotation to the eye (98 mm; SAE, 2009). The horizontal field of view (ϕ) and horizontal viewing angle (|90° – ξ|) varied with the display curvature (table 3.1). The picture of the experimental setting is shown in figure 3.2.

Table 3.1 Horizontal viewing distance, field of view, and viewing angle for different display curvatures and display zones

Display Curvature (R)	Horizontal viewing distance (mm)						Horizontal field of view (°)			Horizontal viewing angle (°)		
	a	b	C	d	e	f	ϕ1	ϕ2	ϕ3	$\lvert 90° – \xi 1\rvert$	$\lvert 90° – \xi 2\rvert$	$\lvert 90° – \xi 3\rvert$
	Z_3	$Z_{2–3}$ $Z_{3–4}$	Z_2 Z_4	$Z_{1–2}$ $Z_{4–5}$	Z_1 Z_5	Z_1 Z_5	Z_3	$Z_{2–4}$	$Z_{1–5}$	Z_3	Z_2 Z_4	Z_1 Z_5
400	500	515	486	487	447	439	27	83	143	0	7	12
600	500	515	509	533	535	565	27	81	132	0	4	8
1200	500	515	533	578	621	684	27	77	118	0	15	26
Infinite (Flat)	500	515	556	620	699	789	27	72	101	0	26	44

(a) Side View



(b) Top view

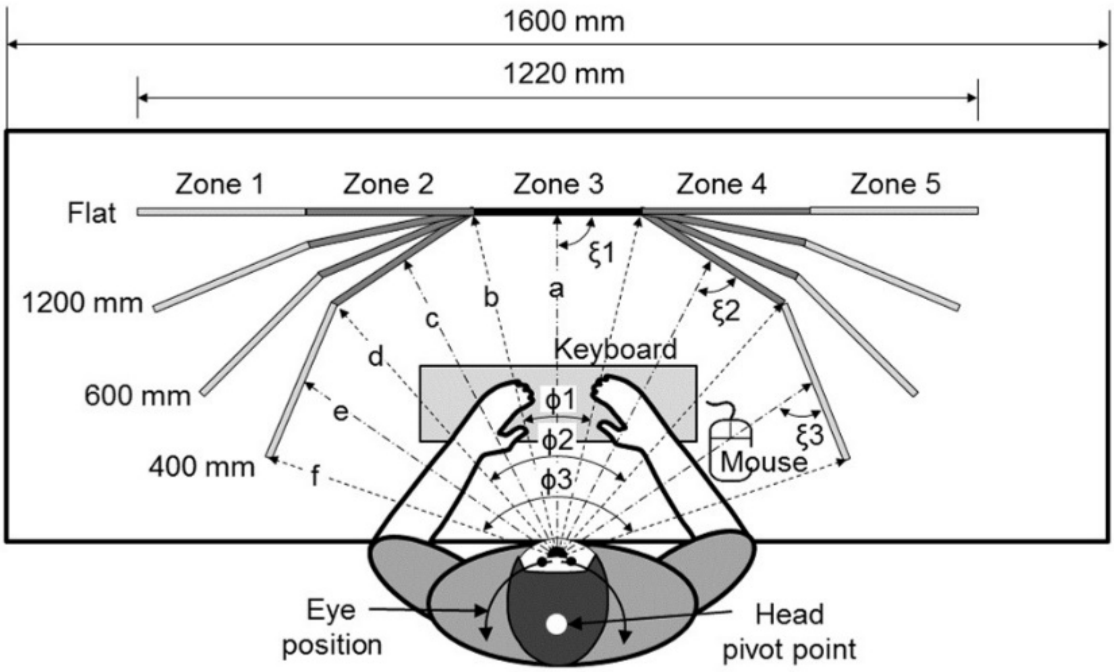


Figure 3.1 Experimental setting (a, b, c, d, e, f = horizontal viewing distance; ϕ = horizontal field of view; |90°– ξ| = horizontal viewing angle), (a) side view, (b) top view

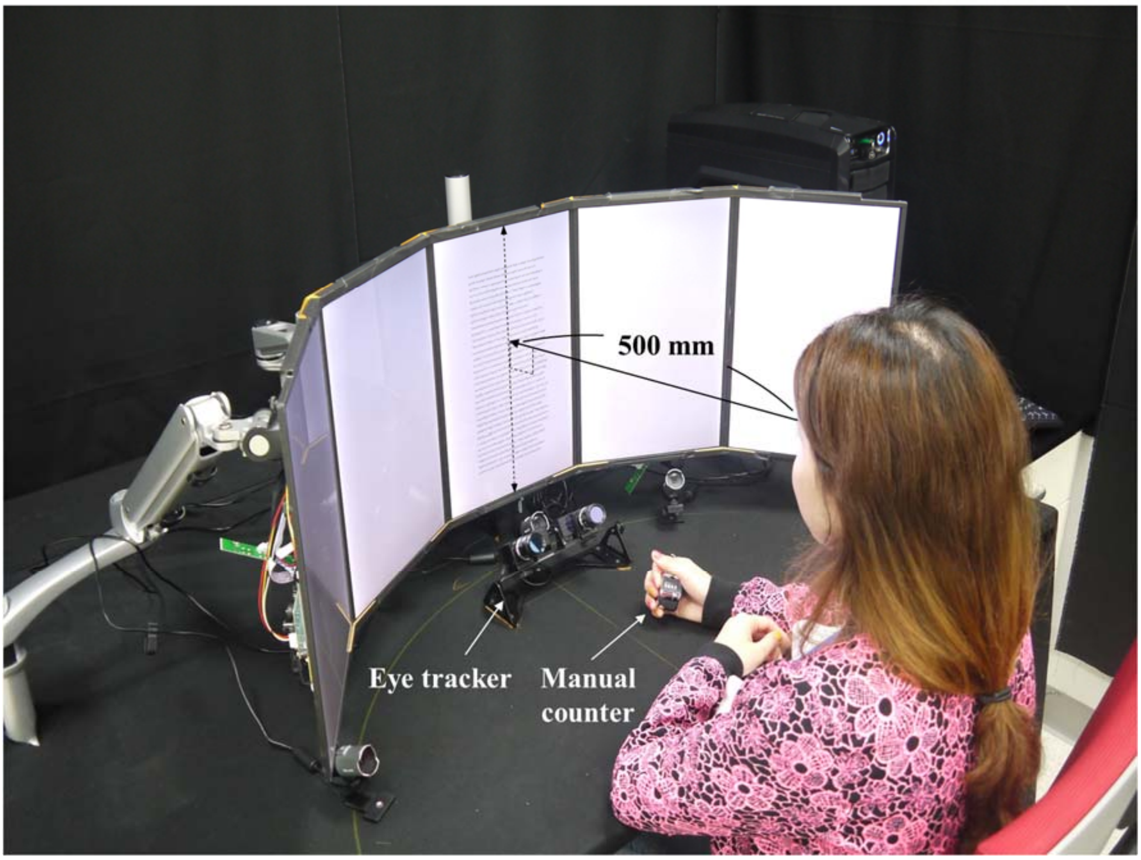


Figure 3.2 Experimental environment

The presentation order of the display curvatures was determined using a 4 × 4 Latin square. Different pseudo-texts were used for each display zone as well as for each curvature setting. The visual search task was a modified version of the task described in the ISO standard (2008b). Each pseudo-text was composed of a total of 3,599 alphanumeric characters (capital and non-capital letters, numerals, and spaces). The target letter "A" accounted for 2%–3% of a pseudo-text and each text line included up to 60 letters. Spaces occupied around 15% of a pseudo-text and were not placed at the beginning or end of a text line. The font used was 11-pt Microsoft Sans Serif TM with single-line spacing (Figure 3.3).

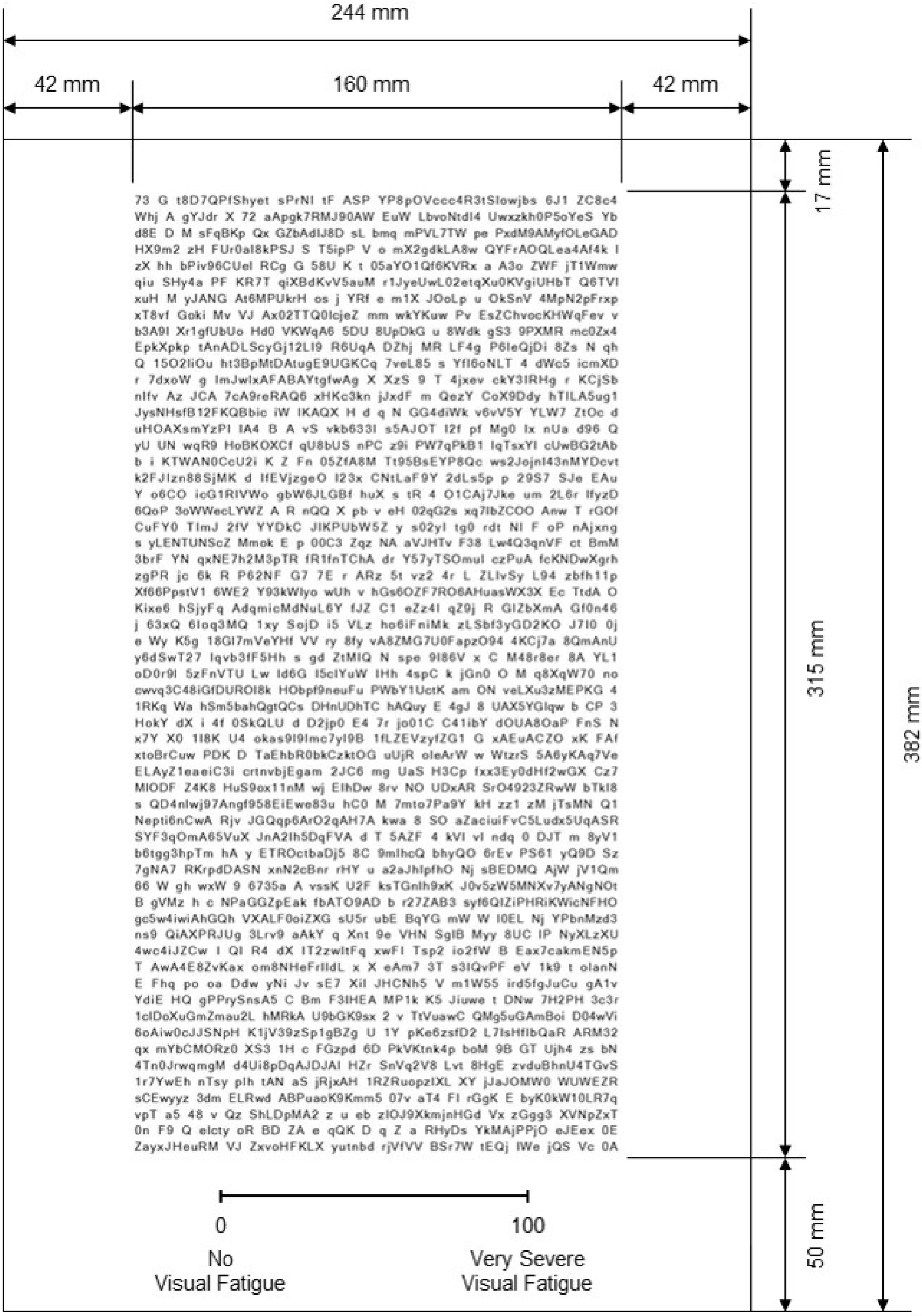


Figure 3.3 Pseudo-text for 3-min visual search task (top) and rating scale for subjective visual fatigue (bottom)

The experimental procedure involved the following steps. (1) The information on the participant's characteristics (e.g., gender and age) was collected, and visual acuity and color blindness tests were conducted. (2) The experimental methods were verbally explained to the participant, and a 30-min training session on the visual search task, subjective rating, and CFF measure was conducted. The participant was instructed to keep both speed and accuracy in mind during the visual search task. (3) The experimental condition was set to a particular display curvature during a 10-min break (or longer if requested). (4) The baseline CFF value and ECQ score were measured after the participant watched a nature scene on the flat monitor located behind him/her for 1 min. (5) During a 3-min visual search task in a particular display zone, the participant counted the occurrences of "A" in the pseudo-text. After the 3-min visual task, the last letter read was marked, and the perceived visual discomfort was rated on a visual analogue scale (VAS) provided below the pseudo-text. The space bar was pressed to move on to the next display zone. (6) After two sets of five visual search tasks (2 x 5 zones) were completed for a particular curvature, the CFF values and ECQ scores were measured again. Steps (3)–(6) were repeated for the next curvature setting (Figure 3.4).

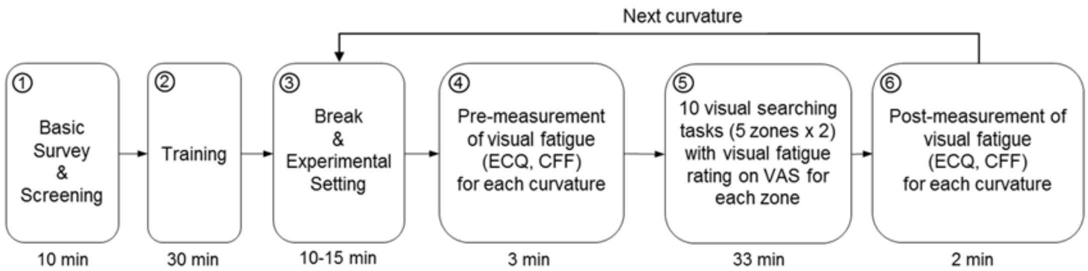


Figure 3.4 Experimental procedure

3.2.3. Data collection and processing

Legibility was assessed in terms of letter searching error and speed. Perceived visual fatigue was reported for each display zone on a 100-mm VAS and each curvature setting on the ECQ. In addition, physiological visual fatigue (CFF) was measured for each curvature setting. About legibility, the participant pressed the button on a manual counter (KW-triO, Taiwan) each time a target letter was found and marked the last letter read using the computer mouse. The VAS for perceived visual fatigue had two descriptors at the ends of a 100-mm horizontal line (0: No visual fatigue, 100: Very severe visual fatigue). The ECQ scores and CFF values were measured before and after two sets of five visual tasks for each curvature setting. A modified version of ECQ was used; it comprised a total of nine items, including an additional item for eye dryness. Each item was rated on a 7-point scale (0: not at all, 1: barely, 2: slightly, 3: somewhat, 4: moderately, 5: considerably, and 6: very much). The Flicker Fusion System (12021A, Lafayette Instrument, US) was used to measure the CFF values. A raw CFF (Hz) value was defined as the mean of a fusion value obtained by increasing a 35-Hz light by 1 Hz and a flicker value obtained by decreasing a 55-Hz light by 1 Hz.

3.2.4. Dependent measures

Five dependent variables were employed. The letter searching error and letter searching speed were measured to account for legibility. The letter searching error (%) was calculated as the ratio of the difference between the number of reported occurrences of "A" and the number (T_o) of actual occurrences of "A" in the text area read during a 3-min visual search task, to T_o. The letter searching speed (letters/s) was the total number of letters including spaces read by the participant per second. A VAS was used to analyze the effects of display zone and task duration on visual fatigue, while the ECQ score and CFF value were used to assess visual fatigue due to display curvature. The ECQ score (%) was the ratio of the sum of the scores of the nine items mentioned above to the maximum value (54), and the CFF value was the mean of three repeated measurements (Kawashima et al., 2013). The CFF value decreases with increasing visual fatigue (Chi and Lin, 1998).

3.2.5. Statistical analysis

First, the internal consistency between the ECQ items and the similarity between the participants in terms of the initial ECQ scores and CFF values were checked using Cronbach's α and the intraclass correlation coefficient (ICC), respectively. Second, a within-subject three-way analysis of variance (ANOVA) was used to examine the effects of display curvature (4 levels), display zone (Z_1–Z_5; 5 levels), and task duration (2 levels; 15 min each) on the letter searching error, letter searching speed, and subjective visual fatigue (VAS score). When the effect of display zone was significant, four linear contrasts, $C1 = (Z_1 + Z_5)/2 – Z_3$, $C2 = (Z_2 + Z_4)/2 – Z_3$, $C3 = (Z_1 + Z_5)/2 – (Z_2 + Z_4)/2$, and $C4 = (Z_1 + Z_2 + Z_4 + Z_5)/4 – Z_3$, were used. Third, a within-subject two-way ANOVA was used to analyze the effects of display curvature and visual tasking (2 levels; pre- and post-conditions of the whole 30-min target search task) on subjective visual fatigue (ECQ score) and physiological visual fatigue (CFF value). For the ANOVA tests, Tukey's honestly significant difference (HSD) test was used when the main or interaction effect was significant. Statistical analyses were performed using JMP™ (v12, SAS Institute Inc., NC, USA), with significance deduced when $p < .05$.

3.3. Results

Cronbach's α between the ECQ items was 0.85 (pre) and 0.83 (post), indicating internal consistency (Gouttebarge et al., 2004; Steenstra et al., 2009). The ICC values for the initial ECQ scores and CFF values (i.e., before the visual tasks) were 0.89 and 0.93, indicating that the participants were homogeneous (Gouttebarge et al., 2004; Steenstra et al., 2009) in terms of their initial ECQ scores and CFF values. The results of the two ANOVA tests, i.e., ANOVA for display curvature, display zone, and task duration and ANOVA for display curvature and visual tasking, are presented in table 3.2.

Table 3.2 p-values for effects of display curvature (DC), display zone (DZ), task duration (TD), and visual tasking (VT) on legibility and visual fatigue (p-values less than 0.05 are underlined)

Effects	Legibility		Visual Fatigue		
	Letter Searching Error	Letter Searching Speed	Subjective (VAS)	Subjective (ECQ)	Physiological (CFF)
Display Curvature (DC)	*.022*	*.0001*	*.039*	*.61*	*.32*
Display Zone (DZ)	*.028*	*<.0001*	*<.0001*		
Task Duration (TD)	*.080*	*.063*	*<.0001*		
DC × DZ	*.021*	*<.0001*	*.009*		
DC × TD	*.70*	*.13*	*.35*		
DZ × TD	*.49*	*.073*	*.58*		
DC × DZ × TD	*.55*	*.59*	*.60*		
Visual tasking (VT)				*<.0001*	*.02*
DC × VT				*.28*	*.27*

3.3.1. Visual searching task performance

3.3.1.1. Letter searching error

For the letter searching error (%), the interaction effect of the display curvature × display zone was significant (Table 3.2 and Figure 3.5). The leftmost display zone (Z_1) of the flat display setting showed the highest letter searching error and was grouped differently from all the other settings, except for the rightmost ones (Z_5) of the 400 R and flat settings. The effect of display curvature was significant. The 1200 R curvature setting was grouped differently from the flat setting, with a mean (SD) letter searching error of 9.8 (7.0) for the former vs. 12.2 (9.8) for the latter. The effect of display zone was also significant, and Z_1 and Z_3 were grouped differently, with a mean (SD) letter searching error of 11.7 (9.1) for Z_1 vs. 9.9 (6.9) for Z_3. Three contrasts (C1, C3, and C4) were significant ($p \leq .03$), with the mean letter searching error of $(Z_1+Z_5)/2$ being higher than those of $(Z_2+Z_4)/2$ and Z_3, and the mean letter searching error of $(Z_1+Z_2+Z_4+Z_5)/4$ being higher than that of Z_3. Further, the mean (SD) letter searching error was 9.9 (6.9), 10.4 (6.5), 11.5 (7.6), and 10.9 (6.5) for Z_3, $(Z_2+Z_4)/2$, $(Z_1+Z_5)/2$, and $(Z_1+ Z_2+Z_4+Z_5)/4$, respectively.

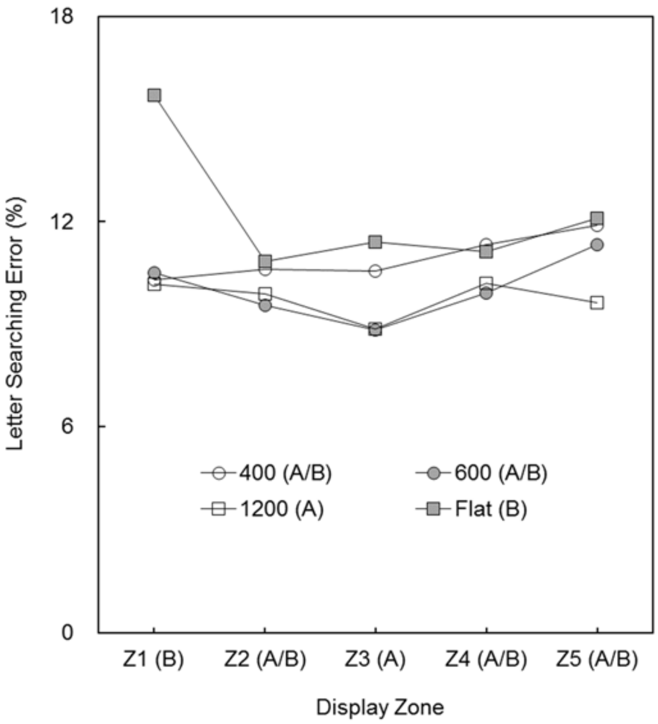


Figure 3.5 Effects of display curvature and display zone on letter searching error (Z denotes display zone, where Z_1 is the leftmost zone, Z_3 is the center zone, and Z_5 is the rightmost zone; Tukey's HSD grouping is indicated in parentheses; SD range: 4.7–10.1)

3.3.1.2. Letter searching speed

For the letter searching speed (letters/s), the interaction effect of display curvature × display zone was significant (Table 3.2 and Figure 3.6). Z_1 in the flat setting showed the lowest speed, and Z_1 and Z_5 in the flat setting were grouped differently from all the other settings. The effect of display curvature was significant with the 400 R and 600 R settings grouped differently from the other settings. The mean (SD) letter searching speed was 12.6 (2.6), 12.6 (2.4), 12.0 (2.5), and 11.8 (2.9) for the 400 R, 600 R, 1200 R, and flat settings, respectively. The effect of display zone was significant. Z_1 and Z_5 were grouped differently from Z_2 and Z_3, with the mean (SD) letter searching speed being 11.9 (2.6), 12.0 (2.7), 12.4 (2.6), and 12.6 (2.7) for Z_1, Z_5, Z_2, and Z_3, respectively. Three contrasts (C1, C3, and C4) were significant ($p < .0001$), with the mean letter searching speeds of Z_3, $(Z_2+Z_4)/2$, and Z3 being higher than those of $(Z_1+Z_5)/2$, (Z1+Z5)/2, and $(Z_1+Z_2+Z_4+Z_5)/4$, respectively. Further, the mean (SD) letter searching speed was 12.6 (2.7), 12.4 (2.5), 12.0 (2.5), and 12.2 (2.4) for Z_3, $(Z_2+Z_4)/2$, (Z1+Z5)/2, and $(Z_1+Z_2+Z_4+Z_5)/4$, respectively.

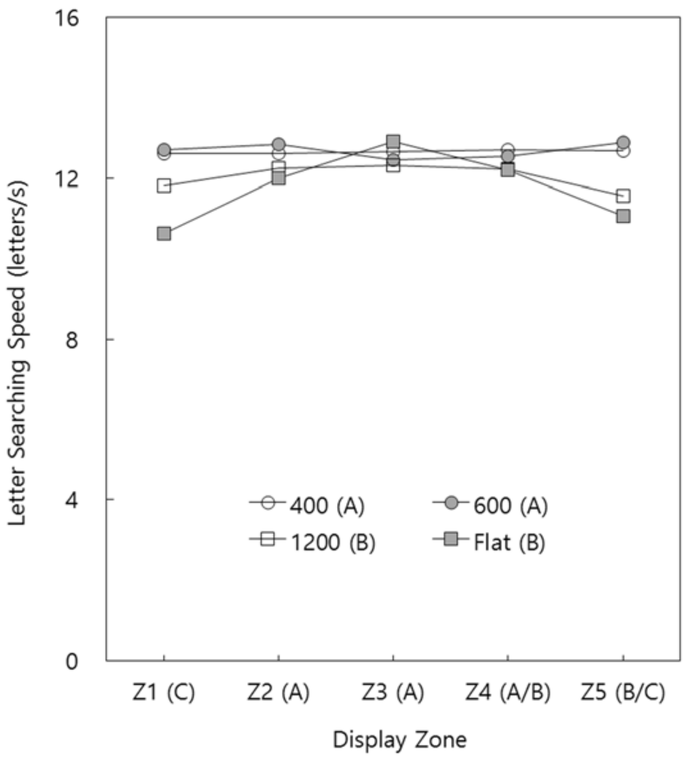


Figure 3.6 Effects of display curvature and display zone on letter searching speed (Z denotes display zone, where Z_1 is the leftmost zone, Z_3 is the center zone, and Z_5 is the rightmost zone; Tukey's HSD grouping is indicated in parentheses; SD range: 2.1–3.0)

3.3.2. Visual fatigue

3.3.2.1. Subjective visual fatigue (VAS)

For the visual fatigue reported on the VAS, the interaction effect of display curvature × display zone was significant (Table 3.2 and Figure 3.7). Z_1 in the flat setting showed the highest visual fatigue and was grouped differently from the other settings except for Z_5 in the flat setting. The effect of display curvature was significant. The 600 R and flat settings were grouped differently, with a mean (SD) VAS score of 42.6 (22.6) for the former vs. 49.1 (24.0) for the latter. The effect of display zone was also significant. Z_3 was grouped differently from Z_1 and Z_5, with a mean (SD) VAS score of 40.6 (23.9), 50.0 (23.4), and 47.0 (21.6) for Z_3, Z_1, and Z_5, respectively. All four contrasts (C1, C2, C3, and C4) were significant ($p \leq .009$), with the mean VAS scores of $(Z_1+Z_5)/2$, $(Z_2+Z_4)/2$, $(Z_1+Z_5)/2$, and $(Z_1+Z_2+Z_4+Z_5)/4$ being higher than those of Z_3, Z_3, $(Z_2+Z_4)/2$, and Z_3, respectively. Further, the mean (SD) VAS score was 40.6 (23.9), 44.0 (21.8), 48.5 (21.2), and 46.2 (20.6) for Z_3, $(Z_2+Z_4)/2$, $(Z_1+Z_5)/2$, and $(Z_1+Z_2+Z_4+Z_5)/4$, respectively. The effect of task duration was significant, with the mean (SD) VAS score being 40.7 (21.6) for the first set vs. 49.5 (23.9) for the second set.

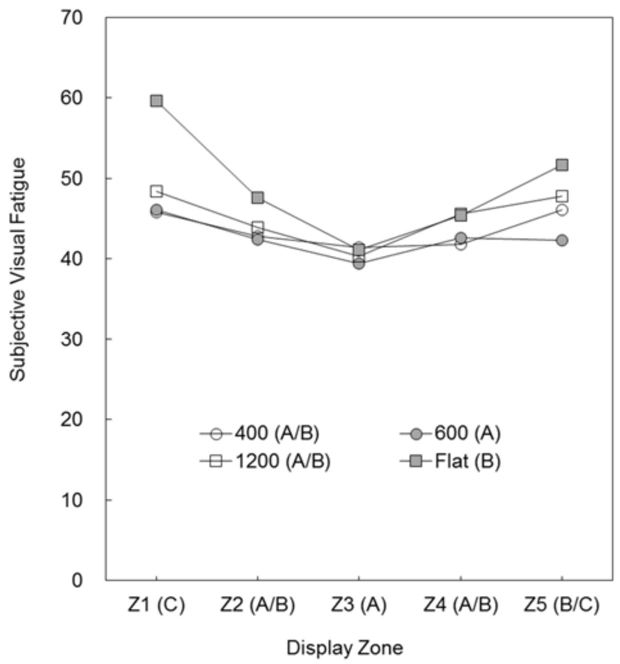


Figure 3.7 Effects of display curvature and display zone on subjective visual fatigue after two sets of visual tasks (0 – no visual fatigue, 100 – very severe visual fatigue) (Z denotes display zone, where Z_1 is the leftmost zone, Z_3 is the centre zone, and Z_5 is the rightmost zone; Tukey's HSD grouping is indicated in parentheses; SD range: 2.1–3.0)

3.3.2.2. Subjective (ECQ) and psychophysiological (CFF) visual fatigue

Based on the ECQ scores measured before and after the two sets of five visual search tasks in each curvature setting, the effect of visual tasking was significant, with the mean (SD) ECQ score increasing from 11.6 (9.4) to 23.4 (12.2) (Table 3.2 and Figure 3.8). Similarly, based on the CFF values, the effect of visual tasking was significant, with the mean (SD) CFF value decreasing from 41.6 (1.4) to 41.3 (1.4) (Figure 3.8).

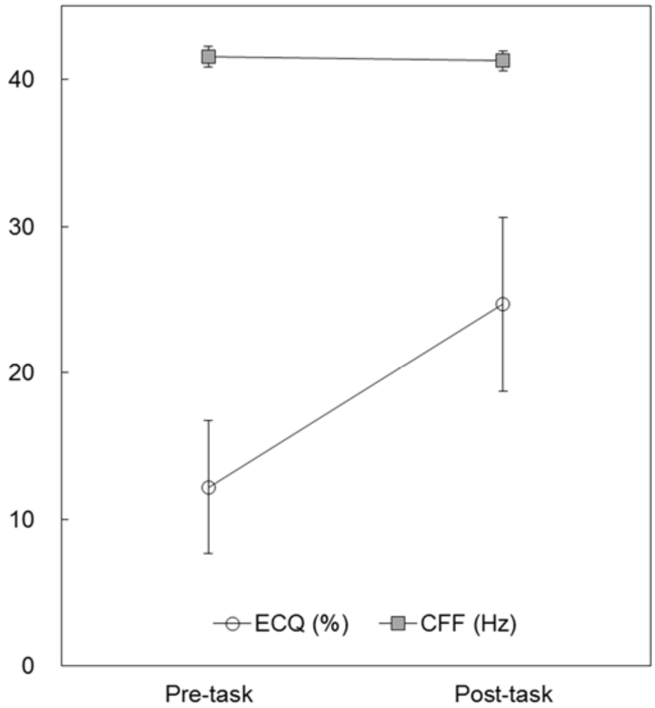


Figure 3.8 ECQ scores and CFF values of pre- and post-tasks (error bars indicate SDs)

3.4. Discussion

This study examined the main and interaction effects of display curvature, display zone, task duration, and visual tasking on legibility and visual fatigue during visual search tasks on a 50" multi-monitor. The similarities and differences between the results of this study and previous studies are discussed below, and further interpretation is provided, where appropriate, in terms of horizontal viewing distance, the field of view, viewing angle, anisotropy, ocular movements (e.g., accommodation and vergence), and horopter.

3.4.1. Visual searching task performance

3.4.1.1. Interaction effects

Legibility decreased when texts appeared on more distant display zones, and such a trend was more prominent with more planar curvature. Specifically, the letter searching errors were similar across display zones at curvature settings of 400 R, 600 R, and 1200 R, while in the flat setting, the letter searching error of Z_1 was 37.4% higher than that of Z_3. Likewise, the letter searching speeds were similar across display zones at curvature settings of 400 R and 600 R. However, for Z_1 and Z_5 in the 1200 R setting, the letter searching speed decreased by 8.5% and 10.3%, respectively, compared to that for Z_3 in the flat setting. Relative to the letter searching speed for Z_3 in the flat setting, the letter searching speeds for Z_1, Z_2, and Z_5 in the flat setting decreased by 17.6%, 7.0%, and 14.2%, respectively. Across display curvatures, the letter searching error increased and the letter searching speed decreased as the display zones became more distant from Z_3. This result is attributable to the viewing angle. Among the various display factors, the viewing angle heavily influences legibility in terms of error (Bezerianos and Isenberg, 2012; Wigdor et al., 2007). As the viewing angle increases, the visual stimuli become distorted (Cai et al., 2013) and anisotropy increases (Oetjen and Ziefle, 2009), resulting in degraded legibility. The anisotropy, which is greater than or equal to 20% of the difference in luminance with the change in the viewing angle (ISO, 2008), negatively affects the visual discrimination speed (Gröger et al., 2005; Gröger et al., 2003; Hollands et al., 2001; Hollands et al., 2002; Oetjen and Ziefle, 2004, 2007, 2009; Oetjen et al., 2005; Ziefle et al., 2003).

3.4.1.2. Curvature effects

Overall, the three curved settings showed better legibility than the flat setting. The letter searching error was the lowest in the 1200 R setting, and the letter searching speed was the highest in the 600 R setting. More specifically, the mean letter searching error in the 1200 R setting was 20.3% lower than that in the flat setting. The mean letter searching speeds in the 400 R and 600 R settings were 7.5% and 7.8% higher than that in the flat setting, respectively.

Curvature radii greater than the 500 mm viewing distance (i.e., 600 R and 1200 R) had a positive effect on the visual search task. If the radius of curvature is smaller than the viewing distance (i.e., the 400 R setting), the positive effect of curvature is reduced owing to image distortion. Na, Jeong, and Suk (2015) found that image distortion was perceived when the radius of curvature was smaller than a viewing distance of 600 mm, regardless of the display size (both 23" and 27").

In addition, they found that the appropriate curvature radius for reading (in terms of preference and visual comfort) on a 23" curved display was 633 R at a viewing distance of 600 mm, and it increased with display size (600–700 mm for 23" display and 700–800 mm for 27" display). Based on these findings, the ergonomic curvature radius for a 50" display setting at a viewing distance of 500 mm is likely to be greater than 500 R.

Similarly, some previous studies have shown that curved displays provide better visual task performance than flat displays. (Na, Jeong, and Suk, 2015) showed that the Korean text reading speed on a 23" monitor was faster on a curved display than on a flat display. Using a 5.8" (13 cm × 7 cm) plastic mock-up display, Häkkinen et al. (2008) found that the reading experience (i.e., legibility) was better on a concave display set parallel to the text reading direction. Czerwinski et al. (2003) and Robertson et al. (2005) demonstrated that computer tasks were performed faster with a 42" curved display than with a 15" flat display, and Kang and Stasko (2008) showed that information searching speeds were faster with a dual-monitor (2 × 17") setting having an included angle of 160° ($r \approx 973$ mm) than with a single 17" flat display. However, in these three studies, display size and curvature were confounded.

In contrast, the non-significant effect of display curvature on legibility has been reported (Lin et al., 2008; Lin et al., 2009; Lin et al., 2008; Wang et al., 2012; Wang et al., 2007), or 'decrease' in visual processing speed has been reported under convex ($r = 50$ mm) display settings (Mustonen et al., 2015). In these studies, printing paper was used as the display (A4-size paper, 4.5"–14"), compared to an actual 50" multi-monitor setting used in this study. In addition, there were differences in the direction and size of the display curvature (±60 R to ±100 R vs. 400–1200 R concave curvatures used in this study). Furthermore, it is necessary to use a sufficient curvature range in order to detect curvature effects, if any, while simultaneously avoiding ceiling/floor effects (Martin, 2007).

3.4.1.3. Display zone effects

Legibility deteriorated with more distant display zones. The letter searching errors for Z_1, $(Z_1 + Z_5)/2$, and $(Z_1 + Z_2 + Z_4 + Z_5)/4$ were 17.6%, 15.5%, and 10.3% higher than those for Z_3, respectively. Further, the letter searching error for $(Z_1 + Z_5)/2$ was 9.8% higher than that for $(Z_2 + Z_4)/2$. In addition, the letter searching speeds for Z_1, Z_5, $(Z_1 + Z_5)/2$, and $(Z_1 + Z_2 + Z_4 + Z_5)/4$ were 5.1%, 4.2%, 4.7%, and 3.1% lower than those for Z_3, respectively. Moreover, the letter searching speed for $(Z_1 + Z_5)/2$ was 3.2% lower than that for $(Z_2 + Z_4)/2$. Such display zone effects on legibility can be explained by image distortion and anisotropy (Oetjen and Ziefle, 2009) with increased viewing distance.

3.4.2. Visual fatigue

3.4.2.1. Subjective visual fatigue (VAS)

a. Interaction effects

Consistent with the legibility results, subjective visual fatigue (reported on the VAS) was degraded as the display zone became more distant from Z_3, and was further exacerbated as the display curvature became closer to the flat setting. The VAS scores were similar across all Zs in the 400 R, 600 R, and 1200 R settings, and Z_2, Z_3, and Z_4 in the flat setting. However, those for Z_1 and Z_5 in the flat setting increased by 45.1% and 25.8% compared to Z_3. Display zones associated with high visual fatigue also showed low legibility (i.e., Z_1 in the 1200 R setting and Z_1 and Z_5 in the flat setting).

Increased visual fatigue with more planar display curvatures and more distant display zones can be partly attributed to an inappropriate viewing angle. The horizontal viewing angle and viewing distance of each display zone varied with the display curvature. The ranges of the viewing angle and viewing distance increased when the display curvature was either more curved or more planar than 600 R or when the display zone was more distant. Among all the settings, Z_1 and Z_5 in the flat setting were the worst for visual tasks. Visual fatigue can result either from prolonged near-viewing settings, where the eyes are maintained at similar focal distances for a long time, or from the repetition of identical eye movements (Boyce, 2014). Visual tasks under such conditions can lead to the excessive exertion of the visual system. The resultant stress and physiological strain can induce visual fatigue and degrade visual system performance (Lambooij et al., 2009). Continuous visual fatigue provokes asthenopic, ocular-surface-related, visual, and extraocular symptoms (Blehm et al., 2005), and degrades visual task performance

b. Curvature effects

Curved displays provide more uniform viewing angles and viewing distances across the display surface than flat displays, which can be both advantageous and disadvantageous from the visual fatigue perspective. Degraded legibility due to image and text distortion (Lee and Chung, 2012) and prolonged accommodative responses (contracting and relaxing movements of ocular muscles) (Hsu and Wang, 2013) can both induce visual fatigue. In this regard, curved displays are advantageous. On the other hand, prolonged VDT tasks at similar focal distances can also trigger visual fatigue (Company, 2009); curved displays are disadvantageous in this regard, especially when the display curvature is equal to the viewing distance. This study showed that visual fatigue was perceived most strongly in the flat setting, indicating a curved setting was advantageous overall.

c. Display zone and task duration effects

Regardless of curvature, visual fatigue (reported on the VAS) increased with more distant display zones, and legibility and visual fatigue were both exacerbated at the most distant zones. The VAS scores for Z_1, Z_4, $(Z_1 + Z_5)/2$, $(Z_2 + Z_4)/2$, and $(Z_1 + Z_2 + Z_4 + Z_5)/4$ were 23.1%, 15.7%, 19.4%, 8.5%, and 8.5% higher than those of Z_3, respectively. Further, the VAS score for $(Z_1 + Z_5)/2$ was 10.1% higher than that for $(Z_2 + Z_4)/2$. Subjective visual fatigue (VAS) increased with task duration as well, with a 21.6% increase during the second set.

3.4.2.2. Subjective (ECQ) and psychophysiological (CFF) visual fatigue

a. Curvature and visual tasking effects

In this study, subjective visual fatigue (reported on ECQ) increased by 102.1% and physiological visual fatigue (measured in CFF) increased (0.3-Hz decrease) after the 30-min visual task. Previous studies on visual fatigue have reported a decrease of 0.54–3.1 Hz in CFF values (table 3.3).

The CFF accounts for mental stress and mental fatigue. Baschera and Grandjean (1977), as cited in Grandjean and Kroemer (1997), reported that the CFF values decreased by 1–2 Hz under high or low (overload/underload) mental stress conditions. Similarly, Oshima (1979), as cited in Mitsuhashi (1996), regarded a 5% decrease in CFF values as the onset of mental fatigue. In the current study, legibility performance was better in the curved settings than in the flat setting. Relatively poor performance during the visual search task in the flat setting (primarily due to viewing angle, anisotropy, and/or distorted image), if perceived, could make the participants mentally stressed, thus resulting in lower CFF values. Therefore, it is necessary to measure mental stress, cognitive workload, and/or mental fatigue in addition to visual fatigue in order to explain the changes in the CFF values more clearly.

Table 3.3 Visual task types, task duration, and CFF changes

Study	Task	Task duration (min)	Decrease in CFF (Hz; Pre-/Post-task)
Lin (2015)	Text entry	4–10	up to 1.85
Benedetto et al. (2013)	Reading	73	0.54–0.95
Chang et al. (2013)	Reading	17–20	2.25–3.10
Hsu and Wang (2013)	Gaming	120	2.1 in total 1.2 during 0–10 min 1.1 during 50–60 min
Lin et al. (2013)	Searching	5–7	1.26–1.57
Kang et al. (2009)	Reading	51–54	1.59–2.52
Lin et al. (2008)	Searching	10–12	1.37–1.76
Lin et al. (2008b)	Tracking	20, 60	0.4(41.1/40.7)–2.0(41.6/39.6)
Iwasaki et al. (1989)	Calculating	60	2.0 after 15 min (in red light); 1.0 after 30 min (in green and yellow lights)
Saito et al. (1994)	Data entry	240	1.3 (36.6/35.3)

3.4.3. Further discussion

3.4.3.1. Horizontal viewing distance

In this study, the viewing distance or depth changed according to the display curvature and display zone. Accommodative responses to changes in the focal distance are categorized into vergence (convergent or divergent) and accommodation (Campbell and Westheimer, 1960; Rashbass and Westheimer, 1961). Prior to their activation, vergence and accommodation have a latency period of 0.16–0.18 s (Mustonen et al., 2015) and a 0.3–1 s (Campbell and Westheimer, 1960), respectively. Such latencies in the visual system could affect the letter searching speed. In addition, visual fatigue is expected to increase when visual tasks are performed continuously under poor legibility conditions, as the stress associated with accommodative responses increases in such conditions. In this study, the horizontal viewing distance for each display zone varied with the display curvature. The smallest variability occurred in Z_3 (15 mm), while the largest variability occurred in both Z_1 and Z_5 (169 mm). In addition, the horizontal viewing distance increased with the curvature radius (from 61 mm in the 400 R setting, to 65 mm, 184 mm, and 289 mm in the flat setting).

3.4.3.2. Horopter and comfortable viewing distance

In this study, curved displays were found to outperform flat displays in terms of legibility and visual fatigue, which can be attributed to the empirical horopter line (Lombard et al., 2009). Horopter is "the locus of points in space which project images onto corresponding points in each retina" [(Howard and Rogers, 1995): p. 48] Objects that form single-vision images on the retina without visual accommodation lie on a more planar line, i.e., the empirical horopter, than a geometrically defined curve, i.e., the theoretical horopter (Ogle, 1950; Shipley and Rawlings, 1970). Visual stimuli in curved settings are relatively closer to the empirical horopter than those in the flat setting, unless the curvature is excessive. The more planar curvatures (i.e., 600 R and 1200 R) used in this study are likely to close to the empirical horopter line, while the 400 R curvature appears to be excessive (based on poor legibility and visual fatigue).

Comfortable viewing distance is another important factor in visual tasks. The range of comfortable viewing distances for 500mm viewing distance in light of binocular disparity is 440–580 mm (Lombard et al., 2009), while that of ergonomically recommended viewing distances for VDT task is much wider, 350–1000 mm (Anshel, 2005; Jaschinski et al., 1996; Jaschinski et al., 1998). In the current study, the viewing distance to the centre of Z_3 in all the curvature settings was 500 mm, which was within the comfortable viewing range, while the viewing distances to the centres of Z_1 and Z_5 in the 1200 R and flat settings (621 mm and 699 mm, respectively) were outside the comfortable viewing range.

3.4.3.3. Horizontal field of view and viewing angle

In the present study, the horizontal field of view and the viewing angle of the outer zones increased when the curvature was more planar or more curved than 600 mm. The outer zones of a display with a wide horizontal field of view require excessive eye/head rotation (table 3.4), with additional trunk rotation required for a comfortable posture. Extraocular symptoms of computer vision syndrome in the head, neck, and/or back (Anshel, 2005; Sheedy, 1992b; Sheedy and Parsons, 1990) owing to improper posture could intensify in such cases (Blehm et al., 2005). A primary cause of neck and back pain is improper viewing position (Yan et al., 2008). Szeto and Sham (2008) found that visual tasks that require a horizontal field of view greater than 35° result in muscle fatigue owing to head rotation and restricted trunk rotation.

Table 3.4 Recommended horizontal field of view, range of motion, and corresponding display zone

Recommendation and range of motion	Display zone† in this study (Required field of view)
10°–20° (Easy word recognition by Hatada et al., 1980)	
≤30° (Effective visual field by Hatada et al., 1980)	· Z_3 (0°–27°; head rotation not required)
70° (Maximum eye rotation by Tilley et al., 2002)	
90° (Easy head rotation by Tilley et al., 2002)	· Z_2 and Z_4 (72°–83°; head rotation required)
120° (Maximal head rotation by Tilley et al., 2002)	
124° (Binocular horizontal vision by Tilley et al., 2002)	
160° (Maximum eye rotation + easy head rotation)	· Z_1 and Z_5 (101°–143°; head rotation required)
190° (Maximum eye rotation and head rotation)	

†Z_3: centre zone; Z_1: leftmost; Z_5: rightmost; Z_2: between Z_1 and Z_3; Z_4: between Z_3 and Z_5

When the horizontal viewing angle increases, visual task performance including legibility is degraded. Visual task performance is degraded when the viewing angle is greater than 45° (Vishwanath et al., 2005), reactions are slow when the viewing angle is greater than 55° (Larson et al., 2000), and the word reading time starts to increase at a viewing angle of 75° (Grossman et al., 2007). The horizontal viewing angles involved in this study were up to 44° (see Table 3.1). Thus, legibility degradation due to horizontal viewing angles was more severe in this study compared to the previous studies. Such a discrepancy could be partly attributed to simultaneous changes in the viewing angle and viewing distance in this study (vs. tilted images used on a display in the study by (Larson et al., 2000)) as well as the additional eye and neck movements required in the outer zones with a larger horizontal field of view.

3.4.4. Limitations

The current study has some limitations in terms of the experimental conditions. This study used a multi-monitor setting instead of curved monitors to realize diverse display curvatures. As particular display curvatures were realized by arraying five flat display panels, each display zone was flat, resulting in irregular luminance across each screen. In addition, to generalize the results of this study, it is necessary to consider other visual tasks (e.g., word processing and multitasking using multiple display zones) and typical monitor user behaviors (e.g., performing primary tasks at the centre zone and secondary tasks at the outer zones, with non-constant viewing distances and monitor inclinations). These issues will be explored in a future study.

3.5. Conclusions

This study examined the effects of display curvature, display zone, and visual tasking on legibility and visual fatigue in the case of a 50" multi-monitor setting. The major conclusions are as follows. First, in the outer zones, legibility deteriorated and visual fatigue increased with more planar display curvatures. Second, the three curved settings provided higher legibility and lower subjective visual fatigue than the flat setting. Third, regardless of curvature, legibility improved and subjective visual fatigue decreased toward the center display zone. Accordingly, adjustment of the display viewing angle, especially for the outermost zones, could improve legibility and reduce visual fatigue. In this respect, bendable displays could be an effective solution. Fourth, among the four curvature settings considered in this study, the 600 R setting is recommended when using a 50" monitor at a horizontal viewing distance of 500 mm, in consideration of both legibility and visual fatigue. The ergonomic curvature for such a display setting is expected to lie between 600 R (inclusive) and 1200 R (exclusive).

Chapter 4. Effects of Display Curvature and Task Duration on Proofreading Task Performance, Visual Discomfort, Visual Fatigue, Mental Workload, and User Satisfaction [Study 2: 27” monitors]

4.1. Introduction

Influence of display curvature could vary with display size, visual display terminal (VDT) task type, and task environment. Since the introduction of curved display products (e.g., monitors, TVs, smartphones, and smartwatches), comparative studies between curved and flat displays have been conducted. From the viewpoint of visual ergonomics, display products should be comprehensively evaluated, considering productivity, safety, and well-being as in the case of flat display products (Toomingas, 2014). Display curvature has advantages and disadvantages depending on the type of VDT work and working environment. The productivity of curved display was evaluated in terms of visual task performance (Czerwinski et al., 2003; Häkkinen et al., 2008; Park et al., 2017), safety was assessed in terms of visual fatigue (Park et al., 2017), and well-being was investigated in terms of presence (Na, Jeong, and Suk, 2015). According to the first study, 50” curved monitors at viewing distance 500 mm provide higher legibility and lower visual fatigue than flat monitors of the same size. In the study of Na, Jeong, and Suk (2015), text reading speed in a 23” curved display (mean curvature of 633 R) at 60 cm viewing distance was faster than that in a flat display of the same size. In the study by Häkkinen, Pölönen, et al. (2008), the reading experience (i.e., legibility) in a concave display at a preferred viewing distance was better when the curvature direction of a 5.8” (13 × 7 cm) plastic mockup display coincided with the text direction. Moreover, some studies found that curved displays have a more negative effect than flat displays. According to Mustonen et al. (2015), the visual processing speed on a convex curvature (r = 50 R) display at 45cm viewing distance was degraded.

Meanwhile, some studies found that display curvature did not affect task performance. In Lin et al. (2008)’s study, there was no curvature (-100 R, flat, 100R) effect on legibility during letter-search task for mean search time range of 10.3 min ~ 11.9 min at a viewing distance of 50 cm. In Lin et al. (2009)’s study, there was no display curvature (-100 R, flat, 100 R) effect on legibility during letter-search task for mean search time range of 12.3 min ~ 13.2 min at a viewing distance of 50 cm. In Wang et al. (2012)’s study, there was no curvature (-100 R, flat, 100 R) effect on visual performance during visual acuity test within 9 s for one trial using Landolt-C gap at a viewing distance of 150 cm. In Wang et al. (2007)’s study, there was no display curvature (-100 R, flat, 100R) effect on visual task performance during searching task for 70 s using pseudo text at a viewing distance of 60 cm. However, few studies on curved display products considered these three aspects. A comprehensive evaluation of curved displays from the perspectives of three points, productivity, safety, and well-being, is required to determine display curvature.

Analyzing the duration effect of VDT tasks is important. In Korea, 47.6% of VDT workers use computers for more than 8 h a day and 36.9% use computers from 6 to 8 h daily (Kim et al., 2015). Americans use digital media (computers, mobile devices, and television) for an average of 9.7 h a day (Rosenfield, 2016). In Italy, 26% of VDT workers spend more than 8 h a day and 40% use computers from 6 to 8 h (Leccese et al., 2016). Especially, 41.7% of all responsors reported that they have regular rest time. 30.1% of them had 10-minute break per two work hours, and 14.8% of responders had 10-minute break per one hour (Kim et al., 2015). Prolonged VDT task decreased productivity, may be harmful to workers' safety regarding computer vision syndrome (CVS) (Ostrovsky et al., 2012). Some studies evaluated the change in task performance and visual fatigue according to the working time of the VDT task. In our first study, the performance of a visual search task started to decrease after 15 min. Visual fatigue occurred after a short period of 4–10 min for text entry task (Lin, 2015), while it was measured after a long time of 2 h for a data entry task (Saito et al., 1994). However, considering the actual VDT working time per a day, recent studies on curved display adopted relatively shorter task duration time, which were 12 min [watching the video (Ahn et al., 2014)], 30-min [visual search task (our first study); a combination of visual tasks (Lee and Kim, 2016); watching the video (Mun et al., 2015)], and 55-min [visual search task (Luo et al., 2016)]. Thus, it is necessary to study the appropriate break time and maximum continuous working time based on the studies of the task duration effect on work efficiency and visual safety.

In addition, to evaluate visual display, visual tasks of reading (Hwang et al., 1988; Omori et al., 2008; Sommerich et al., 2001), searching (Wang et al., 2012), watching (Kong et al., 2011), and proofreading (Buchner and Baumgartner, 2007; Buchner et al., 2009; Piepenbrock et al., 2014a; Piepenbrock et al., 2013). Proofreading is one of the typical VDT tasks as a fundamental skill for reading and writing (Chromik, 2002; Enos, 2010). Among the major daily office task categories (search, analyze, create, process, manage, and meeting), proofreading with the analysis is considered as high cognitive demand task (Kalvelage and Dorneich, 2016). Compared to the general reading task, proofreading contains subtasks such as searching the text, identifying errors (e.g., omissions, additions, and replacement), and determining how the text should be changed to eliminate those errors (Schotter et al., 2014).

VDT task performance (speed and accuracy) can be an important index to evaluate display productivity (Hall and Hanna, 2004; Oetjen and Ziefle, 2007, 2009; Ojanpää and Näsänen, 2003; Piepenbrock et al., 2014a, 2014b; Piepenbrock et al., 2013). Proofreading performance could be assessed regarding speed and accuracy. The trade-off between speed and accuracy was found in human works, and speed accuracy trade-off was measured during proofreading task (Förster et al., 2003). In previous studies of proofreading task on VDT, task instruction and error difficulty (Förster et al., 2003), display factor such as text line length, line spacing, and line number (Chan and Ng, 2012; Chan et al., 2014) had an influence on the speed-accuracy trade-off of proofreading performance.

Regarding safety, visual discomfort and visual fatigue are important evaluation factors of visual display. Both concepts have been used interchangeably in display evaluation studies, but the relationship between the two has not yet been systematically verified (Lambooij et al., 2009). Visual discomfort is caused by continuous viewing, increased demand for ocular motor systems, and reduced visibility such as image blur. Visual fatigue, on the other hand, is caused by constant contraction/relaxation of the eye muscles (Hsu and Wang, 2013), constant focal distance during VDT work, and distortion of images on displays (Lee, 2012). The curved display provided more uniform viewing distance in a horizontal direction across display screen than flat display (Mun et al., 2015), this should be beneficial regarding visual discomfort and visual fatigue because using curved displays reduce the number of contractions/relaxations of ocular muscle. On the other hand, it should be disadvantageous because users need to keep constant focal distance during the visual task. Prolonged visual discomfort and visual fatigue could induce headaches and task performance degradation (Sheedy, 1992a, 1992b; Sheedy et al., 2003).

Physiological measures, such as critical fusion frequency [(CFF; increase in visual fatigue = decreased CFF; (Bando et al., 2012; Chi and Lin, 1998; Lin and Huang, 2013; Lin et al., 2013; Lin et al., 2009)], accommodative power (Saito et al., 1994; Saito et al., 1993), pupil size and blink (increase in pupil size and blink frequency (Jaschinski et al., 1996; Kim et al., 2011; Kim et al., 2014; Miyao et al., 1989), electromyogram (EMG) of the orbicularis oculi muscle (increase in visual fatigue = increase in electromyogram; (Nahar et al., 2011)), electrooculogram obtained from the forehead to measure eye blinks (Yagi et al., 2009), visual acuity, pupil diameter, ocular speed (Chi and Lin, 1998), electromyogram (EMG) of the orbicularis oculi (Nahar et al., 2011), and brain signals (Yeh et al., 2013), have been used as objective measures.

Mental workload is another factor that is closely related to visual task performance and visual fatigue (Rocha and Debert-Ribeiro, 2004). VDT tasks induce mental loads and therefore reduce the efficiency of reading tasks (Lee et al., 2011). Appropriate mental workload enhances workers' productivity, safety, and satisfaction (Xie and Salvendy, 2000). However, high workload reduced task performance and induced subjective fatigue (Fan and Smith, 2017). VDT tasks produce mental loads and therefore reduce the efficiency of reading tasks (Lee et al., 2011). Mental workload showed a positive relationship with subjective visual fatigue (Rocha and Debert-Ribeiro, 2004). The mental workload can be measured using various subjective measurement methods. NASA task load index (NASA-TLX), which is a multi-dimensional mental workload rating that contains six subconcepts: mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart, 2006), instantaneous self-assessment (Casner and Gore, 2010), and simplified subjective workload assessment technique (Luximon and Goonetilleke, 2001) were used for measuring mental workload. CFF (CFF decreased as mental workload increased; (Lin, 2015; Luczak and Sobolewski, 2005)), and electrocardiogram (heart rate increased as workload increased; (Fallahi et al., 2016) have been used as objective measures for the mental workload.

Ocular information, which was measured by the eye tracker, applied for VDT related studies. Oculomotor behavioral changes associated with visual task performance, visual fatigue, and mental workload (Matessa, 2004; McKinley et al., 2011). In McIntire et al. (2014)'s study, when visual task performance (percent hits) during 40-min static simulated air traffic control task decreased, blink duration (blinking time) and blink frequency (blinks per minute) increased. In (Kaneko and Sakamoto, 2001)'s study, participants performed 3-min calculation task on 15" monitor at 500mm viewing distance once per hour for 6 hours, and the blink frequency and subjective visual fatigue increased together. In Van Orden et al. (2001)'s study, blink duration and blink frequency declined as mental workload increased during 2-hour visual task. The participant in an effort not to miss relevant information (Fogarty and Stern, 1989) can interpret these changes. Pupil diameter is one of the commonly used physiological measures of visual fatigue and mental workload (Chi et al., 2003). Pupil size negatively correlated with the perceived fatigue (Murata et al., 2001; Urvoy et al., 2013). Pupil diameter, which is affected by ambient illumination, the property of visual stimuli, and accommodative behaviors, increases when the workload is higher (Tsai et al., 2007).

The evaluation of curved displays should consider well-being regarding user experience and satisfaction. The improvement of worker's health and happiness is the goal of well-being (Hoffmeister et al., 2015). Higher satisfaction can increase the consumer's happy. Among various evaluation factors of quality of experience, presence, satisfaction, image quality, preference, and image distortion, etc. are representatively used to evaluate visual display products (Mun et al., 2015; Park et al., 2015). Viewers' satisfaction showed a negative relationship with induced visual fatigue during VDT task. In the study by So and Chan (2013), the eye strain increased, and satisfaction decreased during 1.5-h visual tasks on an LED display (512 mm × 256 mm). In the study by Iatsun et al. (2015), 1-hour 46" 2D and 3D video watching at a viewing distance of 70 cm induced visual discomfort and visual fatigue and reduced the user's satisfaction. Yu et al. (2016) found a negative relationship between physical features of VDT (e.g., display size, screen luminance, screen reflection, and image moving velocity) and visual fatigue.

The purpose of study II was to examine the effects of display curvature and task duration on productivity, safety, and well-being. The specific aims are as follows; 1) investigate the influence of display curvature and task duration on proofreading speed and accuracy, visual discomfort, visual fatigue, CFF, blink duration and frequency, pupil diameter (left and right), mental workload, and user satisfaction, 2) identify the speed-accuracy trade off during proofreading task, 3) determine the degree to which display curvature, task duration, distortion ratio, and their interactions affect the variability of each dependent variable, 4) verify the association between all dependent variables, 5) identify the relationship between visual discomfort and subjective visual fatigue, 6) develop prediction models for visual discomfort, subjective visual fatigue, mental workload, and user satisfaction using display and task characteristics (display curvature, task duration, distortion ratio, and their interactions), objective measures (proofreading speed, accuracy, CFF, blink duration, blink frequency, pupil diameters of left and right eye), and demographic characteristics (gender, age, visual acuity of left and right eye, and eye condition), 7) determine the degree to which composite variables composed of dependent variables affect the subjective visual fatigue and user satisfaction.

4.2. Methodology

4.2.1. Participants

Fifty college students participated in the current study. Their mean (SD) age was 22.3 (1.6). The participants included 17 males [mean (SD) age = 22.1 (1.8)] and 33 females [mean (SD) age = 22.5 (1.6)]. The inclusion criteria were as follows: having visual acuity greater than 0.8 (= 16/20 in the Snellen fractional notation) based on the Han Chun Suk test (Kee et al., 2006), not wearing a pair of glasses, and not being color blind based on the Ishihara test (Ishihara and Force, 1943; Strayer and Johnston, 2001). Twelve participants were in naked eye condition, 25 were with contact lenses, and 15 participants had undergone vision correction surgery. The mean (SD) normal or corrected-to-normal visual acuities of the participants' left and right eyes were 1.1 (0.2) and 1.1 (0.2), respectively. All participants completed informed consent procedures approved by the local IRB and were compensated for their time. The demographic characteristics are given in table 4.1.

4.2.2. Experimental setting and procedure

The windows of the experimental room were covered by blackout curtains to block external light. Two experiment desks and a height-adjustable chair were provided to accommodate stature variability. A mock-up screen being tilted 5° rearwards was located on the front desk. An eye tracker (Seeing Machines, Acton, MA, USA) was installed under the screen, and a tablet and a stylus pen were located in front of the screen (Figure 4.1). Flicker Fusion System (Model 12021A, Lafayette Instrument, US) for measuring CFF and paper type questionnaire to obtain visual comfort, subjective visual fatigue, mental workload, and user satisfaction were on the left side desk, where a chin rest was installed at the edge of the desk (Figure 4.2). Five 27" rear screens (603 mm × 346 mm; 16:9 ratio) with specific display curvatures were made. Each mockup screen was composed of a polycarbonate screen, being fixed to a steel frame with a rear screen film (Exzen, Korea). The distortion of an image projected by a beam projector was corrected using Desktop Warpalizer® (UniVisual Technologies, Sweden) before experimenting. The viewing distance was set to 600 mm referring to the range of 520 mm – 730 mm, which was recommended for VDT works (Rempel et al., 2007). The picture of the experimental setting is shown in figure 4.1.

Table 4.1 Participant characteristics

Display curvature (mm)		600R	1140R	2000R	4000R	Flat	All
# of Participants (n; male, female)		10 (2, 8)	10 (4, 6)	10 (5, 5)	10 (1, 9)	10 (5, 5)	50 (17, 33)
Mean (SD) age (years)		22.2 (1.0)	22.1 (1.9)	21.6 (1.2)	22.9 (2.0)	22.9 (1.8)	22.3 (1.6)
Mean (SD) visual acuity	Left	1.1 (0.2)	1.1 (0.3)	1.1 (0.1)	1.0 (0.1)	1.1 (0.2)	1.1 (0.2)
	Right	1.2 (0.1)	1.1 (0.2)	1.1 (0.2)	1.0 (0.2)	1.1 (0.3)	1.1 (0.2)
Dominant eye (n)	Left	3	2	4	0	2	11
	Right	7	8	6	10	8	39
Eye condition (n)	No lens & no eye surgery	1	2	3	2	3	11
	Lens	7	4	3	7	3	24
	Eye surgery	2	4	4	1	4	15
# of Participants with eye-tracking data for blink duration & frequency (n; male, female)		9 (1, 8)	9 (4, 5)	8 (4, 4)	9 (1, 8)	10 (5, 5)	45 (15, 30)
# of Participants with eye-tracking data for pupil diameter (n; male, female)		9 (1, 8)	9 (4, 5)	9 (4,5)	9 (1,8)	10 (5,5)	46 (15, 31)

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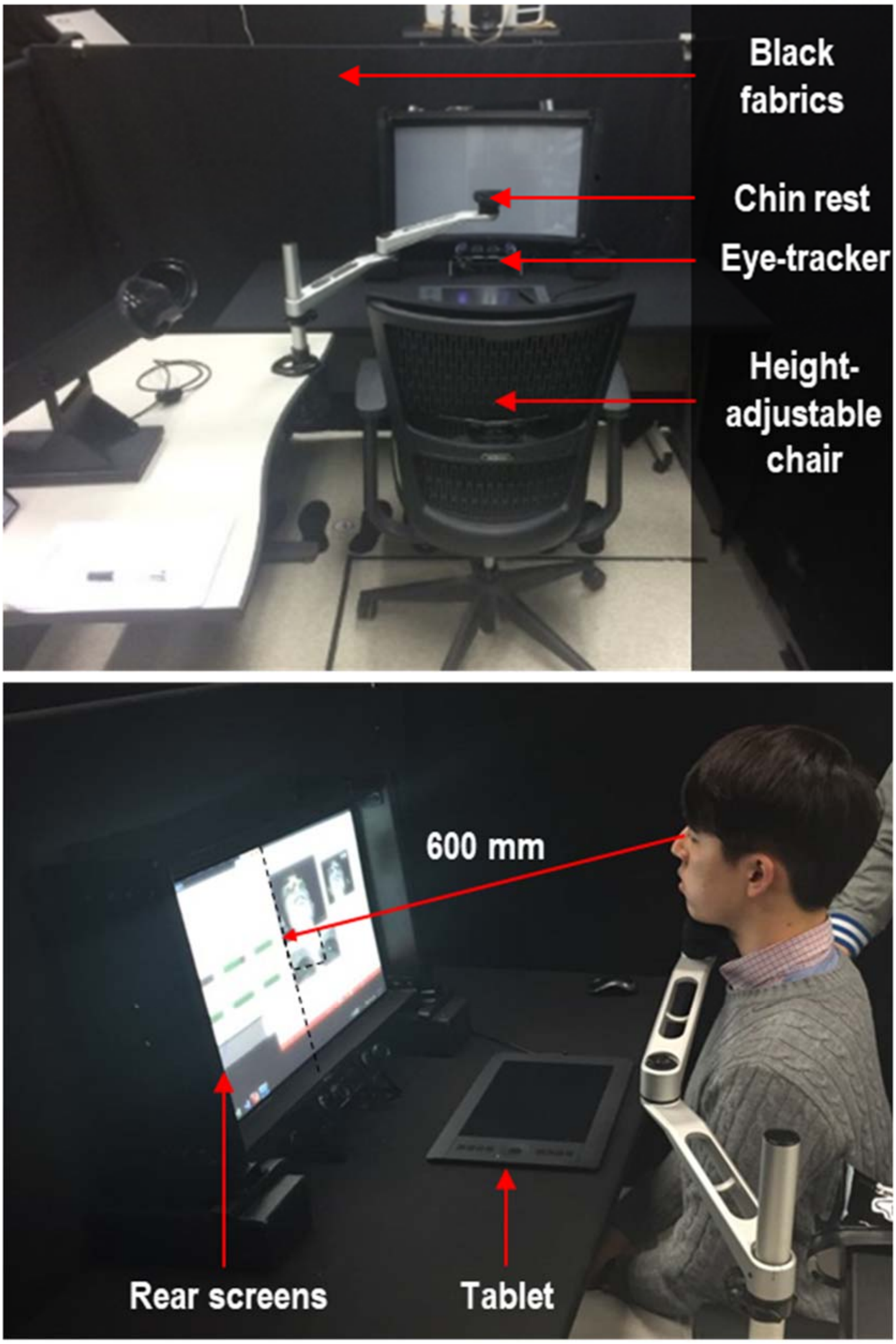

Figure 4.1 Experimental environment

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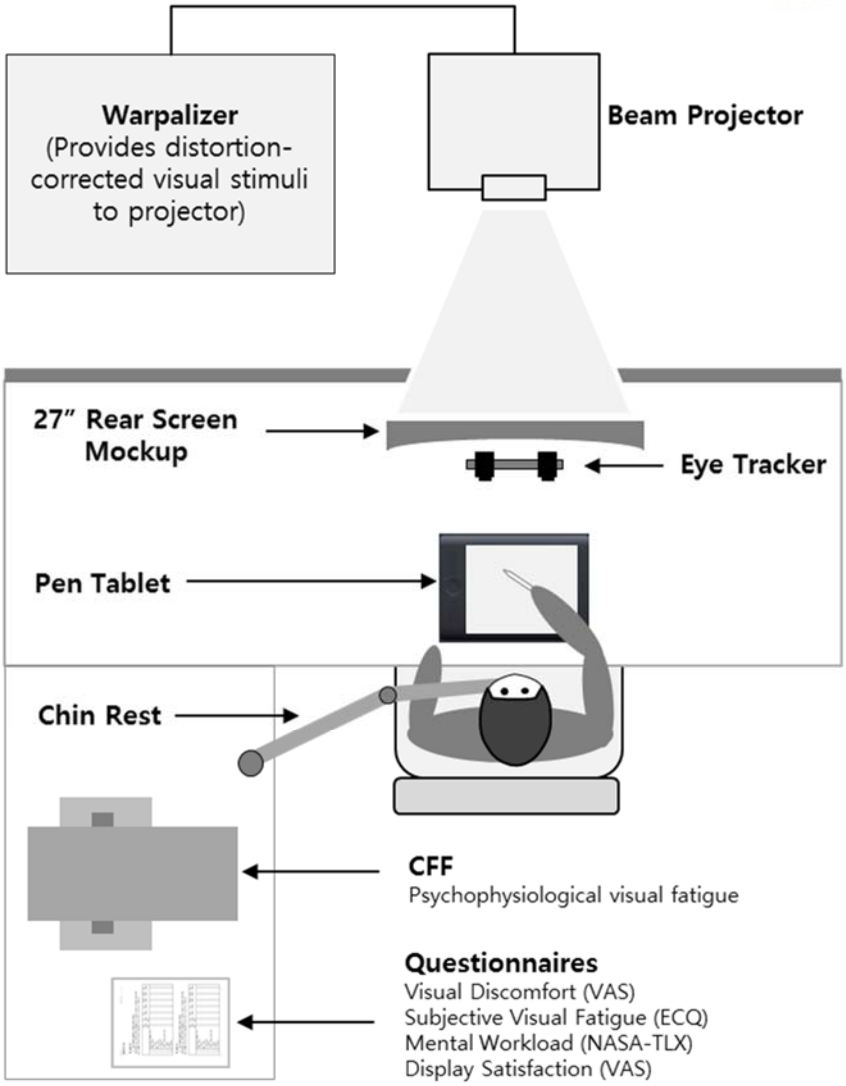

Figure 4.2 Experimental setting

Each participant performed a 15 min proofreading task on a screen with specific curvature level and repeated it four times. Experimental text for proofreading was excerpted from Naver Cast (http://navercast.naver.com/). A reference article (dead copy) without errors and another article (live copy) with errors were displayed on the left and right side of the screen. The given task was to compare the dead and live copies, find errors in the live copy, and then mark it with editing symbols using the stylus pen (Figure 4.3).

Figure 4.3 Example of reference text (left) and proofread text (right)

Fifteen errors (five types × 3 times) were in the live copy (Table 4.2). The current study used the Malgun Gothic font and double spacing. Font size was 15pt based on the study by Kong et al. (2011). Each dead and live copy consists of approximately 470 syntactic words per page, and one 60-minute experiment contained 45 pages in total. The participant was instructed to keep in mind that both speed and accuracy are equally important during the visual search task, and explained that high performers within 10% would be paid additional incentive (1000 won).

Table 4.2 Typographical error, corresponding editing symbols, and examples

Typographical errors	Editing Symbols	Examples
Extra letter		이런 전염궁병이
Missing letter		대분의 의사들이
Wrong letter		먹이가 풍징한
Wrong order		기정가 사기를
Extra spacing		전국 적으로

Participants reported visual discomfort before and after each 15-min proofreading task using a 100 mm VAS (0: 'no discomfort at all', 100: 'very uncomfortable'). Subjective visual fatigue was obtained using a modified version of ECQ of nine items, excluding an item of redness. Each item was rated on a 7-point scale (0: not at all, 1: barely, 2: slightly, 3: somewhat, 4: moderately, 5: considerably, and 6: very much). Mental workload was evaluated using NASA- TLX (Hart, 2006) which includes of six subconcepts (i.e., mental demand, physical demand, temporal demand, performance demand, effort, and frustration), and each concept was rated on an 11-point scale (0: very low, 10: very high). User satisfaction was reported using a 100 mm VAS (0: very unsatisfied' 100: very satisfied).

The experimental procedure was as follows (Figure 4.4): 1) A brief information on the study was explained, and demographic characteristics of each (i.e., name, sex, age, visual acuity, eye condition) were collected. 2) A 15-minute training session on the subjective rating and CFF measure was conducted. 3) The eye tracking system was calibrated for 10 min. 4) Each participant practiced the proofreading task on an assigned display for 15 min. 5) During the 10-minute break for the participant, the experimenter set the seat position, chin rest, and visual stimuli. 6) Before the experiment, psychophysiological visual fatigue (CFF), visual discomfort (VAS), subjective visual fatigue (ECQ), and mental workload (NASA-TLX) were measured as a baseline. 7) During the 15-minute proofreading task on a particular display curvature, eye-tracking data were simultaneously obtained. 8) After each 15-min proofreading session, psychophysiological visual

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fatigue (CFF), visual discomfort (VAS), subjective visual fatigue (ECQ), and mental workload (NASA-TLX) were measured again. 9) Steps 7) to 8) were repeated four times on the same display.

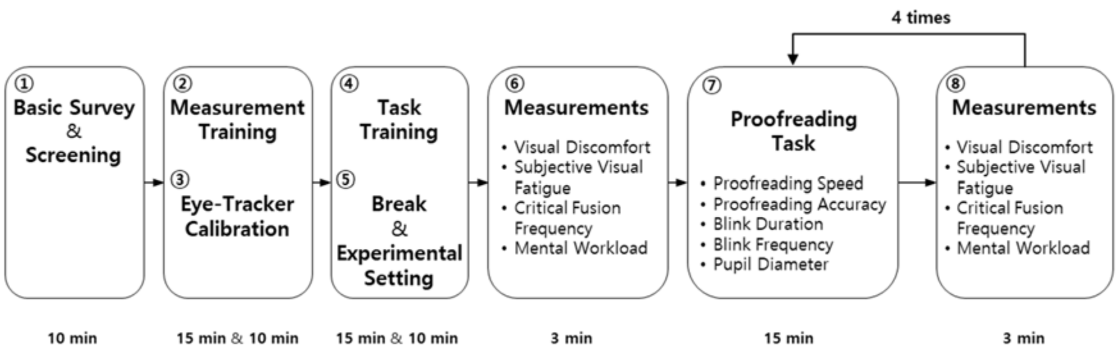

Figure 4.4 Experimental procedure for Study 2

4.2.3. Data collection and processing

The data on detecting errors during the proofreading task was saved after completing the whole task. The total number of errors (*Te*), total number of errors corrected (*Tc*), and total number of syntactic words read (*Tr*) in the text area proofread during the 15-minute task were counted. Using a wrong error symbol was calculated as an error. The CFF (Hz) value, which was used for measuring psychophysiological visual fatigue, was defined as the average of a fusion value obtained by ascending a 35 Hz light by 1 Hz and the frequency value obtained by descending a 55 Hz light by 1 Hz. Eye tracking data were used to calculate blink duration, blink frequency, pupil size at 60 Hz. The outliers in eye tracking data were removed using the Hampel filter (Pearson, 2002). Finally, data on forty-five participants was used for correlation analysis and regression analysis.

4.2.4. Independent variables

Two independent variables were involved in this study. Display curvature was a between-subjects variable with five levels: 600 R, 1140 R, 2000 R, 4000 R, and flat. The 600 R curvature level was equal to the viewing distance used in this study; the 1140 R curvature corresponded to an effective visual angle of 30° (Hatada et al., 1980); the 2000 R (XR3501, BenQ, Korea) and 4000 R (SE591C, Samsung, Korea) were the display curvatures of commercial products; the flat curvature was used as a control condition. Task duration was a within-subjects variable with five levels: 0, 15, 30, 45, and 60 min. Distortion ratio (Dr; Park et al. (2015)) was added as a predictor for regression analysis of each dependent variable. Distortion ratio was calculated as Dr = │(H-h)/H│, where, the parameters H and h denotes width of the flat and curved display.

4.2.5. Dependent variables

Eleven dependent variables were involved in this study. The proofreading speed was defined as Tr/15 min (syntactic words/min), and proofreading accuracy was defined as (1 − Tc/Te) × 100%. VAS score (0 – 100) was used to analyze the visual discomfort. The ECQ score (%) for subjective visual fatigue was calculated as (sum of 9-item scores)/54 × 100%. The CFF value for psychophysiological visual fatigue was the mean of three measurements. Blinking duration (sec) was mean blink duration for thirteen minutes, blink frequency (blinks/min) was mean number of blinks in a minute. Pupil diameters are mean pupil size (mm). The overall mental workload score calculated using the scores of weighted values of six subconcepts of NASA-TLX. VAS score (0 – 100) was used to analyze display satisfaction.

4.2.6. Statistical analysis

Mixed two-way analysis of variance (ANOVA) was used to examine the main and interaction effects of display curvature (5 levels; between-subjects) and task duration (5 levels; within-subjects) on proofreading speed and accuracy, visual discomfort, subjective visual fatigue, CFF, blink duration and frequency, pupil diameter (left and right), mental workload, and user satisfaction. Tukey's HSD (honestly significant difference) test was used when a main or interaction effect was significant. Additional two-way ANOVA was conducted on five different error types and six sub concepts of NASA-TLX. Two simple linear regression of each proofreading speed and accuracy on task duration were analyzed to examine the speed-accuracy tradeoff during proofreading task; then, the coefficient of task duration in each model was compared. For each dependent variable, a stepwise multiple linear regression analysis ($p = 0.25$ to enter, $p = 0.01$ to leave) was performed to determine the degree to which each dependent variable was affected by the display curvature, task duration, distortion ratio, and their interaction.

Pearson correlation analysis was used to analyze associations between dependent variables. Also, a segmented linear regression model was developed to examine the non-linear relationship between visual discomfort and subjective visual fatigue. To develop prediction models of visual discomfort, subjective visual fatigue, mental workload, and user satisfaction, four stepwise multiple regressions; 1) using all independent variables (IVs; display curvature, task duration, distortion ratio, and interactions), 2) using IVs + dependent variables (DVs; proofreading speed, proofreading accuracy, CFF, blink duration, blink frequency, pupil diameter of left eye, pupil diameter of right eye), 3) using IVs + DVs + personal characteristics (PDs; gender, visual acuity of the left eye, visual acuity of the right eye, age, and eye condition (nature, lens, eye correction surgery)), and 4) using IVs + DVs + PCs (on each five-display curvature then comprising them) were developed. All models were made by 70% of the entire data for the train, 15% for validation, and 15% for the test. Then more accurate prediction models were selected based on root mean square error (RMSE). In turn, first principal component regression analysis was performed to examine the degree to which subjective visual fatigue was affected by composite factors, extracted from proofreading speed and accuracy, visual discomfort, CFF, blink duration, blink frequency, pupil diameter (left and right), overall mental workload, and 6 sub-concepts of mental workload). Second principal component regression analysis was performed to examine the degree to which user satisfaction was affected by composite factors, extracted from proofreading speed and accuracy, visual discomfort, subjective visual fatigue, 9 items for ECQ, CFF, blink duration, blink frequency, pupil diameter (left and right), overall mental workload, and six sub-concepts of mental workload. The number of principal components was determined by two criteria, the size of the eigenvalue (> 1) and the cumulative percentage (> 70%) of variance accounted for by the selected principal components (Lehman et al., 2005), which were rotated by the orthogonal varimax method (Kaiser 1958). (1) eigenvalue > 1 and (2) the cumulative percentage of variance ≈ 70% (Lehman et al., 2005). Segmented regression was performed using statistical software R (R Development Core Team, 2012), and all other statistical analyses were performed using JMP ™ (v12, SAS Institute Inc., NC, USA).

4.3. Results

The results of mixed two-way ANOVA tests for display curvature and task duration on proofreading speed, proofreading accuracy, proofreading accuracy of each six-error type, visual discomfort, subjective visual fatigue, CFF, blink duration, blink frequency, pupil diameter of left eye, pupil diameter of right eye, overall mental workload, each six-sub concept in NASA-TLX, and user satisfaction are presented in table 4.3. The results of stepwise multiple regression analysis for eleven dependent variables using display curvature, task duration, distortion ratio, and their interactions, the results of correlation analysis between two of eleven dependent variables, the result of a segmented regression analysis for subjective visual fatigue on visual discomfort, lastly, the results of stepwise multiple linear regression analysis to develop prediction models of visual discomfort, subjective visual fatigue, mental workload, and user satisfaction were described in order.

Table 4.3 p-values for main and interactive effects of display curvature (DC) and task duration (TD)

Dependent Variables			Display Curvature (DC)	Task Duration (TD)	DC × TD
Proofreading Performance	Speed		**0.041**	**<0.0001**	0.226
	Accuracy	Overall	0.830	**0.0004**	0.948
		Extra letter	0.718	0.274	0.972
		Missing letter	0.852	0.220	0.819
		Wrong letter	0.472	**0.009**	0.278
		Wrong order	0.783	0.535	0.189
		Extra spacing	0.951	**0.009**	0.849
Visual discomfort (VAS)			0.271	**<0.0001**	0.743
Subjective visual fatigue (ECQ)			0.912	**<0.0001**	0.939
Psychophysiological visual fatigue (CFF)			0.638	**<0.0001**	0.639
Blink duration			**0.035**	0.096	0.232
Blink frequency			0.698	**0.007**	0.740
Pupil diameter (left)			0.238	0.102	0.329
Pupil diameter (right)			0.082	0.299	0.994
Mental workload (NASA-TLX)		Overall	0.380	**<0.0001**	0.568
		Mental demand	0.554	**<0.0001**	0.218
		Physical demand	**0.048**	**<0.0001**	0.882
		Temporal demand	0.293	**<0.0001**	0.783
		Performance demand	0.304	**0.014**	0.620
		Effort	0.644	**0.0004**	0.751
		Frustration	0.521	**<0.0001**	0.314
User Satisfaction (VAS)			0.894	**0.007**	0.612

4.3.1. Proofreading task performance

Display curvature significantly affected proofreading speed (syntactic words read / min) (*p=0.0009)* and was divided into two groups (600 R-4000 R-Flat-2000 R and 4000 R-Flat-2000 R-1140 R; figure 4.5). The mean (SD) proofreading speed was highest at 600R (119.9 (24.5)) and lowest at 1140R (91.6 (16.4)). Task duration significantly affected proofreading speed ($p<0.0001$) and was divided into three groups (TD_4 -TD_3, TD_3-TD_2, and TD_1). The mean (SD) proofreading speed was highest at TD_4 (117.8(21.3)) and lowest at TD_1 (96.5(22.8)).

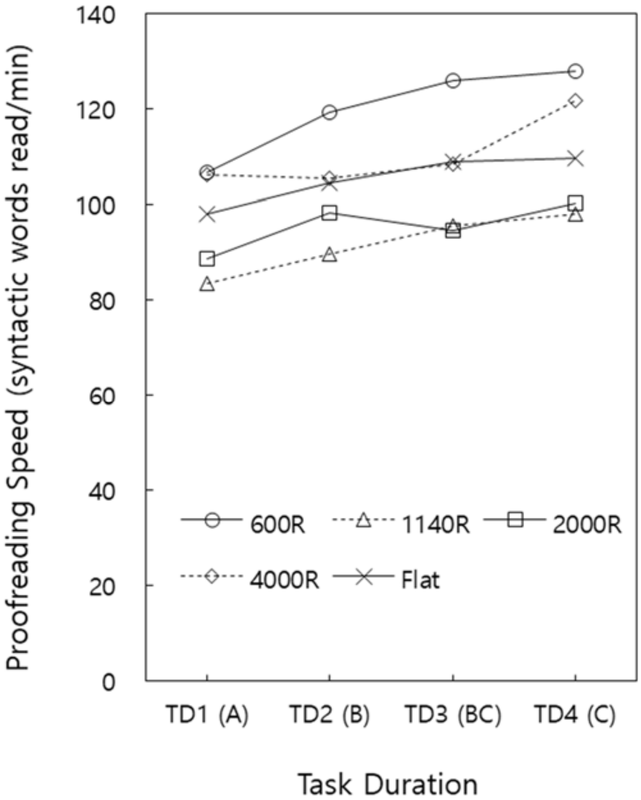

Figure 4.5 Effects of display curvature and task duration on proofreading speed

(Each TD is 15 min; Tukey's HSD grouping denoted in parentheses; Range of SDs = 15.2–31.2)

Task duration significantly affected proofreading accuracy (%) ($p=0.0004$) and was divided into two groups (TD_1-TD_2 and TD_2-TD_3-TD_4; Figure 4.6). The mean (SD) proofreading accuracy was highest at TD_1 (79.8 (13.0)) and lowest at TD_4 (74.2 (13.9)).

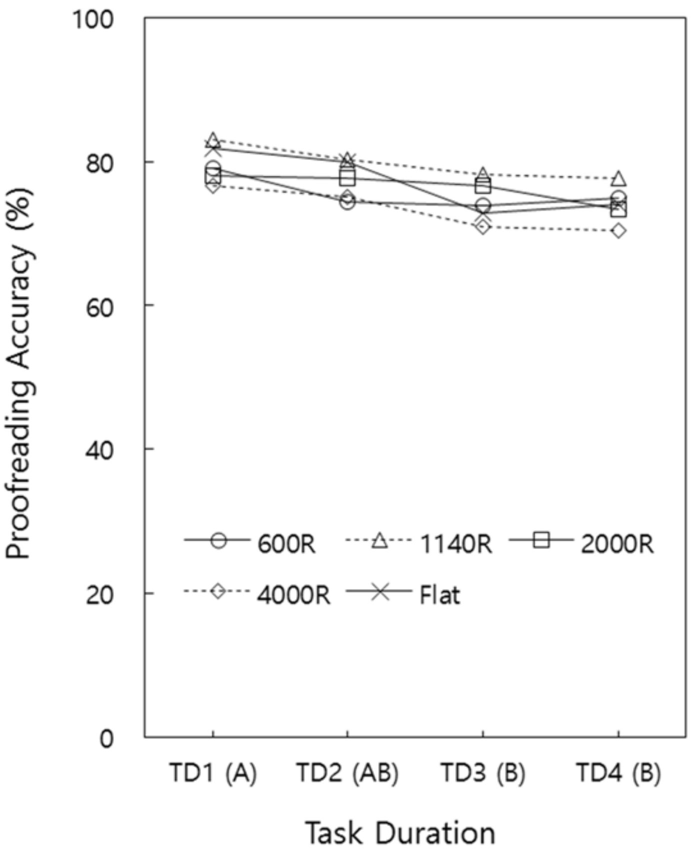

Figure 4.6 Effects of display curvature and task duration on proofreading accuracy (Each TD is 15 min; Tukey's HSD grouping denoted in parentheses; Range of SDs = 7.3–21.1)

For wrong letter, task duration significantly affected proofreading accuracy (*p=0.009*) and was divided into two groups (TD_1-TD_2-TD_3 and TD_3-TD_4). The mean (SD) proofreading accuracy for the wrong letter was highest at TD_1 (82.0 (14.6)) and lowest at TD_4 (73.9 (16.5)). For extra spacing, task duration significantly affected proofreading accuracy (*p=0.009*) and was divided into two groups (TD_1-TD_2-TD_4 and TD_4-TD_3). The mean (SD) proofreading accuracy for extra spacing was highest at TD_1 (83.1 (15.5)) and lowest at TD_4 (75.0 (18.3)) (Figure 4.7).

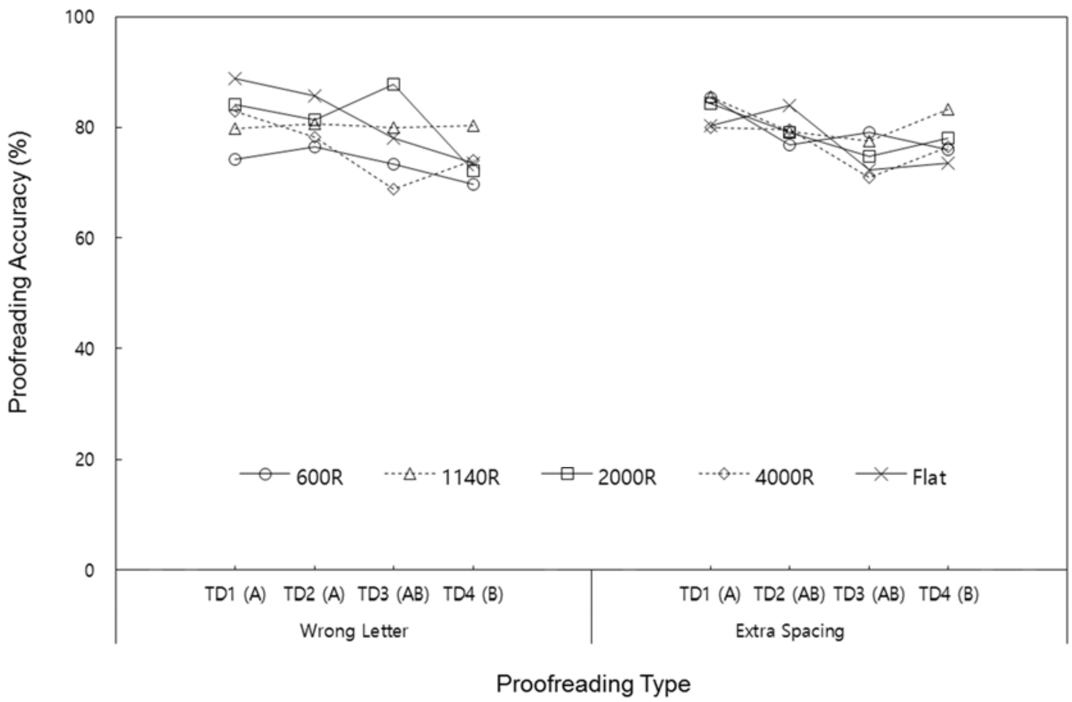

Figure 4.7 Effects of display curvature and task duration on proofreading accuracy for identifying wrong letters and extra spacing (Each TD is 15 min; Tukey's HSD grouping denoted in parentheses; Range of SDs = 6.8–23.5)

Two simple linear regressions of proofreading speed and proofreading accuracy on task duration showed that proofreading speed increased (coefficient of TD = 0.32, $p = 0.002$) and proofreading accuracy decreased (coefficient of TD = -0.13, $p = 0.02$) over 60 min (Figure 4.8).

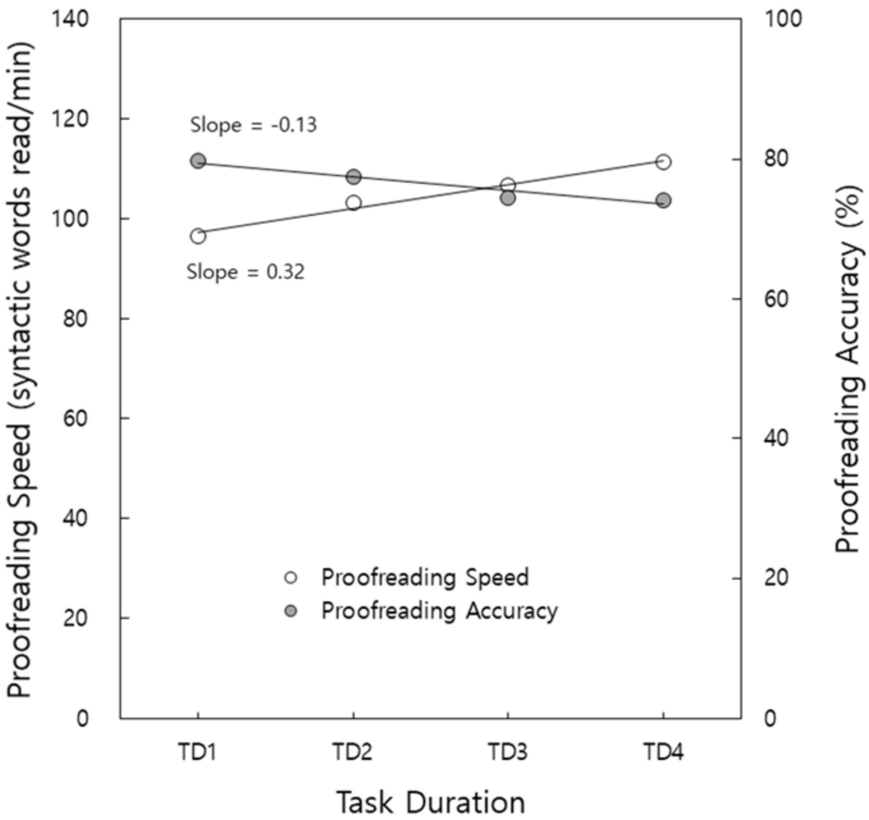

Figure 4.8 Speed and accuracy trade-off during proofreading (Solid lines represent fitted lines using simple linear regression; Data points are the mean values for each task duration across display curvatures; Each TD is 15 min.)

4.3.2. Visual discomfort

Task duration significantly affected visual discomfort (*p<0.0001*), and was divided into four groups (TD_0, TD_1, TD_2-TD_3, and TD_3-TD_4; Figure 4.9). The mean (SD) visual discomfort was lowest at TD_0 (30.2 (21.7)) and highest at TD_4 (62.6 (17.9)).

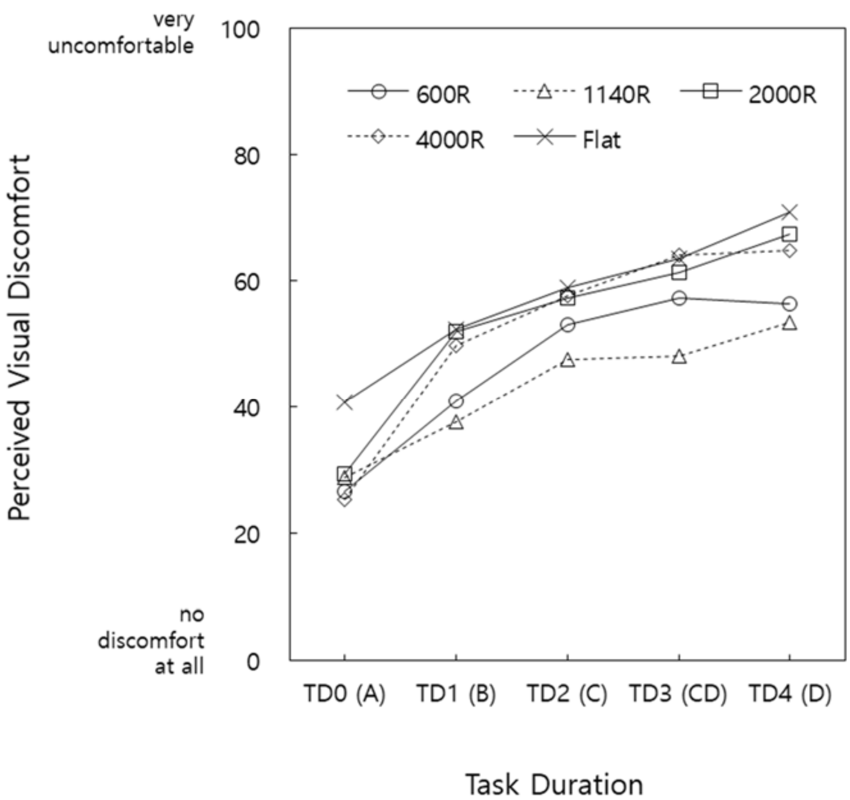

Figure 4.9 Effects of display curvature and task duration (TD) on Visual Discomfort Score [Each TD is 15 min except TD0 (baseline); Tukey's HSD grouping is denoted in parentheses; Range of SDs = 11.7–24.7]

4.3.3. Visual fatigue

Task duration significantly affected subjective visual fatigue (*$p<0.0001$*), and was divided into four groups (TD_0, TD_1, TD_2, and TD_3-TD_4; Figure 4.10). The mean (SD) subjective visual fatigue was lowest at TD_0 (12.1 (10.2)) and highest at TD_4 (35.1(20.3)).

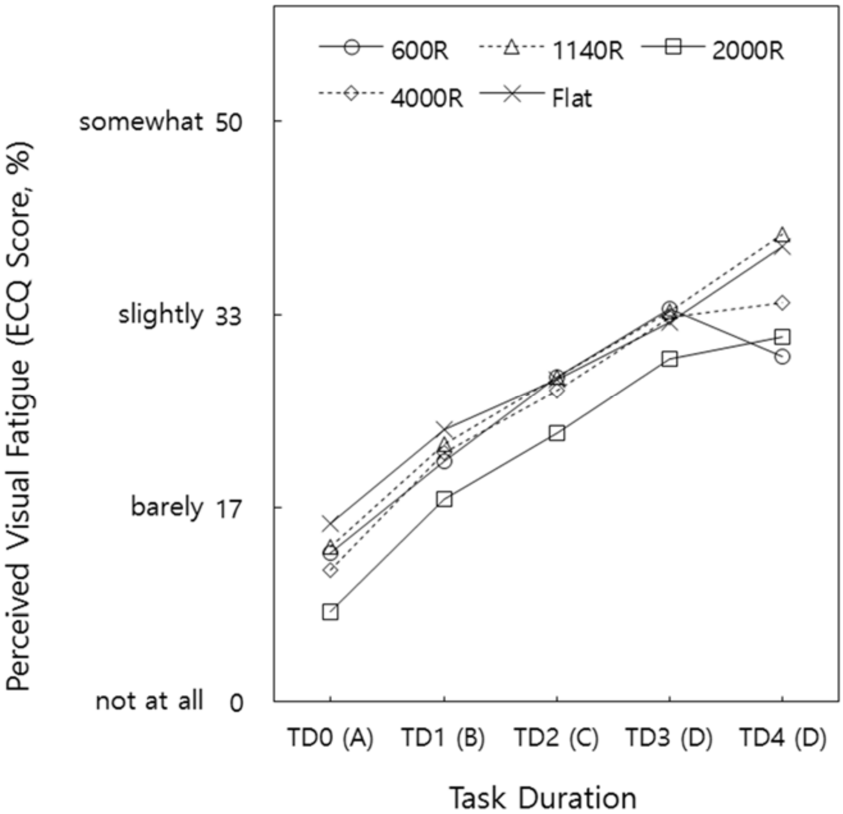

Figure 4.10 Effects of display curvature and task duration on perceived visual fatigue [Each TD is 15 min except TD_0 (baseline); Tukey's HSD grouping is denoted in parentheses; Range of SDs = 7.3–25.0]

Task duration significantly affected CFF (*p<0.0001*), and was divided into two groups (TD_0 and TD_1-TD_2-TD_3-TD_4; Figure 4.11). The mean (SD) CFF was highest at TD_0 (43.1(1.7)) and lowest at TD_4 (42.5(1.5)).

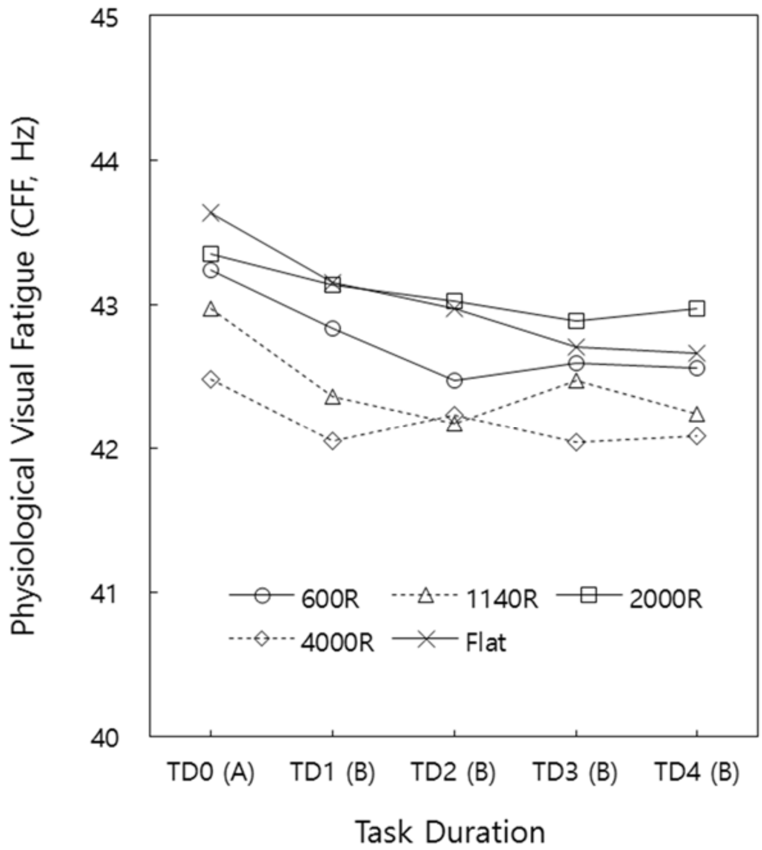

Figure 4.11 Effects of display curvature and task duration on CFF (Each TD is 15 min except TD0 (baseline); Tukey's HSD grouping denoted in parentheses; Range of SDs = 0.68–2.49)

Display curvature significantly affected blink duration (*p=0.04*), but all curvatures belonged to one group. Task duration significantly affected blink frequency (*p=0.007*) and was divided into two groups (TD_1-TD_2-TD_3 and TD_3-TD_4; Figure 4.12). The mean (SD) blink frequency was lowest at TD_1 (0.295 (0.184); less visually fatigued) and highest at TD_4 (0.355(0.197)).

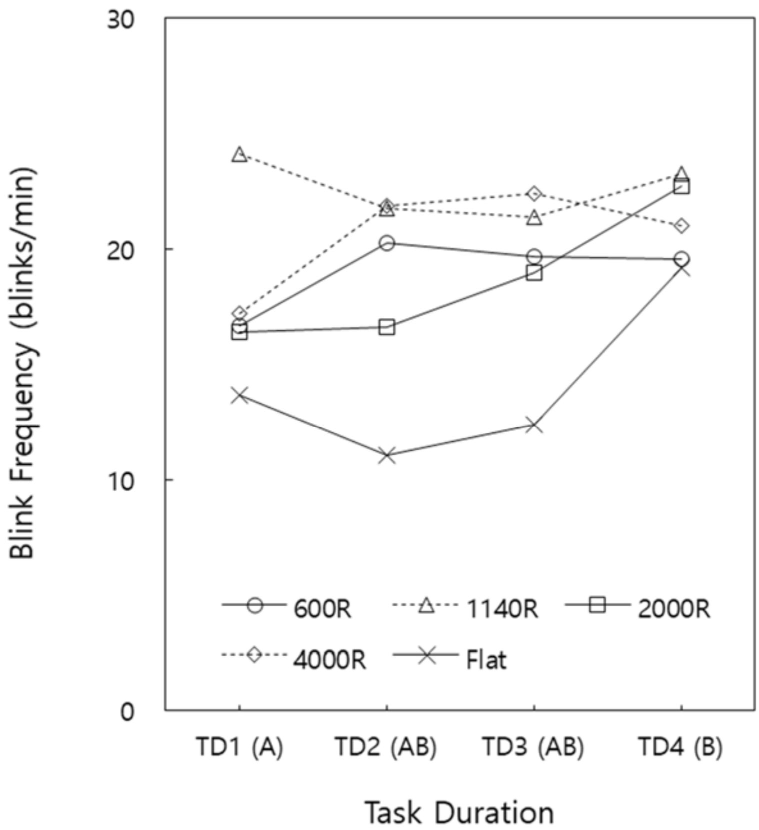

Figure 4.12 Effects of display curvature and task duration on blink frequency (Each TD is 15 min; Tukey's HSD grouping denoted in parentheses; Range of SDs = 0.10–0.33)

4.3.4. Mental workload

Task duration significantly affected mental workload (*p<0.0001*), and was divided into four groups (TD_0, TD_1, TD_2-TD_3, and TD_3-TD_4; Figure 4.13). The mean (SD) mental workload was lowest at TD_0 (3.8 (1.7)) and highest at TD_4 (5.8 (1.6)).

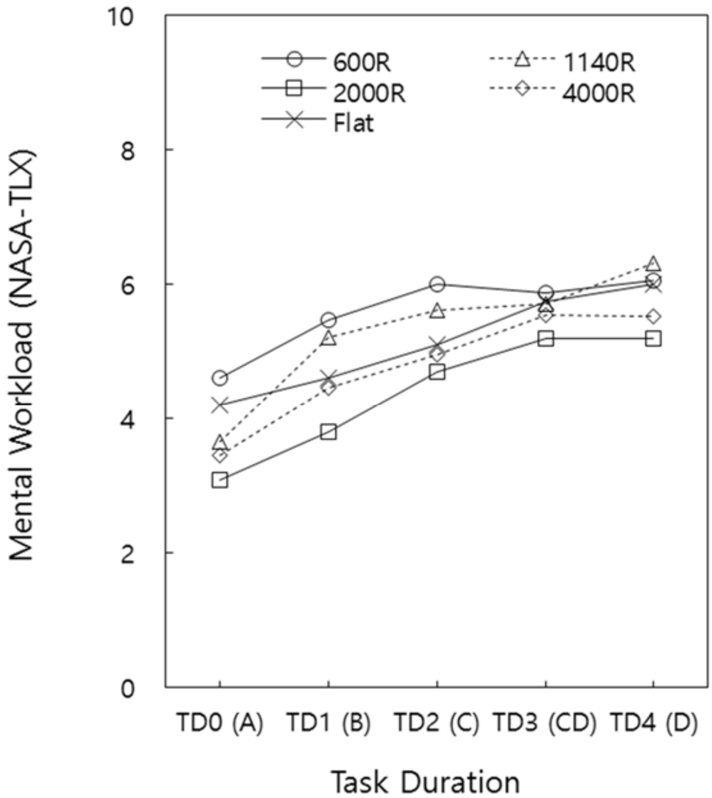

Figure 4.13 Effects of display curvature and task duration on mental workload (Each TD is 15 min except TD0 (baseline); Tukey's HSD grouping denoted in parentheses; Tukey's HSD grouping is denoted in parentheses; Range of SDs = 1.1– 2.2)

Task duration significantly affected six sub concepts of NASA-TLX (*p≤0.01*; Figure 4.14). Mental demand divided into three groups (TD_0-TD_1, TD_2-TD_3, and TD_3-TD_4) and the mean (SD) mental demand was lowest at TD_0 (4.2 (2.3)) and highest at TD_4 (6.5 (2.3)). Physical demand divided into four groups (TD_0, TD_1, TD_2-TD_3, and TD_3-TD_4) and the mean (SD) physical demand was lowest at TD_0 (4.0 (2.3)) and highest at TD_4 (6.5 (2.4)). Temporal demand divided into three groups (TD_0, TD_1-TD_2, and TD_2-TD_3-TD_4) and the mean (SD) temporal demand was lowest at TD_0 (4.3 (2.2)) and highest at TD_4 (6.3 (1.9)). Performance demand divided into two groups (TD_0-TD_1-TD_2 and TD_1-TD_2-TD3-TD4) and the mean (SD) performance demand was lowest at TD_0 (5.6 (1.7)) and highest at TD_4 (5.9 (2.0)). Effort divided into divided into two groups divided into two groups and the mean (SD) effort was lowest at TD_0 (5.9 (2.1)) and highest at TD_4 (6.9 (2.0)). Frustration divided into four groups (TD_0, TD_1-TD_2, TD_2-TD_3, and TD_3-TD_4) and the mean (SD) frustration was lowest at TD_0 (3.9 (1.2)) and highest at TD_4 (5.9 (2.6)).

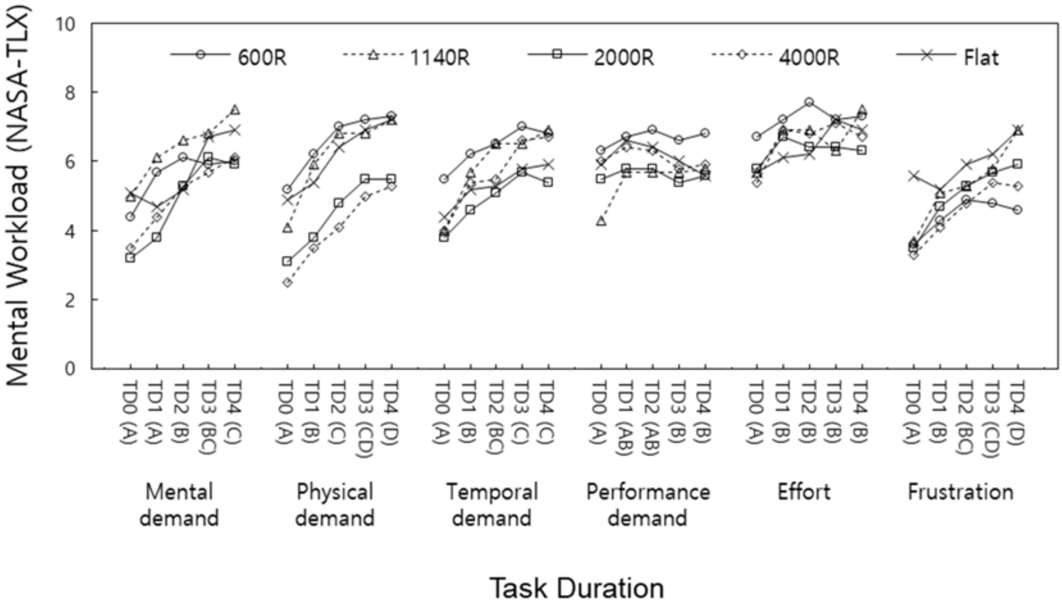

Figure 4.14 Effects of display curvature and task duration (TD) on each of six elements of NASA-TLX [Each TD is 15 min; Tukey's HSD grouping is denoted in parentheses; Range of SDs = 0.6–3.4]

4.3.5. User satisfaction

Task duration significantly affected user satisfaction (*p=0.007*) and was divided into two groups (TD_1-TD_2 and TD_2-TD_4-TD_3; Figure 4.15). The mean (SD) user satisfaction was highest at TD_1 (55.4 (14.8)) and lowest at TD_3 (49.2(18.8)).

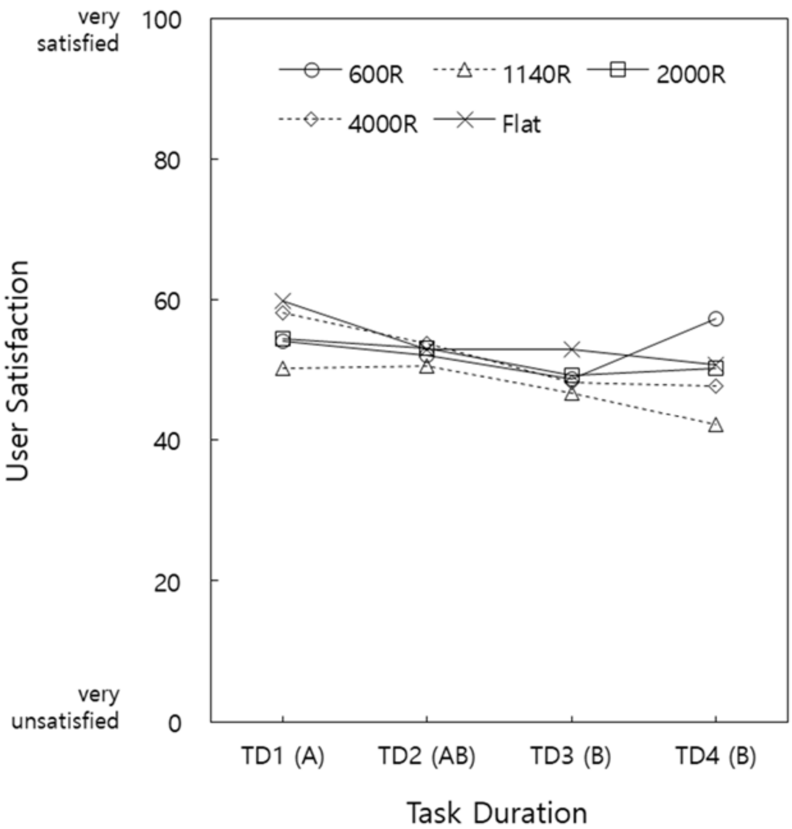

Figure 4.15 Effects of display curvature and task duration on user satisfaction

(Each TD is 15 min; Tukey's HSD grouping denoted in parentheses; Tukey's HSD grouping is denoted in parentheses; Range of SDs = 8.2–26.9)

4.3.6. Stepwise regression of dependent variables on display curvature, distortion ratio, and task duration

Stepwise multiple regressions of each dependent variable on display curvature, task duration, distortion ratio, and their interactions had adjusted R^2 values raging between 0.02 (for proofreading accuracy) and 0.15 (for visual discomfort). These predictors hence accounted for 2 – 15% of dependent variable variabilities (table 4.4).

Table 4.4 Results of Stepwise multiple linear regression of each of eleven dependent variables on display curvature, task duration, distortion ratio, and their interactions

Dependent variables	Coefficients of Predictors (Standardized beta weight, *p-value*)					R^2_{adj}	*p-value*
	Y intercept	Display Curvature (DC)	Task Duration (TD)	Distortion Ratio (D_r)	DC × D_r		
Proofreading speed	81.17	5.6×10^{-5} (0.17, *0.07*)	0.32 (0.21, *0.005*)	2.07 (0.17, *0.005*)	-	**0.07**	*0.002*
Proofreading Accuracy	81.96	-	- 0.16 (0.18, *0.02*)		-	**0.03**	*0.02*
Visual discomfort	47.23		0.39 (0.35, *<0.0001*)	-1.17 (- 0.20, 0.006)	-	**0.15**	*<0.0001*
Subjective visual fatigue	17.36	-	0.34 (0.30, *<0.0001*)		-	**0.09**	*<0.0001*
CFF	-	-	-			-	-
Blink duration	0.16	-1.7×10^{-7} (-0.38, *<0.0001*)	-	-0.002 (-0.37, *<0.0001*)		**0.11**	*<0.0001*
Blink frequency	0.34	-7.3×10^{-7} (-0.16, *0.04*)	-			**0.02**	*0.04*
Pupil diameter (left)	3.41	-7.4×10^{-6} (0.21, 0.007)				**0.04**	*0.007*
Pupil diameter (right)	3.31	1.4×10^{-5} (0.36, <0.0001)				**0.13**	*<0.0001*
Mental workload	5.04		0.03 (0.29, *<0.0001*)	0.11 (0.22, 0.002)		**0.13**	*<0.0001*
User satisfaction	-	-	-			-	-

4.3.7. Correlation analysis between dependent variables

The correlation coefficient between two and p-values of simple linear regressions between two of eleven dependent variables are shown in table 4.5. Proofreading speed positively correlated with visual discomfort and subjective visual fatigue, while negatively associated with proofreading accuracy and CFF. Proofreading accuracy negatively associated with visual discomfort, subjective visual fatigue, blink duration, blink frequency, and pupil diameter of the left eye. Visual discomfort had a positive relationship with subjective visual fatigue, blink duration, the pupil diameter of right eye, and mental workload, while negatively correlated with user satisfaction. Subjective visual fatigue had a positive relationship with blink duration, the pupil diameter of left and right eyes, and mental workload, while negatively correlated with user satisfaction. Blink duration had a positive relationship with blink frequency and mental workload. Blink frequency had a positive relationship with pupil diameter of left and right eyes and mental workload. Pupil diameter of left eye positively correlated with pupil diameter of the right eye and they had a positive relationship with the mental workload, while negatively associated with user satisfaction.

Table 4.5 Bivariate correlation coefficients between eleven dependent variables (below diagonal line, **<0.001, *<0.05) and p-values of simple linear regression lines to verify linear relationship between two variables (above diagonal line)

	SP	AC	VD	ECQ	CFF	BD	BF	PD_L	PD_R	MWL	US
Proofreading speed (SP)	-	**<.0001**	**0.04**	**0.05**	**0.01**	0.74	0.55	0.89	0.94	0.10	0.88
Proofreading accuracy (AC)	**-0.46****	-	**<.0001**	**0.04**	0.10	**<.0001**	**0.02**	**0.02**	0.10	0.06	0.19
Perceived visual discomfort (VD)	**0.15***	**-0.32****	-	**<.0001**	0.82	**0.002**	0.16	0.14	**0.004**	**<.0001**	**0.01**
Perceived visual fatigue (ECQ)	**0.15***	**-0.16***	**0.63****	-	0.52	**0.02**	0.08	**0.03**	**0.05**	**<.0001**	**<.0001**
CFF	**-0.21****	0.13	-0.02	-0.05	-	0.69	0.08	0.21	0.26	0.24	0.90
Blink duration (BD)	-0.03	**-0.30****	**0.24****	**0.18***	0.03	-	**<.0001**	0.54	0.56	**0.003**	0.36
Blink frequency (BF)	-0.05	**-0.18***	0.11	0.13	-0.13	**0.35****	**-**	**<.0001**	**<.0001**	**0.0003**	0.13
Pupil diameter-left (PD_L)	0.01	**-0.17***	0.11	**0.17***	-0.10	0.05	**0.30****	-	**<.0001**	**0.0001**	**0.02**
Pupil diameter-right (PD_R)	0.01	-0.13	**0.22****	**0.15***	-0.09	0.04	**0.32****	**0.87****	-	**<.0001**	**0.02**
Mental workload (MWL)	0.12	-0.14	**0.35****	**0.44****	-0.09	**0.23****	**0.27****	**0.29****	**0.32****	-	0.51
User satisfaction (US)	0.01	0.10	**-0.19***	**-0.32****	-0.01	0.07	0.12	**-0.18***	**-0.18***	-0.05	-

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4.3.8. Association between visual discomfort and subjective visual fatigue

A simple linear regression and a quadratic regression were conducted for subjective visual fatigue regarding visual discomfort with R^2 value of 0.44 (*p<0.0001*) and 0.49 (*p<0.0001*), respectively (Figure 4.16). A segmented regression model for subjective visual fatigue regarding visual discomfort (with one breakpoint at 66.3) had R^2 value of 0.51 and adjusted R^2 value of 0.51 (*p<0.0001*). The slopes of each segment were 0.38 and 1.52, respectively.

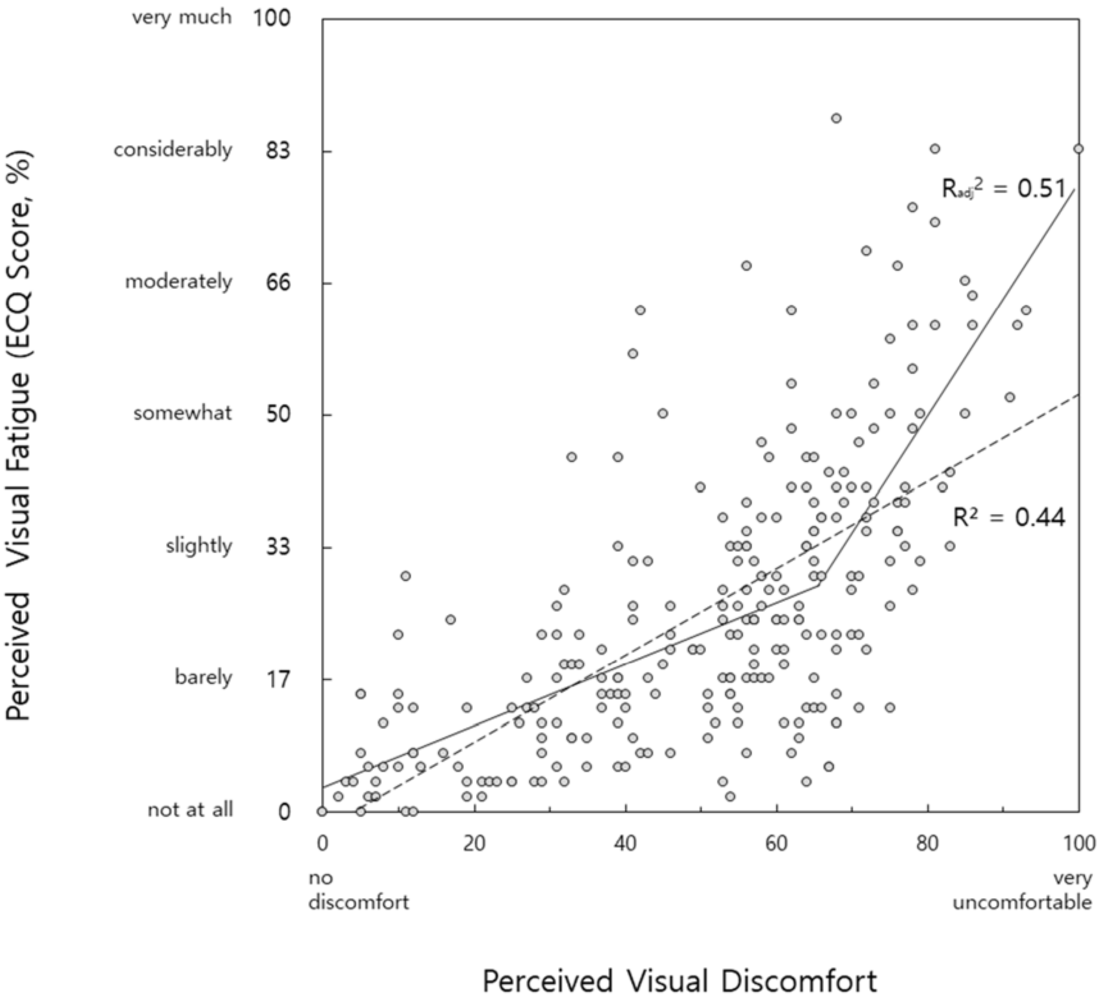

Figure 4.16 Segmented linear regression of perceived visual fatigue on visual discomfort with one break points at 66.3

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4.3.9. Prediction models of visual discomfort, subjective visual fatigue, mental workload, and user satisfaction

A stepwise multiple linear regression model using pupil diameter of right eye, pupil diameter of left eye, task duration, visual acuity of left eye, proofreading accuracy, blink duration, and distortion ratio as predictors accounted for 34.2% of visual discomfort variability ($R^2_{adj} = 0.34$, $p<0.0001$). Based on standardized beta weights, the pupil diameter of the right eye (highest) was more determinative of visual discomfort than distortion ratio (lowest; see Table 4.6).

Table 4.6 The accuracy of model prediction by coefficient of determination (R^2) and root mean square error (RMSE)

Prediction model	Visual discomfort		Subjective visual fatigue		Mental workload		User satisfaction	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
IVs	0.15	17.36	0.10	18.37	0.12	1.45	0.01	17.01
IVs + DVs	0.26	16.20	0.19	17.41	0.30	1.30	0.16	15.64
IVs+DVs+PCs	0.34	15.34	0.23	16.93	0.40	1.20	0.16	15.71
IVs+DVs+PCs by curvature	**0.70**	**10.26**	**0.74**	**9.87**	**0.67**	**0.89**	**0.60**	**10.79**

A stepwise multiple linear regression model using task duration, visual acuity of the left eye, and pupil diameter of left eye as predictors accounted for 22.7 % of subjective visual fatigue variability ($R^2_{adj} = 0.23$, $p<0.0001$). Based on standardized beta weights, the visual acuity of the right eye (highest) was more determinative of subjective visual fatigue than pupil diameter left eye (lowest). A stepwise multiple linear regression model using eye condition, pupil diameter of right eye, distortion ratio, task duration, blink duration, and age as predictors accounted for 37.7 % of mental workload variability ($R^2_{adj} = 0.38$, $p<0.0001$). Based on standardized beta weights, the eye condition_2 (with eye correction surgery or not) was more determinative of mental workload than Age (lowest). A stepwise multiple linear regression model using pupil diameter of right eye, display curvature, blink frequency, eye condition, and task duration as predictors accounted for 15.8 % of user satisfaction variability ($R^2_{adj} = 0.16$, $p<0.0001$). Based on standardized beta weights, the pupil diameter of right eye was more determinative of mental workload than task duration (lowest). Variance influence factors (VIF) for each predictor in four regression models ranged between 1.00–4.22, showing low multicollinearity (Adeyemi et al., 2017). Stepwise multiple linear regressions were conducted for visual discomfort, subjective visual fatigue, mental workload, and user satisfaction regarding IVs, IVs + DVs, IVs + DVs + PCs, and IVs + DVs + PCs by curvature. The predictive accuracy of four models was compared by the values of R^2 and RMES. As results of comparing predictive accuracy, synthesis models composed by stepwise multiple linear regression of each curvature level showed highest R^2 (and lowest RMSE for visual discomfort, subjective visual fatigue, mental workload, and user satisfaction (Table 4.6). Actual data of visual discomfort, subjective visual fatigue, mental workload, and user satisfaction by predictions using four models are presented in figure 4.17.

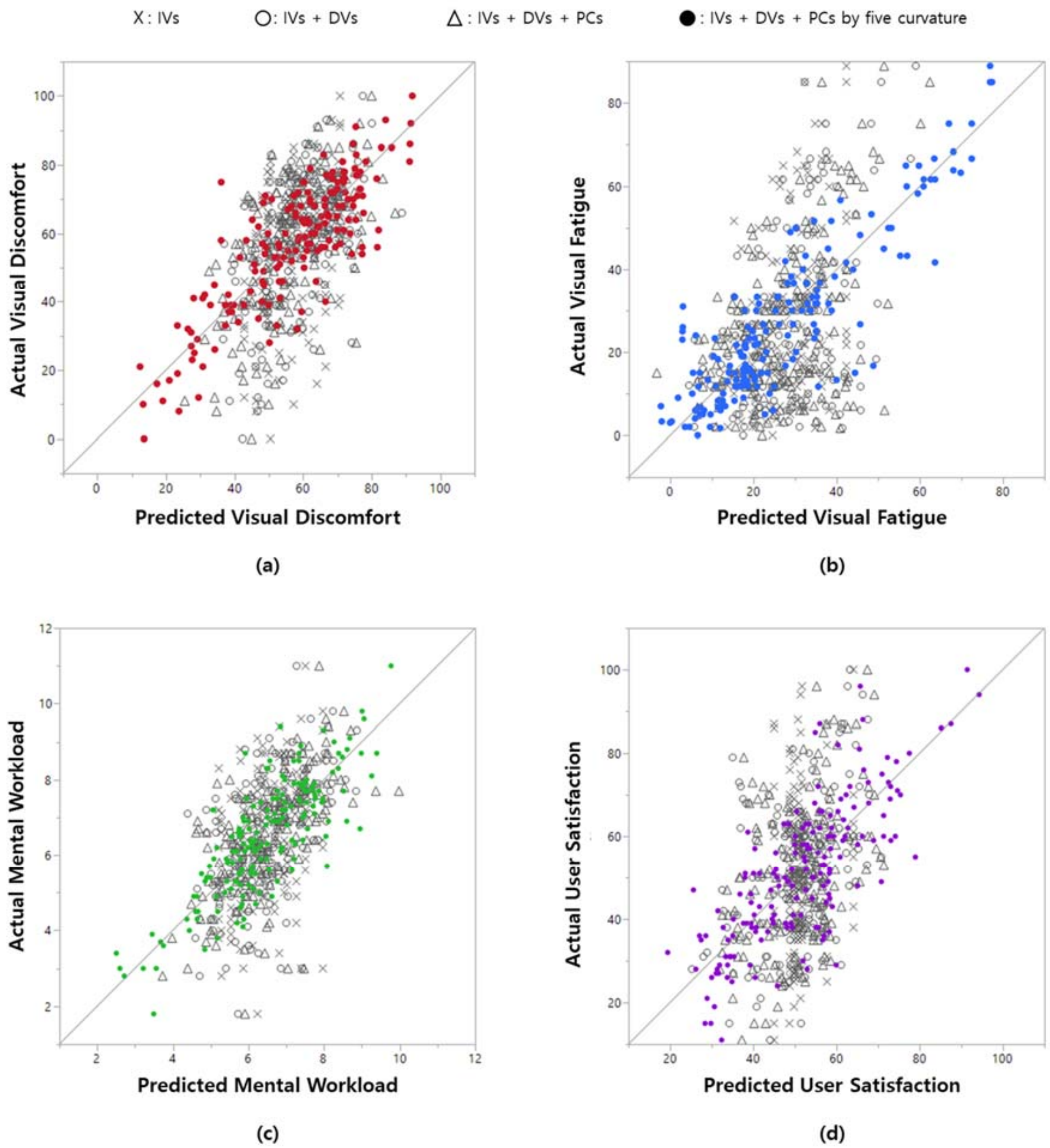

Figure 4.17 Relationship between actual and predicted (a) visual discomfort, (b) subjective visual fatigue, (c) mental workload, and (d)user satisfaction (n=172)

Table 4.7 Regression coefficients, standardized beta weights, and variance influence factors (VIFs) for each stepwise multiple linear regression model of visual discomfort, subjective visual fatigue, and mental workload categorized into five curvature levels

Y	Display Curvature (R)	Equation	VIF	R_{adj}^2	p-value
Visual Discomfort	600	= 101.23 + 0.65*TD - 54.30*VA_L - 19.38*EC_1 - 16.62*EC_2	1.09 - 2.40	0.71	<0.0001
	1140	= 145.77 + 0.27*TD - 50.46*VA_L - 0.60*AC - 22.75*EC_2	1.21 - 1.70	0.82	<0.0001
	2000	= -161.11 + 0.34*TD + 0.37*SP + 146.80*PD_L - 82.07*PD_R	1.27 - 3.82	0.54	0.002
	4000	= 139.24 + 0.27*TD + 11.95*GE + 51.08*VA_L - 0.42*AC - 5.13*AG	1.17 - 2.20	0.73	<0.0001
	Flat	= -334.06 + 0.27*TD + 15.35*GE + 34.19*VA_L + 416.73*BD + 13.01*AG	1.04 - 1.11	0.82	<0.0001
Subjective Visual Fatigue	600	= -437.80 + 0.38*TD + 89.12*GE + 53.55*VA_L + 315.25*VA_R - 0.50*SP - 0.91*AC + 63.63*BF + 21.67*PD_L - 26.70*EC_2	1.79 - 9.14	0.87	<0.0001
	1140	= 39.72 + 0.39*TD - 26.95*GE + 245.82*BD - 10.09*PD_L - 13.53*EC_2	1.02 - 2.14	0.94	<0.0001
	2000	= 415.54 + 0.27*TD - 24.54*GE + 0.20*SP - 81.17*BF - 134.65*PD_R	1.29 - 4.40	0.77	<0.0001
	4000	= 11.05 + 2.51*PD_L - 15.03*EC_1	1.25 - 1.25	0.32	0.005
	Flat	= -283.26 + 0.29*TD - 13.81*GE + 14.27*AG	1.01 - 1.09	0.86	<0.0001
Mental Workload	600	= -40.03 - 0.04*AC + 1.01*CFF + 52.22*BD	1.02 - 1.10	0.72	<0.0001
	1140	= 9.84 + 0.02*TD - 3.21*GE - 0.53*PD_L	1.02 - 1.46	0.74	<0.0001
	2000	= 21.84 + 0.03*TD - 0.43*CFF + 4.30*BF	1.11 - 1.62	0.81	<0.0001
	4000	= 12.47 + 0.03*TD + 5.28*VA_L - 0.34*CFF - 5.39*BF + 0.83*PD_L + 0.84*EC_2	1.44 - 2.99	0.84	<0.0001
	Flat	= 5.66 + 0.02*SP + 65.34*BD + 1.41*EC_1	1.14 - 1.70	0.42	0.001
Display Satisfaction	600	= 152 - 16.19*VA_R + 0.34*SP + 0.54*AC	1.05 - 1.54	0.69	<0.0001
	1140	= -40.45 + 29.86*BF + 3.45*AG	1.02 - 1.02	0.34	0.01
	2000	= 451.79 - 7.72*CFF - 3.16*AG	1.06 - 1.06	0.51	0.001
	4000	= 95.38 + 26.14*VA_L + 0.61*AC - 2.73*CFF	1.00 - 1.02	0.47	0.001
	Flat	= 88.25 - 57.07*VA_L + 0.51*AC - 4.59*PD_R + 24.29*EC_1	1.11 - 1.33	0.67	<0.0001

Display curvature (DC), task duration (TD), distortion ratio (D_r), proofreading speed (SP), proofreading accuracy (AC), blink duration (BD), blink frequency (BF), pupil diameter of left eye (PD_L), pupil diameter of right eye (PD_R), gender (GE), age (AG), visual acuity of left eye (VA_L), visual acuity of right eye (VA_R), and eye condition (with contact lens of not: EC_1 and with eye correction surgery or not: EC_2)

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4.3.10. Principal component regression of subjective visual fatigue

The principal component analysis was applied to dependent variables excepting subjective visual fatigue and user satisfaction. The first five components were retained for rotation, and they accounted for 70.9 % of the total variance. Input factors and corresponding factor loadings are presented in table 4.8. Six factors were found to load on the first component, which was subsequently labeled “workload.” Two factors loaded on the second component, which was labeled “pupil.” Two factors loaded on the third component, which was labeled “discomfort.” Three factors loaded on the fourth component, which was labeled “performance.” Two factors loaded on the fifth component, which was labeled “blink” (Table 4.8).

Table 4.8 Five principal components, extracted from proofreading speed and accuracy, visual discomfort, CFF, blink duration, blink frequency, pupil diameter (right and left), overall mental workload, and six sub-concepts of mental workload for PCR analysis of subjective visual fatigue (after varimax rotation; values > 0.5 underlined)

Factors	PC1 (workload)	PC2 (pupil)	PC3 (discomfort)	PC4 (performance)	PC5 (blink)
Overall mental workload	**0.888**	0.216	0.290	0.045	0.151
Temporal demand	**0.805**	-0.036	0.265	0.037	-0.117
Effort	**0.764**	0.042	-0.051	0.030	0.081
Performance demand	**0.686**	-0.074	-0.451	0.219	0.067
Mental demand	**0.653**	0.218	0.421	-0.156	0.277
Physical demand	**0.572**	0.404	0.352	-0.054	0.060
Pupil diameter (L)	0.091	**0.911**	0.086	0.081	0.045
Pupil diameter (R)	0.093	**0.910**	0.131	0.057	0.050
Visual discomfort	0.108	0.026	**0.775**	0.141	0.182
Frustration	0.220	0.169	**0.706**	-0.021	-0.068
Proofreading accuracy	0.051	-0.037	-0.376	**-0.628**	-0.398
CFF	0.004	-0.218	0.175	**-0.555**	-0.006
Proofreading speed	0.123	-0.107	0.125	**0.860**	-0.116
Blink duration	0.091	-0.105	0.112	0.011	**0.873**
Blink frequency	0.119	0.421	-0.039	0.001	**0.659**
Eigenvalue	4.45	1.93	1.59	1.41	1.26
Cumulative percent	29.66	42.54	53.12	62.53	70.94

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A multiple linear regression model using five principal components as predictors accounted for 49.3 % of subjective visual fatigue variability ($R^2_{adj} = 0.49$, $p < 0.0001$; table 4.9). Based on standardized beta weights, PC3 (discomfort) was most determinative of subjective visual fatigue, followed by PC1 (workload), PC2 (Pupil), PC5 (Blink), and PC4 (Performance)

Table 4.9 Stepwise principal component regression model for subjective visual fatigue using three principal components determined by PCA with Varimax Rotation as Predictors

Predictor	Coefficient	Standardized beta weight	VIF	p-value
Intercept	30.10	0.00	.	<.0001
PC3 (Discomfort)	12.53	0.66	1.00	<.0001
PC1 (Workload)	4.39	0.23	1.00	<.0001
PC2 (Pupil)	1.66	0.09	1.00	0.11
PC5 (Blink)	1.33	0.07	1.00	0.20
PC4 (Performance)	1.03	0.05	1.00	0.32

4.3.11. Principal component regression of user satisfaction

The principal component analysis was applied to dependent variables excepting user satisfaction. The first five components were retained for rotation, and they accounted for 68.0 % of the total variance. Input factors and corresponding factor loadings are presented in table 8. Twelve factors were found to load on the first component, which was subsequently labeled “eye fatigue.” Six factors loaded on the second component, which was labeled “workload.” Three factors loaded on the third component, which was labeled “ocular.” One factor loaded on the fourth component, which was labeled “blink duration.” Three factors loaded on the fifth component, which was labeled “performance” (Table 4.10)

Table 4.10 Five principal components, extracted from proofreading speed and accuracy, visual discomfort, subjective visual fatigue (ECQ) and nine items for ECQ, CFF, blink duration, blink frequency, pupil diameter (right and left), overall mental workload, and six sub-concepts of mental workload for PCR analysis of user satisfaction (after varimax rotation; values > 0.5 underlined)

Factors	PC1 (eye fatigue)	PC2 (workload)	PC3 (ocular)	PC4 (blink duration)	PC5 (performance)
Overall ECQ score	**0.975**	0.141	0.056	0.103	0.043
My eyes hurt	**0.858**	-0.004	0.013	-0.027	0.005
My eyes itch	**0.766**	-0.002	0.187	-0.227	0.002
My eyes water	**0.762**	0.165	0.196	-0.230	0.043
My eyes are dry	**0.762**	-0.064	0.118	0.180	-0.076
My eyes are tired	**0.762**	0.191	0.001	0.422	0.116
My eyelids feel heavy	**0.760**	0.054	-0.083	0.397	-0.036
My eyes burn	**0.737**	0.136	0.265	-0.323	0.125
I have difficulty seeing	**0.704**	0.370	-0.174	0.296	-0.052
I have a strange feeling around my eyes	**0.666**	0.179	-0.097	0.078	0.201
Frustration	**0.644**	0.168	0.182	0.047	-0.016
Visual discomfort	**0.627**	0.076	0.091	0.367	0.119
Overall mental workload	0.300	**0.867**	0.246	0.188	0.021
Temporal demand	0.243	**0.790**	-0.024	-0.004	0.007
Effort	0.048	**0.749**	0.047	0.048	-0.002
Performance demand	-0.250	**0.691**	-0.062	-0.154	0.230
Mental demand	0.283	**0.654**	0.283	0.379	-0.185
Physical demand	0.297	**0.568**	0.446	0.028	-0.041
Pupil diameter (R)	0.091	0.093	**0.880**	-0.022	0.077
Pupil diameter (L)	0.105	0.086	**0.872**	-0.054	0.099
Blink Frequency	0.035	0.082	**0.582**	0.337	-0.012
Blink duration	0.067	0.087	0.061	**0.776**	-0.009
Proofreading Speed	0.116	0.142	-0.136	-0.007	**0.855**
CFF	-0.015	0.053	-0.161	0.045	**-0.538**
Proofreading Accuracy	-0.085	0.001	-0.145	-0.531	**-0.607**
Eigenvalue	8.56	3.05	2.11	1.77	1.51
Cumulative percent	34.25	46.43	54.86	61.94	67.99

A multiple linear regression model using five principal components as predictors accounted for 18.3 % of subjective visual fatigue variability (R2adj = 0.18, p < 0.0001; table 4.11). Based on standardized beta weights, PC1 (eye fatigue) was most determinative of user satisfaction, followed by PC2 (Workload), PC3 (Ocular), PC5 (Blink Duration), and PC4 (Performance).

Table 4.11 Principal component regression model for user satisfaction using five principal components determined by PCA with varimax rotation as predictors

Predictor	Coefficient	Standardized beta weight	VIF	p-value
Intercept	51.19	0.00	.	<.0001
PC1 (Eye Fatigue)	-6.49	-0.38	1.00	<.0001
PC2 (Workload)	3.14	0.18	1.00	0.01
PC3 (Ocular)	-2.56	-0.15	1.00	0.03
PC5 (Blink Duration)	1.30	0.08	1.00	0.28
PC4 (Performance)	-0.81	-0.05	1.00	0.49

4.4. Discussion

This section examined the main effects of display curvature and task duration on productivity (proofreading speed and accuracy), safety (visual discomfort, subjective visual fatigue, CFF, blink duration, blink frequency, pupil diameter (left and right), and mental workload), and well-being (user satisfaction) on a 27" monitor. Then, the speed-accuracy trade-off during proofreading task was identified. Next regression analysis was performed to explain each dependent variable using the investigated variables, distortion ratio as an additional factor, and their interaction terms. The association between eleven dependent variables was examined through correlation analysis. The further relationship between visual discomfort and subjective visual fatigue was determined through a segmented linear regression analysis. Also, four regression models were developed to predict visual discomfort, subjective visual fatigue, mental workload, and user satisfaction in real-time). Additionally, two principal component regression models were developed to explain subjective visual fatigue and user satisfaction and determined the relative importance of each variable.

4.4.1. Effects of display curvature

Regarding display productivity, the curved display of a particular curvature was more advantageous than the flat display. In this study, the display curvature 600 R condition provided the highest proofreading speed, which was 31% faster than 1140 R (the lowest) and 14% faster than flat. These results are similar to those of previous studies. In our second study, with 50” curved monitors at 500 mm viewing distance, the visual searching task speed on 400 R and 600 R were respectively 7.5% and 7.8% lower than those of flat monitors. In the study by Na, Jeong, and Suk (2015), Korean text reading speed on a 23” curved display (manipulated by the participant; mean curvature of 633R) was faster than that on a flat display. In the study of Häkkinen et al. (2008), the reading experience (legibility) on a 5.8" (13 × 7cm) 60 R and 80 R concave display was better than that in flat.

In the current study, the display curvature did not significantly affect the proofreading accuracy. However, previous studies found that VDT tasks on curved displays were advantageous when the display curvature is closer to the viewing distance. In cases where the radius of display curvature is too small or too large, the effects were either absent or negative. Therefore, it may be the result of performing the visual task more quickly, maintaining a similar level of accuracy in a more familiar environment without being influenced by curvature. These results can be explained by the changes in viewing angle and horizontal viewing distance on display depending on the display curvature at specific viewing distances. In this study, a 600 R condition provided the uniform horizontal viewing distance (table 4.12). In comparison proofreading, if the target error was in a different viewing distance within the dead and live copy on the left and right of the display, the focal distance presumably needed to be continuously adjusted. To adjust the focal distance, latency periods of 0.16 - 0.18 s (Mustonen et al., 2015) and 0.3 - 1 s (Campbell and Westheimer, 1960) are required for convergence-vergence and accommodation (Campbell and Westheimer, 1960; Rashbass and Westheimer, 1961), respectively, and this time delay might have had a positive impact on the proofreading speed at a radius of curvature of 600 R.

Table 4.12 Viewing distance, field of view, and viewing angle for different display curvatures

Display Curvature	Viewing Distance (at display center; mm)	Viewing Distance (at left- or right-most area; mm)	Change in Viewing distance (mm)	Field of View (°)	Viewing Angle (at left- or right-most area; °)
600 R	600	600	0	58	0.0
1140 R	600	635	35	56	12.9
2000 R	600	651	51	55	18.8
4000 R	600	661	61	54	22.8
Flat	600	672	72	53	26.7

Regarding safety, curved displays are known to lower visual fatigue than flat displays. However, there was no significant effect of display curvature on visual fatigue in this study. Uniform viewing distance, one of the typical strength of curved display, may have negative aspects that can increase visual fatigue due to maintaining a constant focal distance during visual task (Company, 2009), it is expected to be advantageous regarding reducing demand of accommodative responses (Hsu and Wang, 2013). In this study, the display curvature did not affect visual fatigue because the visual stress caused by continuous accommodative responses might be larger than the visual fatigue accumulated over the task duration. The reason for selecting the comparison proofreading task in this study was to induce visual fatigue sufficiently through the visual task. The 25%ile – mean - 75%ile ECQ values obtained before and after the 60-minute proofreading task were 3.7% - 12.1 - 17.2 and 19.9 - 35.1 - 48.6, respectively. Based on the mean ECQ, subjective visual fatigue increased by 190.1%. The easy-to-understand articles were used in proofreading task to prevent unexpected effects of article difficulty on mental workload. The 25%ile - mean - 75%ile mental workload measured after 15 minutes proofreading were 3.6 - 4.8 - 6.0, respectively. Also, non-contextual errors were used to reduce language-processing demands induced by contextual errors.

4.4.2. Effects of task duration

The productivity of proofreading task decreased as task duration increased. The speed and accuracy of the VDT task were mainly measured to evaluate the productivity of the display (Hall and Hanna, 2004; Oetjen and Ziefle, 2007, 2009; Ojanpää and Näsänen, 2003; Piepenbrock et al., 2014a, 2014b; Piepenbrock et al., 2013). The participants tend to concentrate more on the index of either speed or accuracy according to the task instruction.

In this study, the mean proofreading speed increased to 7.1% and 15.5% for TD2 (30 min) and TD4 (60 min), respectively, compared with TD1 (15 min). Similarly, some previous studies have shown that proofreading speed decreased. In Chan and Ng (2012)'s study, the effects of font size (10 and 14 points), text direction (vertical and horizontal), and copy placement (top-bottom and left-right) on proofreading time was evaluated during comparison proofreading on 17" LCD monitors at viewing distance 400mm. However, this study differs from previous studies in that a proofreading time task duration of approximately 4 minutes and 25 seconds was applied to minimize the effects of mental and visual fatigue.

In contrast, the proofreading accuracy in this study had been steadily decreasing. Proofreading accuracy decreased by 6.6% in TD3 (45 min) compared to TD1 (15 min) and decreased by 7.1%, the maximum, in TD4 (60 min). Proofreading accuracy is easier to correct than non-contextual errors (in words and sentences) (Hacker et al., 1994; Plumb et al., 1994). In this study, proofreading accuracy was higher in non-contextual errors than in contextual errors. Proofreading accuracy of an extra letter, extra spacing, and wrong letter was 14.7%, 15.2%, and 17.8% higher than 'missing letter,' which had the lowest proofreading accuracy among five error types. These results are similar to the results of previous studies. Chan and Ng (2012) also found that extra spacing, missing words, and extra words were higher in accuracy than wrong order and wrong words.

In this study, the speed-accuracy trade-off with proofreading task was shown. Across the display curvature, the proofreading task speed increased, and the proofreading task accuracy decreased as the task time elapsed. As a result of simple linear regression using a task duration of 60 minutes as a predictor, the coefficient of task duration was 0.32 and -0.13 for speed and accuracy, respectively. According to regulatory focus theory by Higgins (1997), the promotion focus is eagerness that focuses on the positive outcome in pursuing the goal and expects a positive outcome. Whereas prevention focuses associated with a desire to avoid negative outcomes. In other words, the promotion-focused worker may endeavor to achieve its objectives, even if there is a risk, whereas a prevention-focused worker may tend to avoid mistakes during work to prevent negative consequences while at the same time trying to achieve the goal. In Förster et al. (2003)'s study, the participants were instructed to perform as quickly and as accurately as possible before the experiment. The participants were divided into two groups (promotion focus vs. prevention focus) according to the instructions of the strategy to perform the 4-min proofreading task. The participants in the promotion focus were informed that they would be paid $3 for the participation fee and would be paid more $1 if their speed/accuracy score were above 60. The participants in the prevention focus were informed that they would be paid $4 for the participation fee and there would be $1 losing possibility if their speed/accuracy score were below 60. The experimental results show that subjects in promotion focus considered speed, more importantly, to achieve faster and more hits during task even if accuracy decreased. In the current study, participants were instructed before the experiment that additional incentives would be paid to top performers considering both speed and accuracy, which corresponds to the promotion focus.

This result can be explained by the effect of visual fatigue that was induced during the proofreading task. Similarly, the speed-accuracy trade-off of proofreading task was observed in previous studies. In Chan et al. (2014)'s study, the effects of typo type (extra word, missing word, wrong word, wrong font type, wrong punctuation mark, wrong order, and extra spacing)line length (26, 36, and 46 characters), line number (2, 4, and 8), and line spacing (1, 1.5, and 2) on proofreading performance was evaluated during comparison proofreading with nine passages (mean number of 901 words) in a day on 17" LCD monitor at viewing distance 400 mm. As a result, proofreading time and typo detection rate showed a positive relationship (r = .171). This result meant that the proofreading accuracy increased when the proofreading speed decreased. In Chan and Ng (2012)'s study, the effects of font type, font sizes, text directions, copy placements on proofreading performance was evaluated during comparison proofreading with one passage (mean number of 547 words) for one experimental condition on 17" LCD monitor at viewing distance 400 mm. As a result, proofreading speed-accuracy trade-off was found. In Wilkinson* and Robinshaw (1987)'s study, the effects of display type on proofreading performance were evaluated during 50-min proofreading on 12" CRT monitor and paper at viewing distance 600 mm. The result showed a speed-accuracy trade-off in which the task speed increased while the accuracy decreased simultaneously.

Visual discomfort and subjective visual fatigue increased as task duration elapsed. Compared with T0 which is the time right before the task begins, mean visual discomfort increased by 54.0%, 81.7%, and 107.2% in TD1 (15 min), TD2 (30 min), and TD4 (60 min), respectively. Compared with T0, mean subjective visual fatigue increased by 74%, 121%, and 169% in TD1 (15 min), TD2 (30 min), and TD3 (45 min), respectively, and increased up to 189% after 60-min task. This result is similar to the results of previous studies. In our first study, the subjective visual fatigue (ECQ) increased by about 102% from 11.6 before task execution to 23.4 after task completion when performing a 30-minute visual searching task with a viewing distance of 500 mm on a 50" multi-monitor. However, this study differs in that the horizontal field of view occupied by the display was more extensive than in the current study. In Choi (2016)'s study, which was conducted on presbyopia and non-presbyopia subjects in the same experimental environment as this study, the subjective visual fatigue measured using the ECQ increased by 207.2%, from 6.1 before the proofreading task, to 29.8 after the 60-minute task. In Murata et al. (2001)'s study, subjective visual fatigue increased up to 15.6 times after 60-minute VDT task.

CFF, blink duration, blink frequency, pupil diameter are valid indices accounting for both visual fatigue and mental workload. CFF, blink duration, blink frequency, pupil diameter are valid indices accounting for both visual fatigue and mental workload. In this study, CFF decreased as proofreading task duration elapsed. However, the measured CFF did not show any significant relationship with visual comfort, subjective visual fatigue, and mental workload. CFF showed a significant decrease of 0.43 Hz (1%) during the initial 15-minute proofreading and decreased up to 0.63 Hz (1.5%) after finishing the 60-minute task. Likewise, CFF decreased 0.3Hz after 30-min visual searching task in our first study and declined 0.4Hz after 60-min proofreading task in the Choi (2016)'s study that conducted in the same environment as this study. In Iwasaki et al. (1989)'s study, the CFF value of red color light significantly decreased (i.e., the occurrence of visual fatigue) after 15 minutes, and the CFF of yellow and green color light dropped after 30 minutes while doing the watching equation task. In Lin et al. (2008) and Lin et al. (2009)'s study, during the visual search task within 15 minutes, CFF measurement showed significant visual fatigue. In several previous studies, a decrease of 0.12 Hz in CFF after a 1–h tracking task (Lin et al., 2008), a reduction of 0.9 Hz in CFF after a 1–h data-entry task (Saito et al., 1994), and a decrease of 1.2 Hz in CFF after 40 min of a proofreading task and a video-watching task (Wu, 2012) were found.

In this study, blink frequency increased as task duration elapsed, and increased up to 20.4% in TD4 (45 min - 60 min) compared with TD1 (0 min - 15 min). Blink duration showed increment trend, and blink frequency increased as task duration elapsed. The measured mean blink duration showed significant relationships with the proofreading accuracy (r = -0.30), visual comfort (r = 0.24), subjective visual fatigue (r = 0.18), and mental workload (r = 0.23). This result is similar to the results of previous studies. In McIntire et al. (2014)'s study, the blink duration and blink frequency increased when the visual task performance decreased. In Kaneko and Sakamoto (2001)'s study, blink duration and blink frequency increased when the task performance decreased. This study was similar to the results of previous studies related to visual fatigue. In Kaneko and Sakamoto (2001)'s study, blink frequency increased when subjective visual fatigue increased. In Victor et al. (2005)'s study, blink frequency increased when the degree of fatigue increased. In Zhang, Zhao, et al. (2015)' study, visual fatigue occurred as visual task sustained, and at the same time, blink duration and blink frequency increased.

In this study, mean pupil diameter (L) showed significant relationships with proofreading accuracy (r = -0.17), subjective visual fatigue (r = 0.17), and mental workload(r = 0.29), and mean pupil diameter (R) showed significant relationships with visual discomfort (r = 0.22), subjective visual fatigue (r = 0.15), and mental workload(r = 0.32) as task duration elapsed. Previous studies showed similar results. In Chi and Lin (1998)'s study, subjective visual fatigue and pupil diameter showed positive relationships ($r = 0.25$) during 20-min VDT task, and subjective visual fatigue increased when pupil diameter increased. In Tsai et al. (2007)'s study, pupil diameter increased in case of the visual task with a higher workload. In Gao et al. (2013)'s study, pupil size increased as the mental workload increased. Also, as visual task performance decreased, blink duration and frequency increased (Matessa, 2004; McIntire et al., 2014; McKinley et al., 2011).

Mental workload increased as task duration increased. Proper mental workloads are positive for workers' productivity, safety, and well-being (Xie and Salvendy, 2000), while excessively high mental workloads increase visual fatigue and reduce task performance (Fan and Smith, 2017). In this study, compared with T0 which was just before starting the task, mean overall mental workload increased by 22.8%, 37.8%, and 51.9% in TD1 (15 min), TD2 (30 min), and TD4 (60 min), respectively. In order to perform a proofreading task that requires all sub-tasks such as finding, comparing, and marking, a long-term memory is needed for top-down detection based on existing knowledge in terms of information processing, and a short-term memory may also be required for quick comparisons of the left and right displays for surface errors such as contextual errors. In general, readers use information from internal (e.g., long-term memory of phonology) and external sources (texts) to understand the content material, and internal information is described as a top-down constraint, and external information is defined as a bottom-up constraint (Kelly, 1995). The two models were mainly used to explain information processing at different levels(i.e., work, sentence, conceptual, topic) of text reading (Chan and Ng, 2012). In this study, if participants consistently compare dead and live copy to find errors, bottom-up cognition is mostly used. Whereas, if participants mainly focused on the live copy and switched to a dead copy only when they presume an error in the live copy, it can be considered as a top-down approach. However, gaze information through eye tracking is required to identify the primary strategy used, but this study has a limitation of not measuring the related data.

Six sub-concepts for mental workload measurement also increased as task duration elapsed. At TD4 (60 min) compared with TD1 (15 min), Physical demand increased 41.7%, showing the maximum increase, and Effort increased 3.8%, indicating the minimum increment. At TD4 (60 min) compare with TD1 (15 min), Mental demand, Temporal demand, Performance demand, and Frustration increased 39%, 21.1%, 6.4%, and 23.8%, respectively.

Regarding productivity and safety, the sustained execution of proofreading task on VDT is adverse to the user. Guidelines for the proper rest-time interval is needed because prolonged VDT task induces computer vision syndrome, and the results of this study can be criteria to suggest appropriate rest-time interval regarding visual fatigue. In consideration of proofreading accuracy, visual discomfort, visual fatigue and mental workload, it is necessary to have a break after 15-minute comparison proofreading, which is considerably faster than previously recommended break time for the VDT task. It seems that the breakpoint should be flexible depending on the type of VDT task. In the present study, visual discomfort showed a tendency to increase continuously after the start of the proofreading task, and compared with TD0 (0 min), it increased by 54.0%, 81.7%, and 107.2% at TD1 (15 min), TD2 (30 min) and TD4 (60 min), respectively. Subjective visual fatigue showed a tendency to increase continuously after the start of the proofreading task, and compared with TD0 (0 minutes), it increased by 73.8%, 120.6%, and 169.1% at TD1 (15 min), TD2 (30 min), and TD3 (45 min), respectively, and it increased by up to 189.3% at TD4 (60 min).

The results of all nine ECQ sub-items increased during 60-min proofreading task. Compared with the ratings at TD0 (0 min), the response to "My eyes water" showed the greatest increase by 345.5% at TD4 (60 min), and the response to "My eyes are dry" reported the lowest increase by 134.3% at TD4 (60 min). This trend can also be confirmed by CFF measurement. A decrease in CFF means an increase in visual fatigue. CFF continuously decreased after the start of the proofreading task and decreased by 0.04 Hz at TD1 (15 min) and by up to 0.63 Hz at TD4 (60 min) compared to TD0 (0 min).

In previous studies, rest-break was studied on VDT task. In Shieh and Chen (1997)'s study, during the 3-hour visual search task on 14" CRT monitor, short and frequent breaks (5 min break for 25 min work) was more advantageous than long and infrequent breaks (10 min break for 50 min work) regarding visual fatigue. In Galinsky et al. (2000)'s study, while data entry workers did 8.5-hour working, visual fatigue was lower in frequent breaks (15 min break for 1-hour work) than in infrequent breaks (15min break for 2-hour work). In Balci and Aghazadeh (2003)'s study, task speed, accuracy, physical discomfort, and visual fatigue were measured during 2-hour data entry task and the mental arithmetic task with 20-min rest. As a result, the most frequent and short breaks schedule (15-minute work/micro breaks (30 s, 30 s, 30 s, 3 min, 30 s, 30 s, 30 s, 3 minutes, and 14 minutes) showed the fastest and most accurate task performance of data entry task and mental task. Visual fatigue (eyestrain and blurred vision) was lowest at 30-minute work / 5-minute rest condition. Boucsein and Thum (1995) suggested that VDT worker should take a 7.5-minute rest break after 50 minutes in the morning (before noon) and a 15-minute break after 100 minutes in the afternoon. A recent study by Henning et al. (1997) investigated the influence of frequent and short rest breaks on VDT workers' productivity and well-being. They found that having four breaks (one 3-minutes and three 30- seconds) every hour followed by a conventional 15-minute break enhanced productivity. The guideline of the rest-time according to the execution of the VDT task was also presented. NewZealand Accident Compensations Corporation (2010) recommended 5-10 min breaks per hour, and OSHA (1997) suggested 10 min of rest after continuous work for 1 or 2 hours. The National Institute for Occupational Safety and Health (NIOSH) recommended 15 min of rest after 1 hour for high visually demanding work and 15 min of rest after 2 hours for moderate visually demanding work.

User satisfaction decreased while doing the proofreading task. Regardless of the display curvature level, user satisfaction decreased as a 60-minute task duration elapsed. In this study, user satisfaction decreased by 11.2% in TD3 (45 min) compared with TD1 (15 min). It seems that user satisfaction was reduced due to increased mental workload caused by the demand of sustained oculomotor movement during dead and live copies proofreading, and due to the effect of lowered legibility caused by the increment of visual discomfort and visual fatigue. Likewise, in a study by So and Chan (2013), satisfaction was negatively correlated with mental demand as well as eye strain, while four kinds of visual tasks were performed for 1.5 hours on LED display (512 mm x 256 mm). However, Choi (2016)'s study, which was conducted on presbyopia and non-presbyopia subjects in the same experimental environment as this study, did not find any change in user satisfaction according to proofreading task duration. This difference may be due to the difference in the proofreading task method applied to this study and his study. In this study, the participants were required to mark the symbols corresponding to each error type among the five types of errors in the live copy. However, Choi (2016)'s study used a method of marking errors regardless of their type. Thus, the proofreading task of this study may require a higher level of mental demand, resulting in reduced satisfaction.

4.4.3. Explaining the impact of display curvature, distortion ratio, and task duration on each independent variable

The regression model developed for each dependent variable can contribute to the determination of the display curvature and the task duration to improve the evaluation factor which is important according to the task characteristics in performing the visual task for the VDT. Of the nine models, six models except for CFF, blink frequency, and user satisfaction were significant. The model using display curvature, distortion ratio, task duration, and their interactions as predictors explained the variability of each dependent variable from 1% to 15%. Based on regression coefficient, the proofreading speed increased as the task duration and distortion ratio increased, and the proofreading accuracy decreased as the task duration elapsed. Visual discomfort increased as task duration elapsed and as distortion ratio decreased. Subjective visual fatigue increased as task duration elapsed. Blink duration decreased as display curvature, and distortion ratio increased. Mental workload increased as task duration and distortion ratio increased. User satisfaction increased as task duration decreased. Based on standardized beta weight, for the proofreading speed, the task duration and the interaction between display curvature and distortion ratio were 2.6 times (= 0.26 / 0.1) and 2.2 times (= 0.22 / 0.1) more determinative compared to the distortion ratio. For visual discomfort, the task duration was 1.62 times (0.34 / 0.21) more determinative than the distortion ratio. The 2nd degree polynomial of display curvature and distortion ratio have the same influence on Blink duration. For metal workload, task duration was 1.45 times (0.29 / 0.20) more determinative than the distortion ratio.

4.4.4. Investigating the association between proofreading speed and accuracy, visual discomfort, subjective visual fatigue, CFF, blink duration, blink frequency, pupil diameter (left and right), mental workload, and user satisfaction

Among 11 measures obtained in this study, associations between two variables whose linearity was verified through simple linear regression were analyzed and compared with previous studies. Proofreading speed was negatively correlated with proofreading accuracy and CFF, and was positively associated with visual discomfort and subjective visual fatigue. Proofreading accuracy was negatively related to visual discomfort, subjective visual fatigue, blink duration, and mental workload, and positively associated with CFF. Visual discomfort was negatively correlated with user satisfaction, and positively related to subjective visual fatigue, blink duration, and mental workload. Subjective visual fatigue was negatively associated with user satisfaction and positively correlated with the mental workload. CFF was negatively correlated with blink frequency. Blink duration had positive relationships with blink frequency and mental workload. Blink frequency had a positive relationship with the mental workload. Information processing can be impaired by the levels of mental workload (Young et al., 2015). Rocha and Debert-Ribeiro (2004) found an association between visual fatigue and mental workload as a result of a questionnaire of 553 subjects. The regression analysis of visual fatigue showed that the mental workload estimate was 0.21 and the visual fatigue was increased as mental workload increased. Fogarty and Stern (1989), a reduced blink frequency reflects the increased visual demands of a task, as a simple mechanism to reduce the probability of missing relevant information.

4.4.5. Identifying the relationship between visual discomfort and subjective visual fatigue

The long-term effect of visual discomfort is related to visual fatigue (Lebreton, 2016). As explained by Lambooij et al. (2009), visual discomfort is usually related to visual fatigue. Visual discomfort is defined as "the subjective counterpart of visual fatigue," and visual fatigue is defined as "the decrease in performance of the human visual system." According to Urvoy et al. (2013), visual discomfort can be evaluated by subjective measurement method, but visual fatigue is considered to be measurable by objective measurement. However, few studies have revealed the relationship between visual discomfort and subjective visual fatigue. In this study, first, linearity between two factors was estimated, then the positive linear relationship was found (r=0.63). Next, through the residual plot, the possibility of the nonlinear relation was checked. Then, through additional analysis of simple linear regression, quadratic regression, and segmented regression, the segmented relationship was selected based on the value of R^2. Among the regression models using visual discomfort as a predictor, the explanatory power of segmented regression was the highest at 51%. The breakpoint of the segmented regression was 66.3 of the VAS value used in the measurement of visual discomfort. Based on the slope of the fitting line of the regression model, the subjective visual fatigue gradually increased (slope = 0.38) until the visual discomfort reached 66.3, and drastically increased from 66.3 (slope = 1.52). When the visual discomfort is above a certain level, the subjects experience more visual fatigue. These results enable a quick and simple measure of the visual safety assessment of VDT tasks.

4.4.6. Developing real-time prediction models for visual discomfort, subjective visual fatigue, mental workload, and user satisfaction

Four prediction models developed. They can diagnose the amount of visual discomfort and subjective visual fatigue, mental workload, and user satisfaction so that they can be used as fundamental data to determine proper break time. The stepwise regression models using task duration, objective measures (proofreading speed and accuracy, CFF, blink duration, and blink frequency, pupil diameter of left and right), and individual characteristics (gender, age, visual acuity of left and right, and eye condition) as regressors accounted for the variabilities of visual discomfort, subjective visual fatigue, mental workload, and user satisfaction about 73.9 %, 70.4 %, 66.7%, and 60.2%, respectively. Predictive models of visual discomfort, subjective visual fatigue, mental workload, and user satisfaction were also analyzed to obtain the greater explanatory power. In regression models of each display curvature, the explanatory power based on adjusted R^2 was from 54% (600 R) to 82% (1140 R) for visual discomfort, 32% (4000 R) to 94%(1140 R) for subjective visual fatigue, from 42% (flat) to 84% (2000 R) for mental workload, and from 34% (4000 R) to 69% (flat) in case of user satisfaction.

4.4.7. Determining the degree to which composite variables composed of dependent variables affect the subjective visual fatigue and user satisfaction

The PCR model developed to explain subjective visual fatigue, which accounted for about 49.3% variation in subjective visual fatigue. Based on standardized beta weights, PC3 (discomfort), PC1 (workload), PC2 (pupil), and P5 (blink) were 12.2 times (0.66/0.05), 4.3 times (0.23/0.05), 1.6 times (0.09/0.05), and 1.3 times (0.07/0.05) more determinative of subjective visual fatigue than PC4 (performance). Attempts to explain the visual fatigue have also been done in previous studies. Murata et al. (2001) developed visual fatigue model using the minimum pupil diameter, velocity of focal accommodation for constriction, and width of focal accommodation, and the value of R^2 for that model was 0.78. Kim and Sohn (2010) developed visual fatigue prediction model by examining the horizontal and vertical disparity characteristics of 3D images. The correlation between predicted and measure subjective visual fatigue were in the range of 79% to 85%. Lin et al. (2010) developed visual fatigue model using working time, rest time, inspection number, repair number, illumination, difficulty, and day shift or night shift as predictors. Moreover, the value of R^2 for that model was 0.90. Choi et al. (2012) developed visual fatigue model using functions of spatial complexity, depth position, temporal complexity, scene movement, depth gradient, crosstalk, brightness, and different characteristics. The correlation between predicted algorithm and measure subjective visual fatigue was 0.77. Choi et al. (2012) developed visual discomfort model using spatial factors (average of disparity, maximum negative disparity, range of disparity, ratio of disparity summations, spatial complexity, depth position) and temporal factors (temporal complexity and scene movement) as predictors. Moreover, the values of R^2 for those models were in the range of 0.70 to 0.73. Iatsun et al. (2015) developed visual fatigue prediction model using visual disparity changes, visual disparity range, value of motion activity, and previous state of visual fatigue. Moreover, the value of R^2 for that model was 0.98. Some studies showed similar results to this study. So and Chan (2013) found that the eyestrain increased negatively correlated with satisfaction decreased during visual tasks.

The PCR model developed to explain user satisfaction accounted for about 25.0% of user satisfaction variability. Based on standardized beta weights, PC1 (eye fatigue), PC2 (workload), PC3 (Ocular), and PC5 (blink duration) were 8.0 (0.38/0.05), 3.9 times (0.18/0.05), 3.1 times (0.15/0.05), and 1.6 times (0.08/0.05) more determinative of user satisfaction than PC4 (performance). The result of the study was similar to the previous study. Iatsun et al. (2015) found that user's satisfaction decreased when visual discomfort and visual fatigue increased during watching 2D and 3D video. User satisfaction increased as proofreading speed increased, but CFF decreased. The increase of proofreading speed could be caused by visual fatigue. The decrease of CFF indicates that the degradation of visual performance. Perhaps, participants might recognize they were doing well when their proofreading speed increased, even though they could not know their task accuracy.

4.4.8. Limitations

The use of the mockup display (rear screen) differs regarding resolution, luminance, color temperature and reflected glare compared to the actual display. Moreover, because this study used only a single task (proofreading), it is necessary to consider other tasks such as cognitive tasks, gaming, and watching video. Also, relatively low levels of visual fatigue were reported during the task duration (60 min) adopted in this study. In previous studies, subjective visual fatigue was reported sufficiently during watching a 2D display after 78 min (Kwon et al., 2012). In this study, the characteristics of the participants (male to female ratio: 1:9 to 5:5, eye condition, visual acuity) among display curvature conditions were not uniform. However, based on the results of Fisher's exact test across experimental conditions, there was no difference of gender ($p = 0.21$) and eye condition ($p = 0.50$) among the display curvature conditions. Based on the results of the one-way ANOVA across display curvatures, there was no significant difference in visual acuity ($p \geq 0.52$). According to the study by Blehm et al. (2005), dry eye related to ocular surface symptoms was more prevalent in women than in men, whereas other studies had no difference in visual fatigue (Endukuru et al., 2016; Lin et al., 2015) and visual task performance (Kang and Liao, 2013) between genders. The instruction was given to emphasize both speed and accuracy, and accuracy of proofreading was low. In fact, accuracy is more important in proofreading task. Also, the speed increased with time may be a learning effect or a visual fatigue effect, but it cannot be known which effect was larger in this study.

4.5. Conclusions

The current study analyzed the influence of display curvature and task duration on task performance, visual discomfort, visual fatigue, mental workload, and user satisfaction for the proofreading task on 27” monitors. The major findings are as follows. First, the fastest proofreading speed was observed on the 600 R of display curvature. Second, across curvatures, proofreading accuracy declined, subjective visual discomfort, visual fatigue, and mental workload increased after 15minutes, respectively. Third, a segmented linear relationship between visual discomfort and subjective visual fatigue was revealed. Fourth, four real-time prediction models were developed for display discomfort, subjective visual fatigue, mental workload, and user satisfaction, and they accounted for the variability of each factor about 70.4%, 73.9%, 66.7%, and 60.2%, respectively. Fifth, among each five-composite measures for subjective visual fatigue and display satisfaction, 'discomfort' explained the variabilities of subjective visual fatigue the most, and 'eye fatigue' explained the variabilities of user satisfaction the most. The findings provide insight into the relationship between visual discomfort and subjective visual fatigue. To generalize the findings of the current study, it is required to apply actual displays, consider diverse VDT tasks, measure other objective measures for visual fatigue in the further study.

Chapter 5. Effects of Display Curvature, Viewing Distance, and Lateral Viewing Position on TV Watching Experience: Presence, Visual Comfort, Image Quality, and Display Satisfaction [Study 3: 55” TVs]

5.1. Introduction

Many elements of the TV watching experience have been investigated: presence (Baranowski et al., 2016; Moon, 2014), visual comfort/discomfort (Park, J. et al., 2015; Zhang et al., 2015), image quality (Bracken, 2005; Häkkinen et al., 2008), satisfaction (Zhang et al., 2015), visual fatigue (Chen et al., 2013; Zhang et al., 2015), motion sickness (Baranowski et al., 2016; Polonen et al., 2013), image distortion (Kim et al., 2014), and emotional reactions (Häkkinen et al., 2008). No widely known study, however, has comprehensively considered diverse TV watching experience elements or explained display satisfaction using other experience elements.

Media form factors affecting geometric distortion and brilliance (Goldmark and Dyer, 1940)., including display size, viewing distance, and image quality (Lee (2009), influence the watching experience. Display curvature can increase presence (Park et al., 2016), visual comfort (Na and Suk, 2016), image quality (Park et al., 2016), preference (Park et al., 2015), and legibility (Park et al., 2017) while reducing visual fatigue (Park et al., 2014); however, it can also induce negative shape aftereffects (Ohtsuka et al., 2015; Ohtsuka et al., 2016) and longer visual processing times (Mustonen et al., 2015). It is, therefore, necessary to carefully determine TV display curvatures to improve watching experience. Viewing distance is determined by display size and image quality. Although presence generally increases as viewing distances decrease, it can suffer at excessively short viewing distances (Kim, 2003; Lombard, 1995). Studies on the non-high definition (HD) flat TVs involved viewing distances of 2–14 W (Gausewitz, 1964; Wadsworth, 1968) and 5 H (Kwon and Lee, 2007), where W and H respectively represent display width and height, whereas HD TV studies used relatively shorter viewing distances (3–4 W or 0.8–6 H) (Ardito et al., 1996; BT.2022, 2012; Matsumoto et al., 2011; McVey, 1970; Narita et al., 2001; Sakamoto et al., 2008). To date, little is known regarding how viewing distance and display curvature influence watching experience.

Lateral deviations in viewing position (the viewing angle) also affect watching experience. Although images viewed at an angle experience trapezoidal distortions (Todd et al., 2007), non-central viewing positions are sometimes inevitable, especially in multi-view conditions ranging between ±60° (Nathan et al., 1985), with a mean viewing angle of 23.3° (Kubota et al., 2006)). In South Korea, 73% of households in 2015 (Statistics Korea 2015) and 70% of US households in 2012 (Vespa et al., 2013) had two or more members. However, the degree to which viewing angle affects watching experience is largely unknown.

Although valid user experience studies should allow for in-context settings (Maguire, 2001), previous studies on both flat and curved TVs have used restrictive settings [involving single viewing distances (Choi et al., 2015; Ohtsuka et al., 2016), centralized viewers (Choi et al., 2015; Mun et al., 2015), or exclusively static images (Blankenbach et al., 2015; Na, Jeong, and Suk, 2015)]. Further research is thus required to examine the effects of these media form factors on dynamic images watched on curved TVs.

The purpose of study III was to generate ergonomic guidelines for improving overall and specific TV watching experiences using media form factors. Three media form factors (display curvature, viewing distance, and lateral viewing position) and seven TV watching elements (spatial presence, engagement, ecological validity, negative effects, visual comfort, image quality, and display satisfaction) were investigated, with specific consideration for 1) the main and interactive effects of the media form factors on each element, 2) the degree to which these factors accounted for variability in each element, and 3) the degree to which the remaining six watching experience elements, except for display satisfaction, accounted for variability in display satisfaction.

5.2. Methodology

5.2.1. Participants

This study utilized 56 young volunteers (table 5.1), selected with criteria of 1) normal or corrected–to–normal visual acuity ≥ 0.8 for both eyes (Wu, 2011) using the Han Chun Suk visual acuity chart (Kee et al., 2006), 2) non-colour blindness using the Ishihara colour blindness test (Strayer and Johnston, 2001), 3) no vision-related illnesses in the last six months, and 4) non-glasses wearer. All participants gave informed consent approved by a local institutional review board and were compensated for their time.

Table 5.1 Participant characteristics: age and visual acuity

Display curvature	# of participants (male, female)	Mean (SD) age	Mean (SD) visual acuity	
			Left	Left
2300 R	14 (6, 8)	22.4 (1.1)	1.1 (0.3)	1.1 (0.2)
4000 R	14 (4, 10)	22.4 (1.1)	1.0 (0.2)	1.0 (0.2)
6000 R	14 (8, 6)	20.9 (1.9)	1.0 (0.2)	1.0 (0.2)
Flat	14 (2, 12)	20.1 (1.4)	1.0 (0.2)	1.0 (0.2)

5.2.2. Experimental setting and procedure

The laboratory experiment was conducted with external lights blocked using black curtains and black cloth covering the TV stand and walls to minimize color and light reflection. Each experimental TV mock-up consisted of projection film (Sunnano, Korea) attached to the front surface of a 55" (1218 mm × 685 mm; 16:9 aspect ratio) custom Styrofoam panel, and was placed on a stand (320 mm high) elevating the center 648 mm from the floor. Each Styrofoam panel had one of four curvatures (2300 R, 4000 R, 6000 R, and flat). A 5.1 channel speaker system (BR-5100T2, Britz, Korea) was used: one subwoofer was placed on the left side of the stand, one speaker on the right and one additional speaker was placed at each of the four-room corners. Video images were projected on each projection film using a beam projector (EB-4950WU, Epson), and distorted images were corrected using Desktop WarpalizerTM (UniVisual Technologies, Sweden). Participants watched the videos from a sofa (width × depth × height: 2500 × 600 × 450 mm) in randomly selected pairs. The first 50% of participants started at a viewing distance of 2.3 m, whereas the remainder started at 4 m. Assuming viewers sat with lateral symmetry, only right side viewing positions were considered (Figure 5.1). With one exception (P5-P1), viewers sat 70 cm apart (Nussbaumer, 2013). The actual viewing distance (m), viewing angle (°), and field of view (°) varied with viewing distances and lateral viewing positions. The field of view also varied with display curvatures (table 5.2). The picture of the experimental setting is shown in figure 5.1.

(a) viewing distance of 2.3 m

(a) viewing distance of 4.0 m

Figure 5.1 Experimental environment

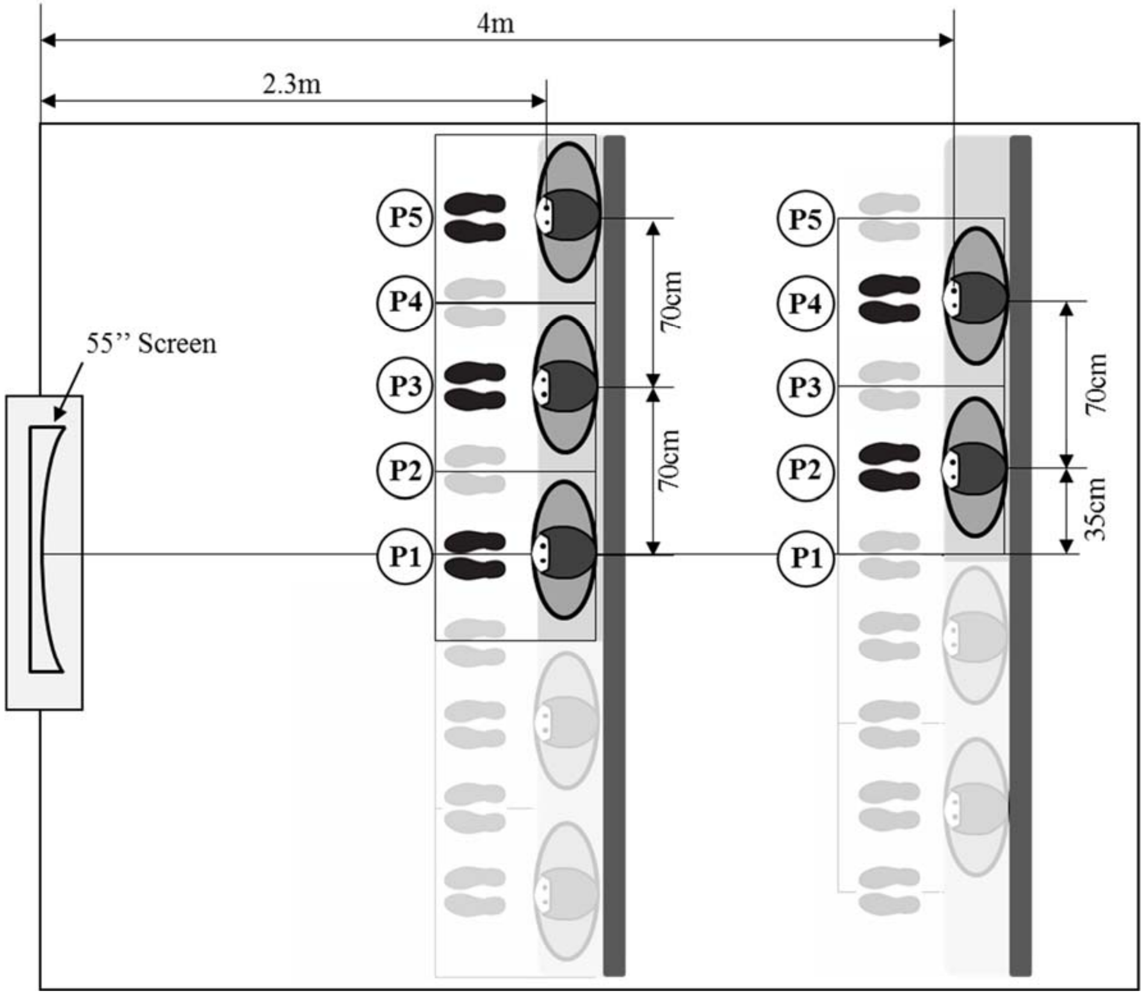

Figure 5.2 Viewing distances and lateral viewing positions (Five pairs of viewing positions, P_1-P_3, P_2-P_4, P_3-P_5, P_4-P_2, and P_5-P_1, were used at both 2.3 m and 4 m.)

Table 5.2 Actual viewing distance, viewing angle, and field of view according to the display curvature, viewing distance, and lateral viewing position

Viewing distance (m)		Display curvature (mm)	Lateral viewing position				
			P_1	P_2	P_3	P_4	P_5
2.3	Actual viewing distance (m)	-	2.3	2.3	2.4	2.5	2.7
	Viewing angle (°)	-	0.0	8.7	17.0	25.0	31.0
	Field of view (°)	2300R	30.3	29.7	27.9	25.2	22.3
		4000R	30.1	29.5	27.7	25.2	22.3
		6000R	30.0	29.4	27.6	25.1	22.3
		Flat	29.7	29.1	27.4	24.9	22.2
4.0	Actual viewing distance (m)	-	4.0	4.0	4.1	4.1	4.2
	Viewing angle (°)	-	0.0	5.0	9.9	15.0	19.0
	Field of view (°)	2300R	17.5	17.3	16.9	16.3	15.5
		4000R	17.4	17.3	16.9	16.3	15.6
		6000R	17.4	17.3	16.9	16.3	15.5
		Flat	17.3	17.2	16.8	16.2	15.5

Previous studies on presence, visual comfort, image quality, and display satisfaction used multiple viewing durations: 90 s–1 h (Bracken, 2005; Cho et al., 2010; Christou, 2014; Hou et al., 2012; Kwon and Lee, 2007; Oh and Lee, 2016; Sakamoto et al., 2012; Yang and Chung, 2012), 24–60 min (Lambooij, Ijsselsteijn, and Heynderickx, 2011; Tam et al., 2011), 24–30 min (Ardito et al., 1996; Lambooij, Ijsselsteijn, and Heynderickx, 2011), and 4 h (Zhang, liu, et al., 2015). This study used ten 5 min videos. Each experiment contained five 1 min clips (motorcycling, car chases, roller coaster riding, combat flying, and scenic flying) and used one of ten viewing distance × lateral viewing position settings. This procedure is depicted in figure 5.3. The experimental procedure was as follows. 1) Basic information on each participant (e.g., gender, age) was collected, and their visual acuity and color blindness were checked for ten min. 2) During a 10-min break, a TV display mockup with a specific curvature level, a viewing distance, and a pair of lateral viewing positions were selected, and the experimental sofa was moved if needed. 3) Two participants sat in their designated viewing position and watched a 5-min video shown on the TV display mockup. 4) After watching a 5-min video, subjective ratings on ITC-SOPI, visual comfort, image quality, and display satisfaction were done for two min. At the same viewing distance, Steps 3) - 4) were repeated at each of the remaining four viewing positions. Step 2) was repeated. At the second viewing distance, Steps 3) - 4) were repeated five times.

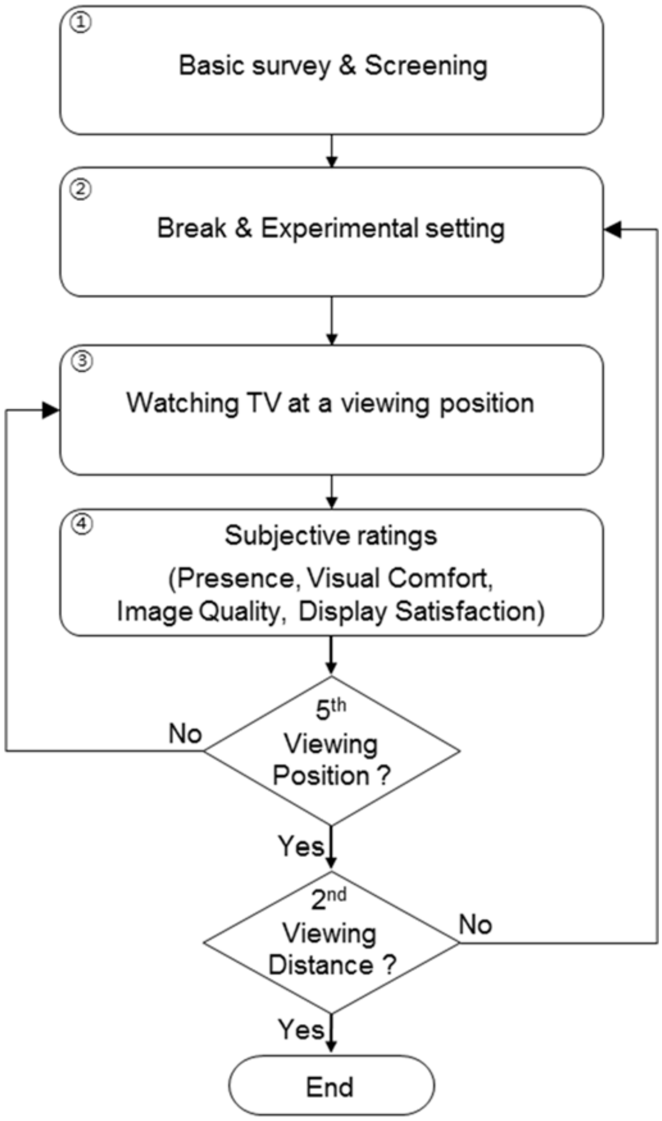

Figure 5.3 Experimental procedure

5.2.3. Independent variables

Three independent variables were investigated. The display curvature varied between subjects at four levels: 2300 R (providing a 30° 'effective' field of view at 4 m viewing distance), 4000 R and 6000 R (adopted in commercialized TV models: UN55JU7550F, Samsung, Korea; and 105UC9, LG, Korea), and flat (the control). All participants used five lateral viewing positions [P_1 (centred in front of the TV), P_2 (35 cm to the right of P_1), P_3 (70 cm off-centre), P_4 (105 cm off-centre), and P_5 (140 cm off-centre)] and two viewing distances [2.3 and 4 m, respectively equivalent to 1.9 display width (W), 3.4 display height (H); and 3.3 W and 5.8 H]. A wide range of viewing distances, 2–14 W and 0.8–7 H, have been used in previous studies (see table 5.5). Five pairs of viewing positions (P_1-P_3, P_2-P_4, P_3-P_5, P_4-P_2, and P_5-P_1) were used in random order, with the second individual 70 cm to the right of the first except in P_4-P_2, and P_5-P_1 (see figure 5.2).

5.2.4. Dependent variables

Seven dependent variables were used to assess watching experience: spatial presence, engagement, ecological validity, negative effects, visual comfort, image quality, and display satisfaction. The first four were sub-concepts of presence (Lessiter et al., 2001), which was assessed using 13 items selected from the Independent Television Commission-Sense of Presence Inventory (ITC-SOPI): three regarding spatial presence ('I had a sense of being in the scenes displayed', 'I felt I was visiting the places in the displayed environment', 'I felt that the characters and/or objects could almost touch me'), three regarding engagement ('I felt involved (in the displayed environment)', 'I enjoyed myself', 'My experience was intense'), three regarding ecological validity ('The content seemed believable to me', 'The displayed environment seemed natural', 'I had a strong sense that the characters and objects were solid'), and four regarding negative effects ('I felt dizzy', 'I felt nauseous', 'I felt I had a headache', 'I felt I had eyestrain'). Each item was rated on a 5-point Likert scale (0: strongly disagree, 1: disagree, 2: neutral, 3: agree, 4: strongly agree), and the mean item values of each sub-concept were used in statistical analyses. Visual comfort, image quality, and display satisfaction were respectively rated on a 100 mm visual analogue scale (VAS) (0: Very uncomfortable, 100: Very comfortable), a 5-point scale (bad, poor, fair, good, and excellent), and a 100 mm VAS (0: Very unsatisfied, 100: Very satisfied).

5.2.5. Statistical analysis

A mixed three-way analysis of variance (ANOVA) was used to examine the main and interaction effects of display curvature, viewing distance, and lateral viewing position on the seven dependent variables described above. When an effect was significant, a Tukey's honestly significant difference test was conducted. In addition, when the main effects of display curvature and lateral viewing position were significant, two linear contrasts were used – C_1: (2300 R + 4000 R + 6000 R) / 3 vs. flat and C_2: P_1 vs. (P_2 + P_3 + P_4 + P_5) / 4. A stepwise multiple linear regression analysis was performed for each element to determine the degree to which their variability was accounted for by display curvature, viewing distance, lateral viewing position, and these interactions. The flat condition was defined as 100,000 mm. An additional stepwise multiple linear regression analysis was performed to examine the degree to which display satisfaction variability (satisfaction associated with watching TV) was accounted for by the six other watching experience elements. P-values of 0.1 (for predictors to enter or leave the model) were applied as thresholds when constructing the stepwise multiple linear regression models (Huang et al., 2015; Sharma et al., 2016). All statistical analyses were performed using JMP™ (v12, SAS Institute Inc., NC, USA), with a significance threshold of $p < 0.05$.

5.3. Results

5.3.1. Presence

5.3.1.1. Spatial presence

The interaction effect of display curvature × viewing distance × lateral viewing position was significant for spatial presence (*p = 0.004*). Twenty of the 40 treatments were in the same group (A) using the 4000 R–4 m–P_1 condition, which provided the highest mean (SD) spatial presence of 3.3 (0.5) (Figure 5.4). Lateral viewing position also had a significant effect (*p <0.0001*), with four groups (P_1-P_2, P_2-P_3, P_3-P_4, and P_5). The mean (SD) spatial presence was highest at P_1 (2.8 (0.9)) and lowest at P_5 (2.2 (1.1)). The C_2 was significant (*p <0.0001*) with a higher mean (SD) for P_1 vs. ($P_2 + P_3 + P_4 + P_5$) / 4 (2.8 (0.9) vs. 2.5 (0.8)).

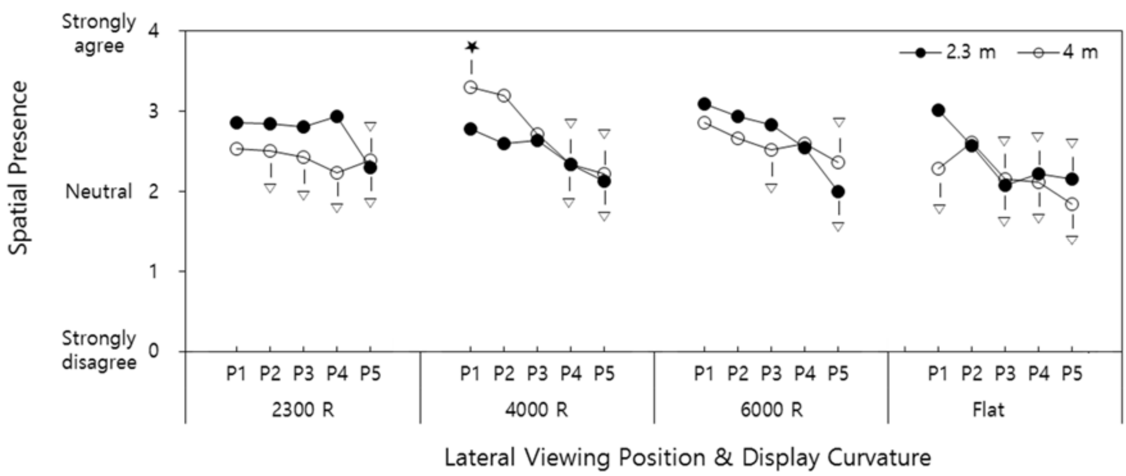

Figure 5.4 Effects of display curvature, viewing distance, and lateral viewing position on Spatial Presence (P_1: Center position, P_5: Rightmost position; ★: highest spatial presence and in group 'A', ▽: not in group 'A'; Range of SDs: 0.4 – 1.4)

5.3.1.2. Engagement

The interaction effect of display curvature × viewing distance × lateral viewing position was significant for engagement (*p = 0.022*). Twenty-five of 40 treatments were in the same group (A) as that of the 4000 R–4 m–P_1 condition, which provided the highest mean (SD) engagement of 3.1 (0.6) (Figure 5.5). Lateral viewing position also had a significant (*p <0.0001*), with three groups (P_1-P_2, P_2-P_3-P_4, and P_4-P_5). The mean (SD) engagement was highest at P_1 (2.9 (0.9) and lowest at P_5 (2.3 (1.1). The C_2 was significant (*p <0.0001*) with a higher mean (SD) for P_1 vs. (P_2 + P_3 + P_4 + P_5) / 4 (2.9 (0.8) vs. 2.5 (0.7)).

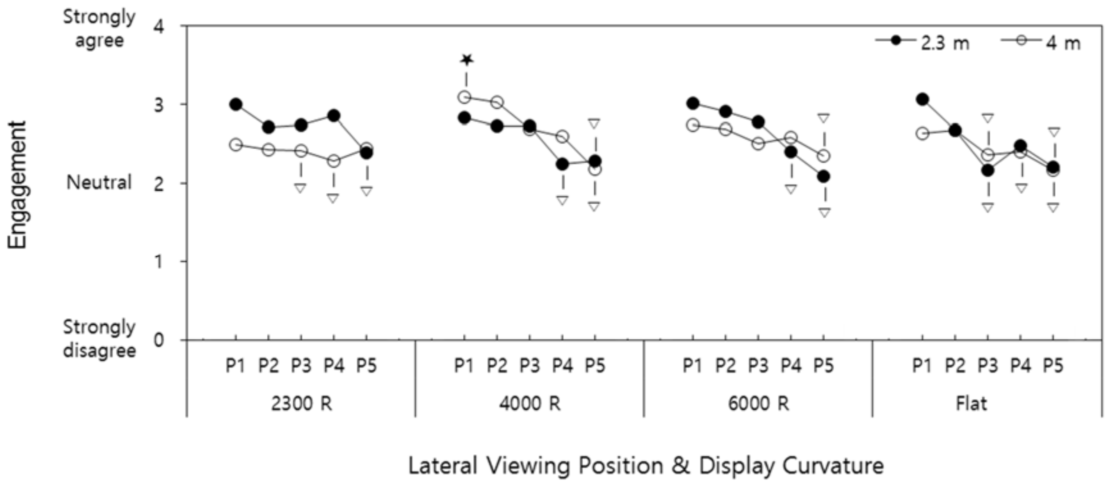

Figure 5.5 Effects of display curvature, viewing distance, and lateral viewing position on Engagement (P_1: Center position, P_5: Rightmost position; ★: highest engagement and in group 'A', ▽: not in group 'A'; Range of SDs: 0.5 – 1.2)

5.3.1.3. Ecological validity

The interaction effect of viewing distance × lateral viewing position was significant for ecological validity (*p = 0.031*). Six of ten treatments were in the same group (A) as that of the 4m–P_1 condition, which provided the highest mean (SD) ecological validity of 3.0 (0.6) (Figure 5.6). Lateral viewing position was also significant (*p <0.0001*) with three groups (P_1-P_2-P_3, P_2-P_3-P_4, and P_4-P_5). The mean (SD) ecological validity was highest at P_1 (3.0 (0.8)) and lowest at P_5 (2.6 (1.0)). The C_2 was significant (*p <0.0001*) with a higher mean (SD) for P_1 vs. (P_2 + P_3 + P_4 + P_5) / 4 (3.0 (0.7) vs. 2.7 (0.6)).

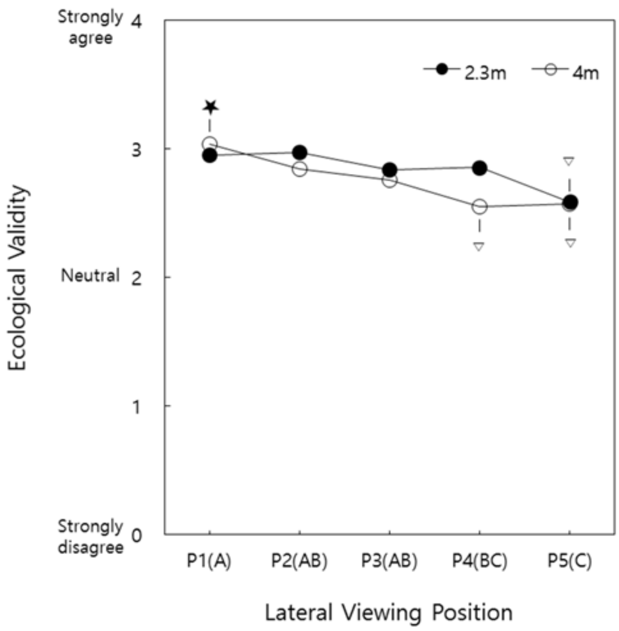

Figure 5.6 Effects of display curvature, viewing distance, and lateral viewing position on Ecological Validity (P_1: Center position, P_5: Rightmost position; ★: highest ecological validity and in group 'A'; ▽: not in group 'A'; Range of SDs: 0.4 – 1.1)

4.3.1.4. Negative effects

Although display curvature (*p=0.027*) and lateral viewing position (*p=0.047*) significantly influenced negative effects, all treatments were grouped into the same group (Figure 5.7).

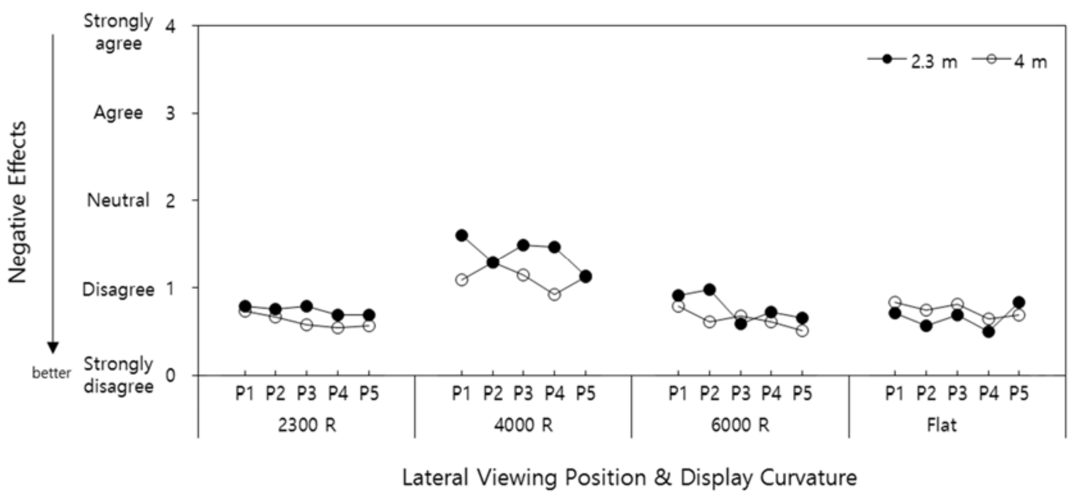

Figure 5.7 Effects of display curvature, viewing distance, and lateral viewing position on Negative Effects (P_1: Center position, P_5: Rightmost position; Range of SDs: 0.4 – 1.0)

5.3.2. Visual comfort

Viewing distance significantly affected visual comfort (*p=0.035*) with a higher mean (SD) at a viewing distance of 4 m vs. 2.3 m (61.4 (19.3) vs. 58.1 (19.6); Figure 5.8).

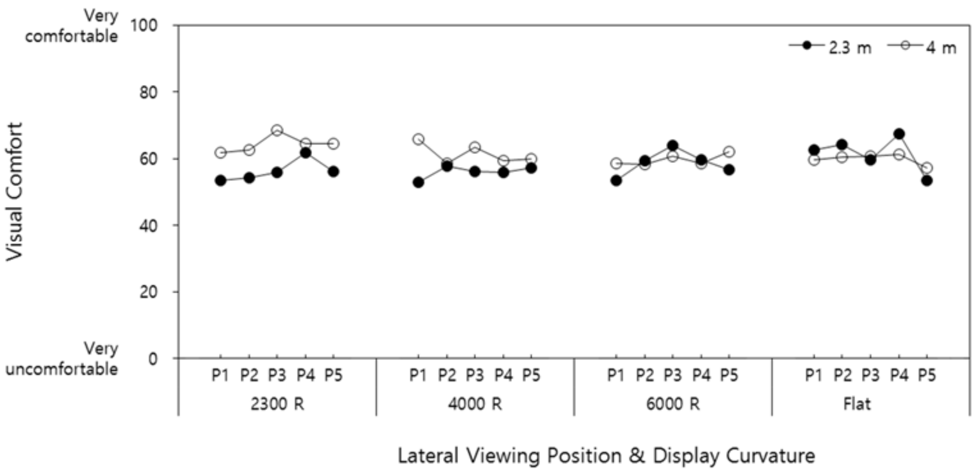

Figure 5.8 Effects of display curvature, viewing distance, and lateral viewing position on Visual Comfort (P_1: Center position, P_5: Rightmost position; Range of SDs: 13.8 – 24.9)

5.3.3. Image quality

Lateral viewing position significantly affected image quality (*p=0.0009*) with two groups (P_1-P_2 and P_2-P_3-P_4-P_5; Figure 5.9). The mean (SD) image quality was highest at P_1 (2.7 (0.9)) and lowest at P_5 (2.4 (0.9)). The C_2 was significant (*p=0.004*) with a higher mean (SD) for P_1 vs. (P_2 + P_3 + P_4 + P_5) / 4 (2.7 (0.9) vs. 2.5 (0.8)).

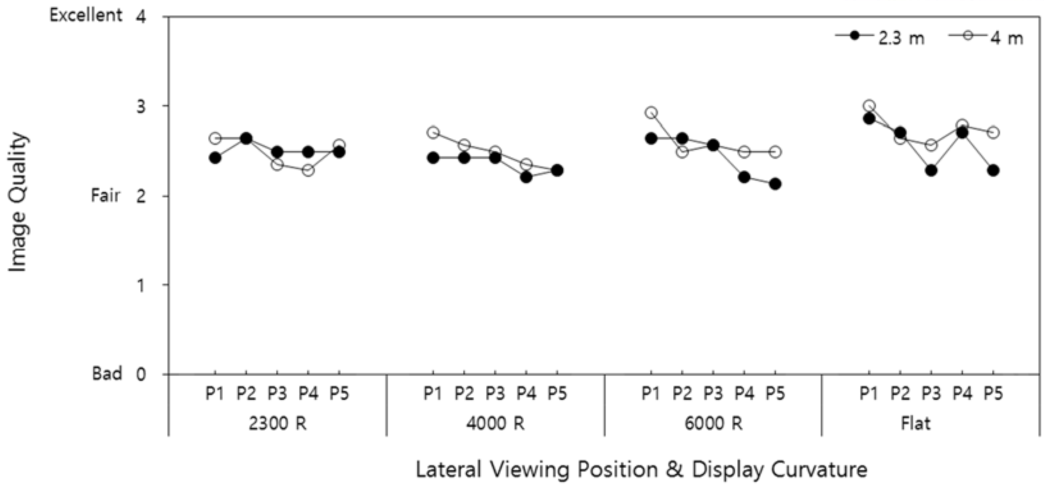

Figure 5.9 Effects of display curvature, viewing distance, and lateral viewing position on Image Quality (P1: Center position, P5: Rightmost position; Range of SDs: 0.7 – 1.2)

5.3.4. User satisfaction

Lateral viewing position significantly affected User satisfaction (*p<0.0001*) with three groups (P_1-P_2-P_3, P_2-P_3-P_4, and P_4-P_5; Figure 5.10). The mean (SD) User satisfaction was highest at P_1 (69.9 (14.4)) and lowest at P_5 (61.2 (17.8)). The C_2 was significant (*p=0.004*) with a higher mean (SD) for P_1 vs. (P_2 + P_3 + P_4 + P_5) / 4 (69.9 (14.4) vs. 65.2 (13.0)).

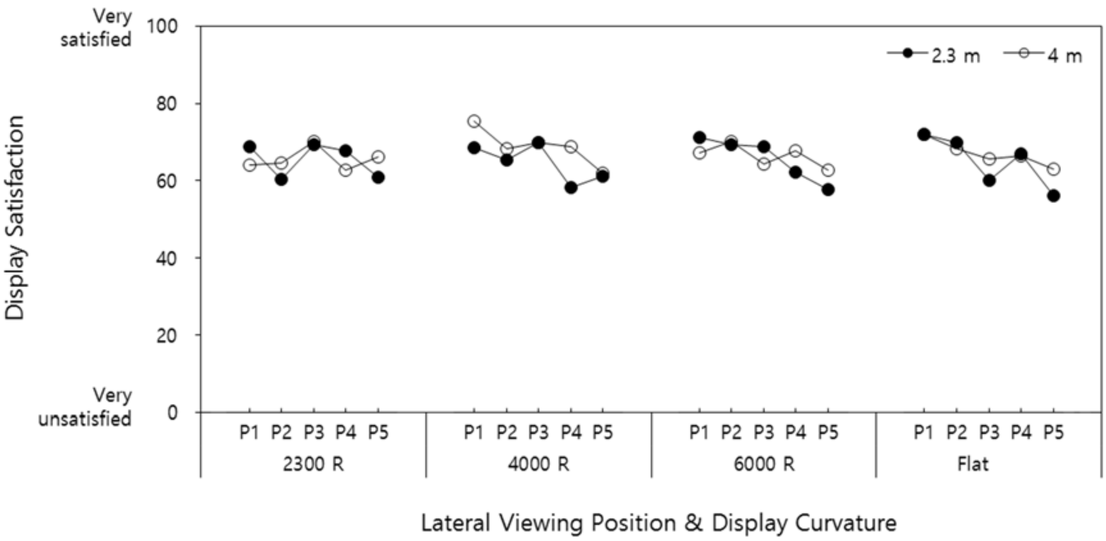

Figure 5.10 Effects of display curvature, viewing distance, and lateral viewing position on Display Satisfaction (P_1: Center position, P_5: Rightmost position; Range of SDs: 7.7 – 23.5)

5.3.5. Stepwise regression of dependent variables on display curvature, viewing distance, and lateral viewing position

Stepwise multiple linear regressions were conducted for each dependent variable regarding display curvature, viewing distance, lateral viewing position, and their interactions, with adjusted R^2 values ranging between 0.01 (for visual comfort) and 0.08 (for spatial presence). These three independent variables and their interactions hence accounted for 1–8% of watching experience element variabilities (Table 5.3).

Table 5.3 Results of stepwise multiple regression of each of seven watching experience elements on display curvature, viewing distance, lateral viewing position, and their interactions

Dependent variables		Spatial presence	Engagement	Ecological validity	Negative effects	Visual comfort	Image quality	User satisfaction
Coefficient (standardized beta weight)	Y intercept	2.96	2.87	2.95	1.21	53.74	2.62	70.0
	Display curvature (DC)	-3×10^{-6} (-0.14)		2×10^{-6} (0.10)	-2×10^{-6} (-0.11)		2×10^{-6} (0.08)	
	Viewing distance (VD)				-7×10^{-5} (-0.08)	0.002 (0.08)		
	Lateral Viewing Position	-0.0005 (-0.25)	-0.0004 (-0.23)	-0.0003 (-0.20)	-0.0001 (-0.07)		-0.0002 (-0.12)	-0.006 (-0.17)
	DC × VD				2×10^{-9} (0.08)			
Adjusted R^2		0.08	0.05	0.05	0.02	0.01	0.02	0.03
p-value		<0.0001	<0.0001	<0.0001	0.004	0.05	0.003	<0.0001

5.3.6. Stepwise regression of user satisfaction using other dependent variables

A stepwise multiple linear regression model using six watching experience elements as predictors accounted for 67.1% of display satisfaction variability ($R^2_{adj} = 0.67$). Variance influence factors (VIF) for each predictor ranged between 1.2–1.6 (table 5.4), indicating non-severe multicollinearity (Adeyemi et al., 2017). Based on standardized beta weights, the engagement (highest), visual comfort, and image quality were more determinative of display satisfaction than negative effects (lowest; see table 5.4). Two elements, spatial presence and ecological validity, were not included in the final regression model.

Table 5.4 Regression coefficients, standardized beta weights, and variance influence factors (VIFs) for the stepwise regression model of display satisfaction on six watching experience elements

Predictor	Coefficient	Standardized beta weight	VIF	p-value
Intercept	17.60	0	-	<0.0001
Engagement	7.87	0.43	1.3	<0.0001
Visual Comfort	0.33	0.40	1.6	<0.0001
Image Quality	3.94	0.22	1.2	<0.0001
Negative Effects	-1.67	-0.08	1.3	0.006

5.3.7. Principal component regression of user satisfaction

Three selected principal components (PCs) accounted for 68.5% of the total variance in display satisfaction (table 5.5). PC1 ('presence & image quality') consisted of ten items associated with spatial presence, engagement, ecological validity, and image quality. PC2 ('non-visual negative effects') contained three items related to non-visual aspects of negative effects. PC3 ('visual comfort') contained two items, one item on visual aspects of negative effects and the other on visual comfort.

Table 5.5 Three principal components from watching experience elements (after varimax rotation; values > 0.4 underlined)

Watching experience elements	Questions	PC1 (presence & image quality)	PC2 (non-visual negative effects)	PC3 (visual comfort)
Spatial presence	I had a sense of being in the scenes displayed.	0.80	0.12	0.25
	I felt I was visiting the places in the displayed environment.	0.81	0.08	0.23
	I felt that the characters and/or objects could almost touch me.	0.77	0.14	0.20
Engagement	I felt involved in the displayed environment.	0.73	0.15	0.32
	I enjoyed myself.	0.74	0.01	0.26
	My experience was intense.	0.77	0.07	0.25
Ecological validity	The content seemed believable to me.	0.81	-0.11	-0.04
	The displayed environment seemed natural.	0.76	-0.12	-0.08
	I had a strong sense that the characters and objects were solid.	0.70	-0.04	-0.02
Image quality	Evaluate the overall image quality of TV screen.	0.51	-0.13	0.06
Negative effects	I felt dizzy.	0.05	0.75	-0.20
	I felt nauseous.	0.00	0.77	-0.08
	I felt I had a headache.	0.01	0.78	-0.15
Negative effects	I felt I had eyestrain.	-0.14	0.34	-0.65
Visual comfort	Evaluate how comfortable your eyes were during TV watching.	0.26	-0.32	0.66
Eigen value		6.4	2.8	1.1
Cumulative percent		42.5	61.0	68.5

A multiple regression model using the three principal components as predictors accounted for 62% of the variability in display satisfaction ($R_{adj}^2 = 0.62$, $p < 0.0001$; table 5.6). Based on the standard beta weights, PC1 and PC3 accounted for display satisfaction more than PC2.

Table 5.6 Regression model for display satisfaction using three principal components determined by PCA with varimax rotation as predictors

Predictor	Coefficient	Standardized beta weight	VIF	p-value
Intercept	66.13	0	-	<.0001
PC1 (Presence + Image quality)	9.57	0.57	1.01	<.0001
PC2 (Non-visual negative effects)	-2.89	-0.16	1.01	<.0001
PC3 (Visual comfort)	9.00	0.46	1.02	<.0001

5.4. Discussion

This study examined the main and interaction effects of display curvature, viewing distance, and lateral viewing position on seven watching experience elements. In addition, three regression models were developed: 1) to explain each watching experience element using display curvature, viewing distance, lateral viewing position, and their interactive terms, and 2) to determine the relative importance of each watching experience element in explaining display satisfaction, and 3) to explain display satisfaction used three principal components comprised of 15 items associated with six watching experience elements as its predictors. This section discusses the similarities and differences between the observed results and those in previous studies while providing further interpretation.

5.4.1. Interaction effects of display curvature × viewing distance × lateral viewing position

The interaction of display curvature × viewing distance × lateral viewing position significantly affected both spatial presence and engagement. Spatial presence increased when the display curvature approached the viewing distance but decreased across display curvatures at more lateral viewing positions. Additionally, lateral viewing positions more adversely affected spatial presence in the flat condition than in curved conditions for all viewing distances. The 4000 R–4 m–P_1 condition provided the highest spatial presence. For 2.3 m viewing distance, spatial presence decreased by more than 30% (relative to 4000 R–4 m–P_1) at P_5 for 2300 R, 4000 R, and 6000 R conditions, but experienced this same decrease at P_3 for the flat condition. At 4 m viewing distance, this decrease was observed at P_5 for 4000 R, P_4 for 2300 R, P_3 for 6000 R, and P_1 for flat conditions. Engagement investigations showed similar results, with the highest engagement at 4000 R–4 m–P_1. At 2.3 m viewing distance, engagement decreased by more than 20% from this condition at P_5 for 2300 R, P_4 for 4000 R and 6000 R, and P_3 for flat conditions. At 4 m viewing distance, this decrease occurred at P_3 for 2300 R and flat conditions, but P_5 for 4000 R and 6000 R conditions.

5.4.2. Effects of display curvature

Display curvature had no evident effect on the seven watching experience elements. Though display curvature significantly influenced negative effects, all curvature settings were grouped into the same group during evaluation, with no significant effect on the remaining six elements. Contrarily, some previous studies showed curved displays provided better watching experiences than flat displays. Oh and Lee (2016) found visual presence at a viewing distance of 2 m was 18% (for 2D content) and 9% (for 3D content) higher on a 45" 4200 R curved TV relative to a flat screen, argued to be due to improvements in visual sensitivity at the lateral areas of the curved display. Mun et al. (2015) considered 'realness' as a presence factor during watching, which was higher on curved 55" 3D TVs relative to their flat counterparts when the viewing distance (5 m) was equal to the display curvature. Varying experimental durations and visual stimuli may have created these discrepancies.

Display curvature can also have a negative effect. Ohtsuka et al. (2015) reported negative shape aftereffects could occur when the curvature of an 80" display was smaller than 7692 R. Mustonen et al. (2015) observed slower visual processing speeds during a letter search task when a 4.5" 50 R (convex) display was used relative to 4.5" 100 R and flat display conditions. The effect of display curvature thus appears to depend on display size, curvature direction (convex or concave), curvature level, viewing distance, and lateral viewing position.

5.4.3. Effects of viewing distance

In this study, viewing distance was significant only to visual comfort, with 6% greater comfort at 4 m (5.8 H) than 2.3 m (3.4 H). These two viewing distances were within the range recommended by ITU-R BT.500-13 (2012) (3 H-7 H for flat HD TVs), though the 4 m (5.8 H) viewing distance exceeded the ranges recommended by Kwon and Lee (2007) for non-HD TVs, 5 H (29"), by Ardito et al. (1996), 3–5.2 H (38"), by Narita et al. (2001) and Sakamoto et al. (2008), 3–4 H, and by ITU-R BT. 2022 (2012), 0.8 H–4.8 H for HD TVs (see table 5.6 and figure 5.11). As the median and mean values of viewing distances observed in homes by Matsumoto et al. (2011) were 6 H and 6.5 H, respectively, viewing distances outside these recommended ranges appear common in practice. Lee (2012) reported the mean preferred viewing distance for visual comfort using HD TVs was 3.8 W (6.8 H) for 32" TVs, 3.6 W (6.5 H) for 37" TVs, and 3.6 W (6.5 H) for 42" TVs. These values are also above the values (6 H for 36" and 5 H for 73" HD TVs) recommended by ITU-R BT.500-13 (2012). It should be noted that these studies used different display sizes and resolutions.

Table 5.7 TV viewing distances used in the current study vs. those from the literature

	TV viewing distances	(m)	Relative to display width	Relative to display height	References
	Used in the current study	2.3 m and 4 m	1.9 W and 3.3 W	3.4 H and 5.8 H	-
Recommended for flat TV	Non-HD† TV (analogue TV)		12 W (max)		Chapman (1960)
Recommended for flat TV	Non-HD† TV (analogue TV)		5-14 W		Gausewitz (1964)
Recommended for flat TV	Non-HD† TV (analogue TV)		2-6 W		Wadsworth (1968)
Recommended for flat TV	Non-HD† TV (analogue TV)		4–12 W, and 6.25 W (optimum)		McVey (1970)
Recommended for flat TV	Non-HD† TV (analogue TV)	2 m, 1.3 m, and 3 m		5 H (highest presence) 3 H (median) 7 H (lowest) on 29"	Kwon and Lee (2007)
Recommended for flat TV	HD† TV			3–5.2 H (38")	Ardito et al. (1996)
Recommended for flat TV	HD† TV			3–4 H	Narita et al. (2001)
Recommended for flat TV	HD† TV			3–4 H (42" PDP TV)	Sakamoto et al. (2008)
Recommended for flat TV	HD† TV		3–4 W (32", 37", and 42")		Lee (2012)
Recommended for flat TV	SD or HD TV			7 H (27"), 6 H (36"), 5 H (73"), and 3–4 H (120")	ITU-R BT.500-13 (2012)
Recommended for flat TV	SD or HD TV			4.8 H (1280×720 pixel) 3.2 H (1920×1080 pixel) 1.6 H (3840×2160 pixel) 0.8 H (7680×4320 pixel)	ITU-R BT.2022 (2012)
Recommended for flat TV	SD or HD TV	1.1 m (17") and 1.7 m (42" & 65")		5.2 H (17")/3 H (42")/2 H (65")	Sakamoto et al. (2012)
Recommended for flat TV	UHD TV	2 m (2.5H), 0.5 m (0.6H) 4 m (5H)		2.5 H (highest presence) 0.6 H (median) 5 H (lowest) on 65" TV	Oh and Lee (2016)
	Observed	3.4 m (mean)			Nathan et al. (1985)
	Observed	2.7 m (mean)			Tanton (2004)
	Observed	2.7 m (mean)			Kubota et al. (2006)
	Observed	2.5 m (median)		6.0 H (median) and 6.5 H (mean)	Matsumoto et al. (2011)
	Surveyed	2–3 m (53% of 157 households)			Kwon (2006)

SD = Standard-Definition; HD = High-Definition; UHD = Ultra High Definition; PDP = Plasma Display Panel; †Non-HD includes SD.

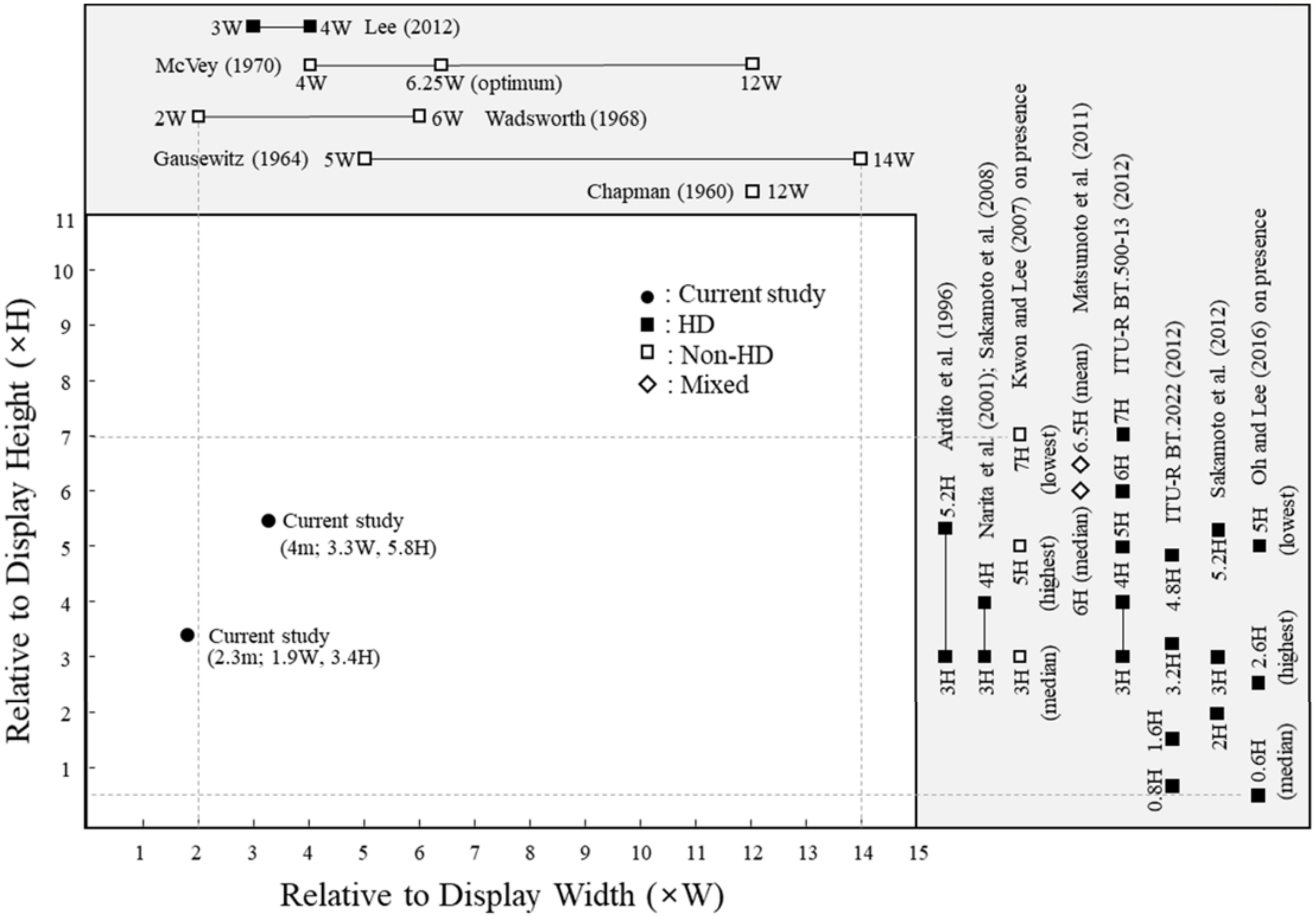

Figure 5.11 Viewing distances used in the current study vs. those from the literature (data in the grey area are available in terms of only one of display height and width; Recommended range values indicated by solid lines)

Although the viewing distance had no significant effect on the four sub-concepts of presence investigated here ($0.10 \leq p \leq 0.29$), three sub-concepts of presence (excluding negative effects) were better at 2.3 m than 4.0 m. An appropriate viewing distance for a given display size is required to enhance presence, whereas watching TV from excessively short or long distances decreases presence (Kim, 2003; Lombard, 1995). Kwon and Lee (2007) found the presence of 29" analogue TVs was highest at a viewing distance of 5 H (2 m), followed by 3 H (1.3 m) and 7 H (3 m). Sakamoto et al. (2012) found involvement, similar to engagement (Lessiter et al., 2001), was highest at a viewing distance of 5.2 H (1.1 m) for 17" TVs, 3 H (1.65 m) for 42" TVs, and 2 H (1.65 m) for 65" TVs, respectively. Oh and Lee (2016) found a viewing distance of 2.5 H (2 m) provided the highest visual presence when watching 2D images on 65" flat ultra-high-definition (UHD) TVs, followed by 0.6 H (0.5 m) and 5 H (4 m). When similar viewing conditions are considered, the current results resemble those of Kwon and Lee (2007), Sakamoto et al. (2012), and Oh and Lee (2016). The Flat-P_1 condition in this study had a greater spatial presence at 4 m (31.9%) than 2.3 m ($p = 0.04$).

5.4.4. Effects of lateral viewing position

This study found watching TVs from lateral viewing positions degraded the watching experience, decreasing spatial presence (11–23% at P_3–P_5), engagement (11–21% at P_3–P_5), ecological validity (10–24% at P_4–P_5), image quality (9–11% at P_3–P_5), and display satisfaction (7–12% at P_4–P_5) relative to P_1. Such watching experience degradations could be associated with the decreasing fields of view and increasing viewing angles created by lateral deviations.

5.4.5. Effects of field of view and viewing angle

Field of view did not appear to substantially influence watching experience in this study. Geometrically, the field of view increases as the display curvature approaches the viewing distance, as the viewing distance decreases, or when the viewing position approaches the center. Presence can increase with sensory area saturation according to decreased viewing distances or increased display sizes (Kim and Biocca, 1997), or with increases in attention and arousal levels related to increased fields of view (Reeves et al., 1999). Though the magnitude of the field of view was predominantly determined by viewing distance in this study, the effects of viewing distance (2.3 m and 4 m) on spatial presence, engagement, and ecological validity were insignificant. A wider field of view at a viewing distance of 2.3 m did not significantly increase presence, potentially partially due to the decrease in visual comfort created by the shorter viewing distance (visual comfort at 2.3 m was 5.4% lower than at 4 m). Conversely, lateral viewing position significantly affected presence, though it affected the field of view less than viewing distance. Fields of view at 2.3 m were wider than those at 4 m by up to 12.8° across lateral viewing positions, whereas the difference in the fields of view between viewing distances 2.3 m and 4.0 m at the same lateral viewing position was ≤ 8° (See Table 5.2). Some prior studies using varying screen sizes rather than viewing distances showed that field of view significantly influenced presence. Hou et al. (2012) found the physical presence during a 30 min gaming task was higher on an 81" (diagonal field of view = 76°) screen than on a 13" (18°) screen. Lin et al. (2002) showed the perceived presence during a driving task on a triple screen comprised of three 2300 × 1750 mm screens was highest with a 180° field of view, followed by with 140°, then 60°. However, the effect of viewing angle changed (as determined by lateral viewing position) on presence was not examined in these two studies.

Increasing the viewing angle reduces both presence and image quality. Viewing angles increase when the lateral deviation of viewing position increases. This study observed decreases in presence (in terms of spatial presence, engagement, and ecological validity) and image quality beginning at viewing angles of 17.0° (2.3 m–P_3) and 9.9° (4 m–P_3). Previous studies showed mixed results. In a study by Oh and Lee (2016), the visual presence of a 2D image on a 65" UHD flat TV at a viewing distance of 2 m deceased by 17% when the viewing angle was increased to 45° from 0°. Conversely, the presences on an 86” screen at a viewing distance of 0.9 H (1.75 m) showed no significant changes between three viewing angles (-19°, 0°, and +19°) in a study by Baranowski et al. (2016). This result could be due to the negative influence of decreases in perceived image quality (Blankenbach et al., 2015; Marsal et al., 2015; Teunissen et al., 2008) resulting from the increase in perceived display distortion as viewing angles exceed a certain level (Park et al., 2015b). This study found a positive relationship between image quality and spatial presence, engagement, and ecological validity, with corresponding bivariate correlations of 0.40, 0.36, and 0.53, respectively.

In order to better consider the effect of an actual TV viewing context on watching experience, it is necessary to allow for wider viewing angles. Though the largest viewing angle considered in this study (30.3° at a viewing distance of 2.3 m) exceeded the mean viewing angle of 23.3° obtained in a field survey (Kubota et al., 2006), it is not sufficiently large. Viewing angles observed in homes have ranged between ± 30° (Zhong et al., 2014), ± 45° (Fujine et al., 2007), and ±60° (Nathan et al., 1985)]. Thus, a future study will be required to consider viewing angles ranging between 30–60°.

5.4.6. Explaining the impact of display curvature, viewing distance, and lateral viewing position on each independent variable (stepwise regression)

The regression model developed for each watching experience element can be used to improve these elements individually by recommending a specific display curvature, viewing distance, or lateral viewing position, or by adjusting correlating TV settings accordingly. The developed regression models showed that viewing distance, lateral viewing position, and their interaction could account for 1–8% of the variability in watching experience elements. Spatial presence increased both when the display curvature decreased, and the lateral viewing position approached P_1. Based on standardized beta weights, the lateral viewing position was 1.8 times (= 0.25/0.14) more influential on spatial presence than the display curvature. Engagement increased as the viewing location approached P_1. Ecological validity increased both when the display curvature increased, and the lateral viewing location approached P_1. The lateral viewing position was 2.0 times (= 0.20/0.10) more influential on engagement than the display curvature. Negative effects reduced as the display curvature or viewing distance increased, and as the lateral viewing position approached P_1. The display curvature, viewing distance, and their interaction were 1.6 times (= 0.11/0.07), 1.1 times (0.08/0.07), and 1.1 times (0.08/0.07) more influential on negative effects as the lateral viewing position. Visual comfort increased as the viewing distance increased. Image quality increased as the display curvature increased or the lateral viewing position approached P_1. The lateral viewing position was 1.5 times (= 0.12/0.08) more influential on image quality than the display curvature. Finally, display satisfaction increased as the lateral viewing position approached P_1.

5.4.7. Predicting display satisfaction using measures of six watching experience elements

5.4.7.1. Stepwise multiple linear Regression analysis

In the current study, a regression model (R^2_{adj} = 0.67) for display satisfaction was developed using six watching experience elements. Based on the standardized beta weights, engagement, visual comfort, and image quality were 5.4 times (=0.43/0.08), 5.0 times (=0.40/0.08), and 2.8 times (=0.22/0.08) more influential on display satisfaction than negative effects.

5.4.7.2. Principal component regression (PCR)

In the PCR model developed for display satisfaction, PC1 (presence + image quality) was the most influential. Based on the standardized beta weights, PC1 and PC3 (visual comfort) had a 3.6 times (= 0.57/0.16) and 2.9 times (= 0.46/0.16) as influential to display satisfaction as PC2 (non-visual negative effects). The PCR model accounted for 62% of the total variation of display satisfaction. According to the standardized beta weights, display satisfaction increases as PC1 increases, PC3 increases, or PC2 decreases. In the study by Lin et al. (2002), enjoyment was positively correlated with presence, in which four out of five items to measure enjoyment were associated with satisfaction. In the study by Sylaiou et al. (2010), enjoyment and perceived spatial presence were also positively correlated. Bracken (2005) found that higher image quality enhanced spatial presence on a 65" TV. Skalski et al. (2011) reported that perceived naturalness during a gaming task increased spatial presence and enjoyment, and spatial presence, in turn, increased users' enjoyment. In Lin et al. (2002)'s study, enjoyment was negatively correlated with simulation sickness, which is consistent with a negative correlation between display satisfaction and PC2 (non-visual negative effects such as dizziness, nausea, and headache) observed in the current study. Also, some studies showed similar results to our findings that display satisfaction was positively correlated with PC3 (visual comfort). In So and Chan (2013)'s study, the LED display satisfaction deceased as eye strain was developed during four kinds of visual tasks for 1.5 h, In Iatsun et al. (2015)'s study, visual discomfort and visual fatigue had a negative influence on users' satisfaction during 1-h 2D and 3D video watching.

5.4.8. Limitations

Some limitations were encountered in the current study. First, display curvatures were simulated using Styrofoam, projection films, and a beam projector rather than using actual display panels. Though we used comparatively high-fidelity mock-ups (vs. static images attached to curved surfaces in (Ohtsuka et al., 2016; Park et al., 2015)), these mock-up displays were still different from actual displays. Second, 5 min videos were used in experiments. Previous studies on presence used task durations ranging from 1.5 min (Yang and Chung, 2012) to 1 hour (Sakamoto et al., 2012). Though 5 minutes is acceptable, a more thorough examination of the effects of longer-term TV watching on diverse watching experiences is warranted. Third, TV watching experience was subjectively evaluated. Some behavioral or physiological measures are available to assess presence, visual comfort, image quality, and display satisfaction (including eye movements (Iatsun et al., 2015), electrocardiograms (Iatsun et al., 2015), and electroencephalograms (Sakamoto et al., 2014)). Fourth, the effects of gender, age, and personal characteristics were not considered. In a study by Lombard et al. (2000), the effect of display size on presence was not significant in the male group, whereas the female group reported higher presence with wider displays. A separate study by Kwon and Lee (2007) saw that those with higher immersive tendencies reported higher presence during TV watching, but observed no significant gender effects. Ocular changes with age could also affect TV watching experiences. For example, functional degradations of the visual system with age (Owsley, 2011) and visual fatigue in presbyopic eyes (Hedman and Briem, 1984) can result in blurry vision. Personal characteristics (such as a willingness to suspend disbelief, knowledge or prior experience with the medium, and personal types (Heeter, 1992)) are also important factors for presence. Fifth, in addition to media form factors (display curvature, viewing distance, and lateral viewing position), media content factors (overall theme, narrative, and story) can influence watching experience in terms of involvement (Wirth et al., 2007), engagement, and ecological validity (Lessiter et al., 2001). To focus on the effects of three media form factors, however, this study controlled media content factors by using similar videos. Despite the above limitations, these findings can help to determine adequate levels of display curvature, viewing distance, and lateral viewing position for a better TV watching experience.

5.5. Conclusions

The current study considered the influence of display curvature, viewing distance, and lateral viewing position on TV watching experience. Spatial presence and engagement increased when the TV display curvature was equal to the viewing distance. The lateral viewing position was the most important factor for spatial presence, engagement, ecological validity, image quality, and display satisfaction, whereas the display curvature was most influential on negative effects and the viewing distance had the greatest effect visual comfort. Engagement and visual comfort had the greatest effects on display satisfaction. These findings can contribute to enhancing TV watching experiences by recommending specific levels of display curvature, viewing distance, and lateral viewing position as well as by providing information on the relative importance of each watching experience element.

Chapter 6. General Discussion and Conclusions

6.1. General Discussion

The major goals of this study were to determine ergonomic display curvatures and develop ergonomic guidelines for curved displays, by evaluating the influence of display curvatures on productivity, safety, and well-being. The detailed objectives are as follows: (1) to determine ergonomic display curvatures for monitors and TVs; (2) to evaluate the influence of display factors on visual ergonomic evaluation elements; and (3) to understand associations between the evaluation elements.

Three studies were conducted in a laboratory environment, and three types of curved display mock-up settings were developed that corresponded to commercialized monitors and TVs. The first study examined the effects of display curvature, display zone, task duration, and visual tasking on productivity (visual search speed and accuracy) and safety (visual fatigue) using 50" multi-monitors. The second study investigated the effects of display curvature and task duration on productivity (proofread speed and accuracy), safety (visual discomfort, subjective and objective visual fatigue, and mental workload), and well-being (user satisfaction) using 27" monitors. The third study evaluated the effects of display curvature, viewing distance, and lateral viewing position on seven TV watching elements (spatial presence, engagement, ecological validity, negative effects, visual comfort, image quality, and display satisfaction) for well-being with 55" TVs.

6.1.1. How display curvature affects productivity, safety, and well-being?

The results of this study indicate that curved displays can be more beneficial compared to flat displays regarding productivity, safety, and well-being. Some display curvature settings showed a higher productivity compared to the flat setting. In the 50" multi-monitor study, visual search speed and accuracy were both better at the 600 R and 1200 R settings compared to the 400 R and flat settings. Also, proofreading speed was fastest at the 600R setting on the 27" monitor. A curved display appeared to be partially better over a flat display regarding safety. Some display curvature settings induced lower visual fatigue compared to the flat setting. Visual fatigue was lower at the 600 R and 1200 R settings compared to the flat setting on the 50" multi-monitor. In the 27" monitor study, however, display curvature did not affect visual fatigue. The curved display appeared to be more advantageous over a flat display regarding well-being. Compared to the 55" flat TV setting, a curved display provided viewing positions without the degradation of spatial presence and engagement was broader when its display curvature radius approached the viewing distance.

The concepts of viewing angle, viewing distance, and empirical horopter can explain the advantages of curved displays in this study. Viewing angle increased when the curvature was more planar or more curved than a specific viewing distance. These changes may influence the visual task performance. In previous studies, an increase in the viewing angle led to a distortion of images on displays (Cai et al., 2013; Lee, 2012) or an increase of anisotropy (Oetjen and Ziefle, 2009), leading to a fall in legibility in terms of error (Bezerianos and Isenberg, 2012; Wigdor et al., 2007), an increase in perceived image distortion (Oh and Lee, 2016) and a decrease in perceived image quality (Blankenbach et al., 2015; Teunissen et al., 2008). The curved display provided a more uniform viewing distance compared to flat displays. Display curvature changed the viewing distance from the user to the display surface. Accommodative responses may be required to read the visual stimuli on the displays during the visual tasks. Time latencies of 0.16 - 0.18 s for vergence (Mustonen et al., 2015) and 0.3 - 1 s for accommodation (Campbell and Westheimer, 1960) can affect the letter searching speed. Curved displays were more beneficial when display curvature was closer to the empirical horopter than flat horopter. Visual stimulus in the curved settings of 600 R and 1200 R for the 50” multi-monitor at a 500 mm viewing distance and the 600 R of the 27” curved monitor at 600 mm were relatively closer to the empirical horopter. They provided higher task performance and lowered visual fatigue compared to flat conditions. Both the 2300 R- 2300 mm and 4000 R- 4000 mm conditions for the TV were relatively closer to the empirical horopter and showed better watching experiences.

The results of this study supported the fact that an ergonomic curvature corresponds to a specific viewing distance during a visual task. The suitable curvature radius for a 50" display setting at a viewing distance of 500 mm was likely to be slightly greater than 500 R. For the 27” monitor at a viewing distance of 600 mm, proofreading speed was faster, at 600 R compared other curvature levels. For the 55” TV, watching experience was greater when the display curvature equaled the viewing distance. Similar results were reported in previous studies. The appropriate curvature for a 23” curved display was 633R at a viewing distance of 600 mm regarding preference and visual comfort, and the realness on the 55” TV at 5 m was better with 5000 R condition (Mun et al., 2015). However, the positive effect of curvature was reduced owing to image distortion when the radius of the curvature was smaller than the viewing distance (i.e., the 400 R setting). Therefore, an adequate display curvature, considering the other factors that constitute the visual environment, may be effective when using a curved display.

6.1.2. Rest-time interval recommendation

A prolonged VDT task may be averse to workers. Appropriate rest-time criteria were required to diagnose and prevent computer vision syndrome caused by a prolonged VDT task. Frequent and short rest breaks from VDT work increased productivity and the well-being of workers (Henning et al., 1997). The results of this thesis can be used as a criterion to suggest appropriate rest-time intervals from the perspectives of visual discomfort and visual fatigue. Based on the findings of studies 1 and 2, a break was recommended after 15 minutes of a VDT task. In Study 1 (50" multi-monitor), subjective visual fatigue increased with task duration. Subjective (ECQ) and psychophysical (CFF) visual fatigue increased after the 30-min visual search task. In Study 2, proofreading accuracy, visual discomfort, visual fatigue, and mental workload deteriorated after the 15-min proofreading task. Previous studies found that a frequent and short break schedule was more beneficial for enhancing visual task performance and reducing visual fatigue, and the interval of 25 min (Shieh and Chen, 1997) - 60 min (Galinsky et al., 2000) for visual task performance was proposed. A rest-time interval of 1 hour (New Zealand Accident Compensations Corporation, 2010), 1 or 2 hours (OSHA, 1997), and 1 hour for high visually demanding work and 2 hours for moderate visually demanding work (National Institute for Occupational Safety and Health (NIOSH)) were recommended. The rest-time interval proposed in the current study was considerably shorter than the recommended breakpoint. It seems that the breakpoint should be flexible, depending on the type of VDT tasks.

6.1.3. Association between visual discomfort and subjective visual fatigue

Visual discomfort had been known to be usually related to visual fatigue (Lambooij et al., 2009) and prolonged visual discomfort influenced visual fatigue (Lebreton, 2016). In this study, a segmented linear relationship between visual discomfort and subjective visual fatigue showed a higher explanatory power compared to a simple linear regression. The explanatory power of the segmented regression was the highest (51%), compared to the linear and quadratic regression models. Visual discomfort and subjective visual fatigue increased simultaneously. However, the perceived visual fatigue level was more severe when visual discomfort exceeded a specific point. Based on the slopes of the fitting line, visual fatigue gradually increased with low levels of visual discomfort, whereas visual fatigue increased rapidly when visual discomfort was higher than 66.3 (in the range from 0 to 100).

6.1.4. Predictive models for subjective visual fatigue and user satisfaction

Based on predictive accuracy, each stepwise multiple regression model was selected for subjective visual fatigue and user satisfaction during a proofreading task on 27” monitors. The developed stepwise models accounted for 70.4% of the subjective visual fatigue variability and 60.2% of the user satisfaction variability, respectively. Also, each principal component regression analysis was performed to identify the degree to which composite variables affect the subjective visual fatigue and user satisfaction on 27” monitors. The first developed PCR model accounted for 49.3% of the subjective visual fatigue variability and showed that visual discomfort and workload were more determinative of subjective visual fatigue than visual task performance. The second PCR model accounted for 25.0% of the user satisfaction variability and showed that eye fatigue and workload were more determinative of user satisfaction than ocular movement. Furthermore, a stepwise multiple linear model was performed to develop a model accounting for display user satisfaction during TV watching tasks on s 55” TV. The stepwise regression model accounted for 67.1% of the display satisfaction variability and showed that engagement and visual comfort were more influential on display satisfaction compared to negative effects (e.g., dizziness, nausea, and headache).

6.2 Conclusions

6.2.1. Major outcomes

The ultimate goal of this study was to determine ergonomic display curvatures regarding VDT workers' productivity, visual safety, and well-being in order to develop ergonomic design guidelines. The major findings are given below.

An ergonomic display curvature could improve users' productivity, safety, and well-being. Firstly, some display curvature settings showed better productivity compared to the flat setting. Visual search accuracy and speed on a 55" multi-monitor were better at the 600 R and 1200 R settings compared to the 400 R and flat settings. Similarly, proofreading speed was fastest at the 27" 600 R setting. Secondly, some display curvature settings provided greater safety than the flat setting. Visual fatigue was lower at the 50" 600 R and 1200 R settings compared to the flat setting. In the 27" monitor study, however, the effect of the display curvature on visual fatigue was not significant. Thirdly, the curved display appeared to be more advantageous over flat display regarding well-being. Spatial presence and engagement improved when the TV display curvature was similar to the viewing distance. If carefully selected, display curvature can thus increase productivity, safety, and well-being. In this respect, bendable displays can be an effective solution.

Assuming that the experimental result is geometrically symmetrical, it will be appropriate to watch TV at a watching position that is ≤ 35 cm laterally deviated from the display center to improve the watching experience. In the 55" TV study, the lateral viewing position was the most determinative factor for the watching experience. Spatial presence, engagement, ecological validity, image quality, and display satisfaction declined at more lateral viewing positions, while the watching experience elements did not significantly decrease at a 35 cm laterally deviated position.

Although a positive linear relationship between visual discomfort and subjective visual fatigue was found, a segmented linear regression model provided a better fit for the two variables. If visual discomfort is measured instead of visual fatigue, visual fatigue can be predicted before it occurs. Also, four predictive models, developed in Study 2, could account for 70.4% of the variability in visual discomfort, 73.9% in subjective visual fatigue, 66.7% in mental workload, and 60.2% in user satisfaction.

Based on the findings, one general and four specific guidelines were suggested for curved monitors and TVs as follows.

General Guideline

- A display curvature radius similar to the viewing distance provides ergonomic benefits for monitors and TVs. (Based on Studies 1,2, and 3)

Guidelines for Monitors

- A display curvature of 600 R is recommended for office VDT tasks on 50” (1220 mm × 382 mm) monitors at the viewing distance of 500 mm, in consideration of productivity and safety. (Based on Study 1)

- A display curvature of 600 R is recommended for office VDT tasks on 27” (603 mm × 346 mm) monitors at the viewing distance of 600 mm, in consideration of productivity. (Based on Study 2)

Guidelines for TVs

- A display curvature that equals a specific viewing distance is recommended for watching videos on 55” (1218 mm × 685 mm) TVs to improve presence. (Based on Study 3)

- To maintain a better viewing experience at a viewing distance of 2.3 m or 4 m, it is recommended to watch videos on a 55” TV at a viewing position ≤ 35 cm lateral to the TV center. (Based on Study 3)

6.2.2. Limitations

Some limitations were encountered in this work. Firstly, display curvatures were simulated using multi-monitors (Study 1), rear screens (Study 2), and Styrofoam screens (Study 3), rather than using actual display panels. Although the rear screen and the Styrofoam screen may provide a relatively high accuracy experimental setting compared to the existing studies, our mock-up displays were still different from actual displays in terms of resolution, brightness, color temperature, and reflected glare. Secondly, this work used specific display sizes. Study 1 was conducted on 50" multi-monitors, Study 2 on 27" monitors, and Study 3 on 55" TVs. Thirdly, this study was conducted on horizontally curved displays as only the empirical horizontal horopter was considered. Fourthly, 30 min and 60 min visual tasks were used in Study 1 and Study 2, respectively. A relatively low level of visual fatigue was reported. Also, 5 min videos were used in Study 3. Next, the effects of gender, age, and personal characteristics were not considered. This study was conducted on subjects in their 20s and 30s. In Study 2 and Study 3, the ratio of male and female by curvature condition was not constant, but no significant difference was found by gender in the additional test. Lastly, most of the participants in this study were non-experienced users of a curved display product. Thus users may not have been sufficiently accustomed to using curved displays regarding visual perception.

6.2.3. Expected contributions and future work

This work will contribute to determining ergonomic display curvatures in consideration of productivity, safety, and well-being. The findings of the first and second studies can be used to determine appropriate display curvature ranges depending on the intention of monitor usage regarding productivity and safety. And the results of the third study can contribute to prioritizing elements of the watching experience during the TV design process, and manipulating display factors to enhance the TV watching experience. In addition, the results of the current study can help provide the relative importance of each watching experience element while determining the overall display satisfaction. The developed models in this thesis will be beneficial for human factor engineers and UX designers, allowing them to diagnose display users' visual state and to design display products more efficiently.

Further research is needed regarding the limitations of this study. Firstly, further researches involving actual curved display products and various display sizes are required to ensure the validity of the research results. Secondly, it is necessary to evaluate the vertically curved display or the hemispherical curved display, to investigate the effects of the empirical vertical horopter. Thirdly, to generalize the results of this study, it is required to consider other tasks, such as word processing, graphics designing, and gaming. Fourthly, longer-term VDT task duration should be considered, taking into account the actual context of VDT work, such as daily working time of VDT workers and general playtime of video contents. Lastly, in consideration of personal differences, various individual characteristics, such as presbyopia, gender, age, product experience, and vision correction aids should be considered for the further studies.

Acknowledgements

뒤늦은 결심으로 설렘과 두려움을 안고 시작했던 학위과정을 드디어 무사히 마치게 되었습니다. 이제 모든 과정을 마무리하며 학위과정동안 도움을 주셨던 분들께 감사의 인사를 드립니다.

지난 6 년 6 개월 동안 항상 저의 건강을 걱정해 주시며 응원해 주신 부모님께 감사와 사랑의 마음을 전합니다. 끝의 기약이 없는 학업의 길로 도전하고 싶다는 아들의 고민에 대해 불투명한 미래가 걱정되었지만, 아들을 믿는다는 격려와 함께 흔쾌히 진학을 허락해 주셨습니다. 부모님의 믿음과 사랑은 제가 학위과정을 무사히 마칠 수 있었던 가장 큰 원동력이었습니다. 앞으로도 지금처럼 건강하셔서 자랑스러운 아들로서 오래오래 효도할 수 있는 기회를 주셨으면 좋겠습니다. 사랑합니다.

비 전공자였던 저를 제자로 받아주시고 인간공학이라는 학문에 즐거움을 깨우쳐 주신 경규형 지도교수님께 큰 감사와 존경의 말씀을 올립니다. 학위논문을 준비하며 부족했던 저를 위해 많은 관심과 애정으로 지도해 주셨고 때로는 따끔한 질책을 통해 나태해진 저를 각성할 수 있도록 이끌어주셔서 인간적인 면에서도 성숙한 연구자가 될 수 있었습니다. 또한, 학위논문을 준비하며 심사를 위해 애써 주시고 어려움에 대해 진심 어린 조언을 주신 존경하는 곽영신 교수님과 권오상 교수님, 심사를 위해 귀한 시간을 내어 먼 곳에서 와 주신 석현정 교수님과 이승배 마스터님께도 감사의 말씀을 올립니다.

서은용과 이지현 두 분에게 특별한 감사의 마음을 전합니다. 푸르렀던 고등학생시절부터 서로 다른 전공이었지만 대학과 대학원까지 같은 학교를 다니며, 20 년 가까이 친구이자 동료이며 멘토로서 인간적, 학문적 고민을 함께 나누었고, 특히, 여러 고비 때마다 언제나 내편으로 나를 도와주었던 친구 서은용! 고맙다! 그리고, 연구실 인턴으로 처음 만나 힘들고 즐거웠던 여러 일들을 함께 겪었고, 연구에 대해 함께 고민해 주었고, 제 졸업 준비를 위해 본인을 희생하며 아낌없는 도움을 준 지현양에게 미안함과 함께 큰 고마움을 전합니다. 언제나 지금처럼 같이 있으며 행복한 사람들로서 함께하길 바랍니다.

마지막으로 디스플레이를 대상으로 한 연구의 시작부터 함께 동고동락했던 듬직한 동지였던 최동희 학생에게도 감사의 마음을 전합니다. 실험 환경을 제작하기 위해 밤늦도록 함께 보냈던 시간과 데이터 분석에 대한 의견을 나누며 함께 발전할 수 있어서 즐거웠습니다. 그리고 저와 연구 분야는 달랐지만 디스플레이의 제작과 실험 진행에 많은 도움을 준 이송일 학생에게도 고마움을 전합니다. 늘 새로운 연구주제를 고민하고 미래를 준비하는 모습에 선배이지만 많이 배울 수 있었습니다. 마지막으로 연구실의 궂은 일은 도맡아 하지만 언제나 밝고 착한 막내 김민중 학생에게 미안함과 함께 고마움을 전합니다.

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Appendix A: Questionnaire for the 50” monitors study

Legibility　　　　　　　　　　　　　　　　　　　　　　　　　　　　피험자 번호 ____

눈의 상태와 관련된 설문조사

> 안녕하십니까? 바쁘신 와중에도 실험에 참가해주셔서 감사합니다.
>
> 저희는 울산과학기술대학교 인간 및 시스템공학과 idealab의 연구원입니다.
>
> 본 실험은 대화면 모니터를 개선하기 위한 연구로 다양한 시각작업이 포함되어 있습니다.
> 본 설문지는 귀하와 관련된 일반적 질문과 실험 전후 귀하의 눈의 상태 (경미한 통증이나 피로감)에 대한 질문 두 가지 영역으로 구성되어있습니다.
> 귀하께서 성심 성의껏 작성해주신 의견은 통계법 제 8조에 의거하여, 비밀이 보장되고 본 연구의 진행을 위한 통계적 자료로 사용되는 목적 이외에는 사용되지 않습니다.
>
> 다시 한번 실험에 참가해주셔서 감사 드립니다.

I. 일반적 특성

- 귀하와 관련된 일반적 질문 또는 간단한 눈 검사가 필요한 사항입니다.
  아래 질문에서 답해 주시기 바랍니다.

0. 이름: (　　　　　　　　　　　　　　　)
1. 성별: □ 남　　　□ 여
2. 연령: 만 (　　　　) 세
3. 시력 (검사후 기입): 좌 (　　　) 우 (　　　)
4. 색맹유무 (검사후 기입): (　　　　　　　)
5. 우위안 (더 자주 쓰는 눈) (　　　　　　　) * 안내되는 절차에 따라 확인됩니다.
6. 현재 본인의 눈 건강 상태에 대해 서술해 주십시오 (과거에 앓았던 질병이나, 최근 눈에 문제가 있어 병원에 갔었다 등의 의견을 구체적으로 서술해 주십시오)

Legibility

피험자 번호 ____

실험조건 (1)

● 실험 전

1. 눈의 경미한 통증이나 피로감 확인 (ECQ)

다음 항목은 눈의 상태에 관련된 항목들입니다. 1번부터 10번의 각 항목에 대해 현재 눈의 상태를 가장 잘 나타내는 곳을 골라 하나만 체크 (v) 해 주시기 바랍니다.

	전혀 그렇지 않다	거의 그렇지 않다	약간 그렇다	다소 그렇다	적당히 그렇다	상당히 그렇다	매우 그렇다
1. 눈으로 보는데 어려움이 있다	☐	☐	☐	☐	☐	☐	☐
2. 눈꺼풀이 무겁다	☐	☐	☐	☐	☐	☐	☐
3. 눈이 아프다	☐	☐	☐	☐	☐	☐	☐
4. 눈물이 나온다	☐	☐	☐	☐	☐	☐	☐
5. 눈이 화끈거린다	☐	☐	☐	☐	☐	☐	☐
6. 눈이 피로하다	☐	☐	☐	☐	☐	☐	☐
7. 눈 주변이 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈의 건조하다	☐	☐	☐	☐	☐	☐	☐

● 실험 후

2. 눈의 경미한 통증이나 피로감 확인 (ECQ)

다음 항목은 눈의 상태에 관련된 항목들입니다. 1번부터 10번의 각 항목에 대해 현재 눈의 상태를 가장 잘 나타내는 곳을 골라 하나만 체크 (v) 해 주시기 바랍니다.

	전혀 그렇지 않다	거의 그렇지 않다	약간 그렇다	다소 그렇다	적당히 그렇다	상당히 그렇다	매우 그렇다
1. 눈으로 보는데 어려움이 있다	☐	☐	☐	☐	☐	☐	☐
2. 눈꺼풀이 무겁다	☐	☐	☐	☐	☐	☐	☐
3. 눈이 아프다	☐	☐	☐	☐	☐	☐	☐
4. 눈물이 나온다	☐	☐	☐	☐	☐	☐	☐
5. 눈이 화끈거린다	☐	☐	☐	☐	☐	☐	☐
6. 눈이 피로하다	☐	☐	☐	☐	☐	☐	☐
7. 눈 주변이 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈의 건조하다	☐	☐	☐	☐	☐	☐	☐

Appendix B: Questionnaire for the 27” monitors study

Proofreading 피험자 번호 ____

눈의 상태와 관련된 설문조사

안녕하십니까? 바쁘신 와중에도 실험에 참가해주셔서 감사합니다.

저희는 울산과학기술대학교 인간 및 시스템공학과 idealab의 연구원입니다.

본 실험은 곡면 모니터를 개선하기 위한 연구로 proofreading 작업이 포함되어 있습니다.
본 설문지는 귀하와 관련된 일반적 질문과 실험 전, 실험 중, 실험 후 귀하의 눈의 상태 (경미한 통증이나 피로감)에 대한 질문 두 가지 영역으로 구성되어있습니다.
귀하께서 성심 성의껏 작성해주신 의견은 통계법 제 8조에 의거하여, 비밀이 보장되고 본 연구의 진행을 위한 통계적 자료로 사용되는 목적 이외에는 사용되지 않습니다.

다시 한번 실험에 참가해주셔서 감사드립니다.

Ⅰ. 일반적 특성

- 귀하와 관련된 일반적 질문 또는 간단한 눈 검사가 필요한 사항입니다.
  아래 질문에서 답해 주시기 바랍니다.

0. 이름: ( )
1. 성별: □ 남 □ 여
2. 연령: 만 ( ) 세
3. 시력 (검사 후 기입): 좌 ( ) 우 ( )
4. 색맹유무 (검사 후 기입): ( )
5. 현재 본인의 눈 건강 상태에 대해 서술해 주십시오 (과거에 앓았던 질병이나, 최근 눈에 문제가 있어 병원에 갔었다 등의 의견을 구체적으로 서술해 주십시오)

Proofreading 피험자 번호 ____

측정 (1) - 실험 전

1. 눈의 경미한 통증이나 피로감 확인 (ECQ)

다음 항목은 눈의 상태에 관련된 항목들입니다. 1번부터 10번의 각 항목에 대해 현재 눈의 상태를 가장 잘 나타내는 곳을 골라 하나만 체크 (v) 해 주시기 바랍니다.

항 목	전혀 그렇지 않다	거의 그렇지 않다	약간 그렇다	다소 그렇다	적당히 그렇다	상당히 그렇다	매우 그렇다
1. 눈으로 보는데 어려움이 있다	□	□	□	□	□	□	□
2. 눈꺼풀이 무겁다	□	□	□	□	□	□	□
3. 눈이 아프다	□	□	□	□	□	□	□
4. 눈물이 나온다	□	□	□	□	□	□	□
5. 눈이 화끈거린다	□	□	□	□	□	□	□
6. 눈이 피로하다	□	□	□	□	□	□	□
7. 눈 주변이 이상한 느낌이 든다	□	□	□	□	□	□	□
8. 눈이 가렵다	□	□	□	□	□	□	□
9. 눈이 빨갛다	□	□	□	□	□	□	□
10. 눈이 건조하다	□	□	□	□	□	□	□

2. 눈의 불편함 (Visual Discomfort)

Proofreading 작업을 진행하는 동안 눈은 얼마나 불편함을 느꼈나요?

(0) 전혀 불편하지 않음 ———————— (100) 매우 불편

3. 만족도 (Satisfaction)

전체적으로 proofreading 작업을 수행하는 동안 어느 정도의 만족감을 느꼈나요?

(0) 전혀 만족하지 않음 ———————— (100) 매우 만족

Proofreading 피험자 번호 ____

4. 정신적 작업부하 (NASA-TLX)

다음 항목은 proofreading 작업의 수행 시 느낀 정신적 부하를 평가하는 항목들입니다. 1번부터 6번까지의 각 항목에 대해 항목별 작업부하를 가장 잘 나타내는 곳을 골라 하나만 체크 (v) 해 주시기 바랍니다.

No.	항 목	극도로 낮음	매우 낮음	상당히 낮음	낮음	다소 낮음	보통	다소 높음	높음	상당히 높음	매우 높음	극도로 높음
1	정신적 요구수준	□	□	□	□	□	□	□	□	□	□	□
2	신체적 요구수준	□	□	□	□	□	□	□	□	□	□	□
3	시간적 요구수준	□	□	□	□	□	□	□	□	□	□	□
4	임무 성취감	□	□	□	□	□	□	□	□	□	□	□
5	노력 수준	□	□	□	□	□	□	□	□	□	□	□
6	불쾌감 수준	□	□	□	□	□	□	□	□	□	□	□

5. 정신적 작업부하의 항목간 상대적 중요도 평가

각 평가 항목 쌍에서, 정신적 작업 부하를 증가시키는데 상대적으로 더 중요한 영향을 미친 항목에 체크 (v) 해 주시기 바랍니다.

No.	평가 항목 쌍	No.	평가 항목 쌍
1	정신적 요구수준 □ / □ 신체적 요구수준	10	시간적 요구수준 □ / □ 임무 성취감
2	정신적 요구수준 □ / □ 시간적 요구수준	11	시간적 요구수준 □ / □ 노력 수준
3	정신적 요구수준 □ / □ 임무 성취감	12	시간적 요구수준 □ / □ 불쾌감 수준
4	정신적 요구수준 □ / □ 노력 수준	13	임무 성취감 □ / □ 노력 수준
5	정신적 요구수준 □ / □ 불쾌감 수준	14	임무 성취감 □ / □ 불쾌감 수준
6	신체적 요구수준 □ / □ 시간적 요구수준	15	노력 수준 □ / □ 불쾌감 수준
7	신체적 요구수준 □ / □ 임무 성취감		
8	신체적 요구수준 □ / □ 노력수준		
9	신체적 요구수준 □ / □ 불쾌감 수준		

Appendix C: Questionnaire for the 55” TVs study

몰입감 피험자 번호 ___

TV시청의 몰입감 조사

안녕하십니까? 바쁘신 와중에도 실험에 참가해주셔서 감사합니다.
저희는 울산과학기술대학교 인간 및 시스템공학과 idealab의 연구원입니다.

본 실험은 TV로 시청 동안 발생하는 몰입감을 평가하기 위한 연구입니다.
본 설문지는 귀하와 관련된 일반적 질문과 TV시청 이후 귀하가 느끼는 몰입감과 만족도에 대한 질문으로 구성되어있습니다.
귀하께서 성심 성의껏 작성해주신 의견은 통계법 제 8조에 의거하여, 비밀이 보장되고 본 연구의 진행을 위한 통계적 자료로 사용되는 목적 이외에는 사용되지 않습니다.

다시 한번 실험에 참가해주셔서 감사 드립니다.

Ⅰ. 일반적 특성

- 귀하와 관련된 일반적 질문이 필요한 사항입니다. 아래 질문에 답해 주시기 바랍니다.

0. 이름: (   )

1. 성별: ☐ 남 ☐ 여

2. 나이: 만 (   ) 세 / 생일: (   )년 (   )월 (   )일

3. 경험: ☐ 듀얼모니터 사용 ☐ 멀티모니터 사용 ☐ 경험 없음

4. 주로 사용하는 모니터의 크기: (   )인치

5. 기술 혁신성 관련 문항

✓ Compared with my fri2ends I own a lot of high-tech products.
(내 친구들과 비교했을 때, 나는 최첨단의 제품들을 많이 가지고 있다.)

|—|—|—|—|—|—|

매우 그렇지 않다 … 매우 그렇다

✓ In general, I am the first in my circle of friends to know the names of the latest high tech products.
(일반적으로, 나는 내 친구무리들 중 최신 첨단의 제품들의 이름을 많이 알고 있다.)

|—|—|—|—|—|—|

매우 그렇지 않다 … 매우 그렇다

몰입감 피험자 번호 ____

실험 1

TV시청의 몰입감과 관련된 질문입니다. 본인이 느낀 대로 아래 위치에 체크(v) 하세요. 체크하기 전에 각 위치 위의 문구를 확인하시기 바랍니다. 정답이 없으므로 느낀 대로 솔직하게 평가하면 됩니다.

질문 1: 물리적 공간 (Physical Space) 관련

1-1. "I had a sense of being in the scenes displayed," (나는 TV 화면 속 장면에 있는 것 같은 느낌을 받았다)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

1-2. "I felt I was visiting the places in the displayed environment," (나는 TV 화면 속 환경의 장소에 방문한 것 같은 느낌을 받았다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

1-3. "I felt that the characters and/or objects could almost touch me." (나는 등장인물 혹은 물체들이 나를 건드릴 수 있었을 것 같은 느낌을 받았다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

몰입감 피험자 번호 ____

질문 2: 참여도 (Engagement) 관련

2-1. "I felt involved (in the displayed environment)," (나는 TV 화면 속 환경에 관여한 것처럼 느껴졌다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

2-2. "I enjoyed myself," (나는 즐겁게 TV를 시청했다)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

2-3. "My experience was intense." (나의 TV를 보는 경험은 강렬했다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

몰입감 피험자 번호 ____

질문 3: 생태학적 타당도 (Ecological Validity) 관련

3-1. "The content seemed believable to me," (영상의 내용은 나에게 그럴듯해 보였다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

3-2. "The displayed environment seemed natural," (영상 속 환경은 자연스러워 보였다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

3-3. "I had a strong sense that the characters and objects were solid." (나는 등장인물이나 물체들이 견고함을 강하게 느꼈다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

질문 4: 부정적 효과 (Negative Effects) 관련

4-1. "I felt dizzy," (나는 어지러움을 느꼈다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

4-2. "I felt nauseous," (나는 메스꺼움을 느꼈다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

4-3. "I felt I had a headache," (나는 두통을 느꼈다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

4-4. "I had eyestrain." (나는 눈의 피로를 느꼈다.)

전혀 그렇지 않다	조금 그렇지 않다	보통이다	조금 그렇다	매우 그렇다

몰입감 피험자 번호 ____

본인이 느낀 대로 수평선에 체크(v) 하세요. 체크하기 전에 양 끝의 두 문구를 확인하시기 바랍니다. 수평선상의 아무 위치에나 체크 가능합니다. 정답이 없으므로 느낀 대로 솔직하게 평가하면 됩니다.

질문 5: 눈의 편안함 (Visual Comfort) 관련

TV를 시청하는 동안 눈은 얼마나 편안함을 느꼈나요?

(0) 매우 불편함	(100) 매우 편함

질문 6: 화질 (Image quality) 관련

TV 화면의 전반적인 화질을 어떻게 평가하나요?

(0) 나쁨	떨어짐	보통	좋음	(100) 매우 좋음

질문 7: 시청 만족도 (Satisfaction) 관련

앞서 체크한 7가지 항목 (현존감, 참여도, 전이성, 멀미, 시각피로, 화질, 눈의 편안함 등)을 고려하면, 전체적으로 TV 시청시 어느 정도의 만족감을 느꼈나요?

(0) 매우 불만족	(100) 매우 만족