Effects of task duration, display curvature, and presbyopia on physiological and perceived visual fatigue for 27" desktop monitors

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ABSTRACT

With the advancement of display technologies, more diverse display products are available around us. VDT (Visual Display Terminal) tasks are, however, associated with various visual fatigue symptoms that can reduce work efficiency and task performance. Such results can be more severe for older individuals with diminished visual abilities, which typically start around the age of 40. However, studies on visual fatigue of older individuals are relatively fewer than those for younger individuals. Though, proper work-rest schedules are deemed to reduce visual fatigue, workers have difficulty in taking rest breaks due to many reasons. It is expected that a real-time rest reminder will be effective because the time to onset of visual fatigue can vary as visual fatigue is affected by many factors including individual and task characteristics. Curved displays provide relatively even viewing distances across their display surface for the center viewer than flat displays, which could benefit viewing experience while reducing visual fatigue. Indeed, some studies on display curvature demonstrated that curved displays are more effective than flat displays in terms of task performance, visual fatigue, and preference. Previously, various physiological measures (e.g. accommodation amplitude and near point accommodation) were considered as indices of visual fatigue. Using these measures to predict visual fatigue in daily life are, however, not practical because of difficulties in measuring and/or needs for high-cost equipment.

The aims of the current study were 1) to examine the effects of task duration, display curvature, and presbyopia on physiological and perceived visual fatigue and display satisfaction associated with performing proofreading tasks on 27” displays, and 2) to develop a prediction model for visual fatigue using pupil- and bulbar conjunctiva-related measurements which can be easily obtained in daily life.

A total of 64 participants (32 for each age group) performed a 1-hr proofreading task. The current study considered task duration (within-subjects; 0, 15, 30, 45, and 60 min), display curvature (between-subjects; 600mm, 1140mm, 4000mm, and flat) and age group [between-subjects; younger (20-35 yrs) and older (45-60 yrs)] as independent variables. Pupil diameter, bulbar conjunctival redness, perceived visual fatigue [measured in ECQ (Eye Complaint Questionnaire) scores], and display satisfaction were obtained every 15 minutes, while CFF (Critical Fusion Frequency) was obtained pre and post the 1-hr proofreading task.

The rear-projection environment was comprised of 27” curved rear screens, a beam projector, and the Warpalizer software. Environmental factors that can affect visual fatigue were controlled. An eye tracking system, a digital camera, and a flicker fusion system were used to measure physiological measures of visual fatigue, and a series of questionnaires were used to measure perceived visual fatigue and satisfaction of display. 3-way ANOVA was used to examine how 3 independent variables and their interactions affected each of 5 dependent variables. Four methods were considered in developing prediction models for visual fatigue and display satisfaction, and the developed models were compared in terms of predictive accuracy.

The results showed that over the 1-hr task, pupil diameters decreased (5.1%), bulbar conjunctival redness increased (18.8%), CFF thresholds decreased (0.94%), and ECQ scores increased (207%), all indicating an increase in visual fatigue. Even with a 15 min of VDT task, visual fatigue increased significantly. At the 1140mm curvature, pupil diameters were the largest, indicating less visual fatigue, and the display satisfaction of the older group, though not significant, gradually increased over the 1-hr task, indicating a less increase in visual fatigue. Display satisfaction was not affected by any independent variables. In terms of predictive accuracy of visual fatigue, the artificial neural network model was the best followed by the 3rd degree polynomial regression model.

The results of this study can be utilized when scheduling work-rest, determining a better display curvature for 27" displays, and predicting visual fatigue in real time to notify the time to take a rest.

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I. INTRODUCTION

1.1. Backgrounds

With frequent use of diverse display products, our eyes are easily exposed to the environment that can lead to visual fatigue. Computers and the Internet are essential tools for our daily life. Portable computers such as smartphones, tablet PCs, and e-books enable us to work almost anytime and anywhere, and can increase productivity (Lin, Chen, Lu, & Lin, 2008a). On the other hand, frequent use of such products could negatively affect our health, especially in terms of visual fatigue (Balci & Aghazadeh, 2003; Murata et al., 1996; Saito, Sotoyama, Saito, & Taptagaporn, 1994; Steenstra, Sluiter, & Frings-Dresen, 2009).

In general, VDT (Visual Display Terminal) tasks could negatively affect our body in various ways. VDT tasks require faster eye movements compared to other tasks (Saito, Taptagaporn, & Salvendy, 1993). Moreover, VDT tasks are known to lead to rapid fatigue than other works as they require high levels of thinking ability, judgment, and attention (Yamamoto, 1987). These requirements can lead to a series of physical symptoms such as headache, visual fatigue, muscular skeletal diseases called VDT syndrome (Chi & Lin, 1998; Turville, Psihogios, Ulmer, & Mirka, 1998). Visual fatigue is one of factors that occur most frequently to VDT workers (Chi & Lin, 1998; Dainoff, Happ, & Crane, 1981; Knave, Wibom, Voss, Hedstrom, & Bergqvist, 1985; Smith, Cohen, & Stammerjohn, 1981) during 1 to 6 hours of work (Gratton, Piccoli, Zaniboni, Meroni, & Grieco, 1990; Mourant, Lakshmanan, & Chantadisai, 1981; Saito et al., 1994; Takeda, Sugai, & Yagi, 2001; Uetake, Murata, Otsuka, & Takasawa, 2000). Generally long-term VDT works require an excessive use of the ciliary muscle and extraocular muscles, leading to visual discomfort, visual fatigue, and temporary degradation of visual functions (Hedman & Briem, 1984). Consequently, such results more likely have negative effects on eye health as well as work efficiency.

Presbyopia, which starts to develop at the age of 40, makes us more easily visually fatigued (Hedman & Briem, 1984). Clear vision requires rapid vergence and accommodation by activating ocular muscles. Older people can feel visual fatigue more easily as such activations are slow, and their crystalline lens is hardened (Hedman & Briem, 1984). As we get older, our visual function is degraded. Short-distance view is blurred because of poor accommodation (Lockhart & Shi, 2010), it becomes hard to change the focus fast because convergence latency increases, the peak velocity of convergence decreases (Rambold, Neumann, Sander, & Helmchen, 2006), and also flicker sensitivity decreases (Wolf & Schraffa, 1964). Such symptoms also have negative effects on work efficiency (Yu & Yang, 2014).

People over the age of 40 have been increasing worldwide. According to the population and housing census, people over 40 occupied 46% of the population of Korea in 2010, exceeds 50% in 2015, and are expected to reach 60% in 2030 (Statistics Korea, 2011). In the case of the United States, according to the Bureau of Census, the population over the age of 40 is 47% in 2015, and is expected to increase to 50% in 2030, and 54% in 2060 (Colby & Ortman, 2015). In addition, according to the data from the United Nations (UN), China's population over the age of 40 is 46% in 2015 and is expected to increase to 56% in 2030 (U.N. Department of Economic and Social Affairs, 2015). Such a phenomenon indeed takes place globally (2015: 35%, 2030: 41%; U.N. Department of Economic and Social Affairs, 2015). It means that more people are likely to suffer from presbyopia, and more people with presbyopia do VDT tasks. Therefore studies on visual fatigue, which is closely related with work efficiency of this age group, is important (Lin, Lin, Hwang, & Jeng, 2008b). Lin et al. (2008b) examined the effects of surface treatment, reflectance, and two age groups (younger, older) during letter finding tasks on e-paper. A compound surface treatment provided lower visual fatigue and higher legibility than the single surface treatment. In addition, visual performance of two age groups was not affected by surface treatment, while reflectance affected the younger group's visual fatigue. Lockhart and Shi (2010) studied the effect of age (younger; age 20-29, middle-aged; age 40-49, older; age 60-69) on dynamic accommodation during reading tasks. More delays at the beginning and end of accommodation and slower accommodation speeds were observed in the older group than the other two groups. Lin and Yeh (2010) examined how screen polarity, letter size and line spacing affected visual performance and visual fatigue of two age groups (younger, older). The older group showed higher visual performance and lower visual fatigue at negative polarity than at positive polarity. In addition, the combination of 14-pt font and double spacing provided a higher visual search performance for both groups. However, in many cases, studies on visual fatigue due to VDT tasks are limited to younger people of 20s (Jaschinski-Kruza, 1991; Murata, Uetake, Otsuka, & Takasawa, 2001; Saito et al., 1994), while comparative studies between the younger and older groups are relatively insufficient.

Though 'visual fatigue' is often interchangeably used with asthenopia, eye strain, visual fatigue, and visual discomfort, these terms should be distinguished. Visual fatigue can be objectively measured by observing performance decrement of the human vision system (Lambooij, Fortuin, Heynderickx, & Ijsselsteijn, 2009), while visual discomfort is subjectively evaluated based on perceived annoyance (Li, Barkowsky, & Le Callet, 2014), and includes visual discomfort (e.g. focusing problems), ocular discomfort (e.g. sore eye), and systemic discomfort (e.g. headaches) [Howarth and Bullimore (2005)]. Asthenopia, a medical term of eye strain, covers both visual fatigue and visual discomfort (Choi, 2004; Lambooij et al., 2009; Sheedy, Hayes, & Engle, 2003). Asthenopia is further divided into accommodative asthenopia and muscular asthenopia (Choi, 2004; Krupinski & Berbaum, 2009; Westman & Liinamaa, 2012). Accommodative asthenopia occurs with strain of the ciliary muscles, while muscular asthenopia occurs with strain of the external ocular muscles (Choi, 2004; Krupinski & Berbaum, 2009; Westman & Liinamaa, 2012). Performance decrement of the human vision system or visual fatigue is accompanied by physical symptoms such as fatigue at and around the eyes, tear, headache, double vision, and blurred vision (Krupinski & Berbaum, 2009; Lambooij et al., 2009). Subjective evaluation of these symptoms is visual discomfort.

Visual fatigue has been classified by its physical symptoms. Sheedy et al. (2003) discovered two groups of factors, internal factors and external factors, by using a factor analysis of such symptoms. These two factors are further classified by the type and location of the symptoms. Internal factors include ache or strain at the posterior segment of the eye, headache, whereas external factors include burning, tearing, irritation, and dryness at the anterior segment of the eye. Blehm, Vishnu, Khattak, Mitra, and Yee (2005) classified the symptoms associated with visual fatigue more specifically into three types, ocular surface mechanisms, accommodative mechanisms, and extraocular mechanisms according to pathophysiological causes. Ocular surface-related symptoms include dryness, burning, and grittiness caused by environmental factors, decrease of eye blink rates, and increase of exposed eye surface areas. Visual fatigue by accommodative mechanisms includes presbyopia, double vision, blurred vision, and slowness of focusing. Lastly, neck pain, back pain, and shoulder pain are classified into the symptoms of visual fatigue by extraocular mechanisms. Sullivan (2008), similar to Blehm et al. (2005), classified the symptoms of visual fatigue into ocular surface-related symptoms, oculomotor-related symptoms, and non-ocular symptoms. Ocular surface-related symptoms include dry, burning, and scratchy eye which are related to environmental stimuli and insufficient lubrication of eyes. Oculomotor-related symptoms include accommodation and convergence. Prolonged use of these functions decreases sensitivity of accommodation and convergence, and results in blurred vision or double vision. Non-ocular symptoms include headache, neck pain, back pain, drowsiness, and diminished levels of arousal. Sheedy et al. (2003) only considered subjective visual discomfort, but not physiological visual fatigue related to the degradation of human vision performance such as accommodation and convergence, whereas Blehm et al. (2005) and Sullivan (2008) considered physiological degradation of vision performance as well as visual discomfort. In summary, visual fatigue by symptoms can be classified into diminished vision performance, visual discomfort (perceived visual fatigue), and non-ocular visual discomfort (e.g. headaches, drowsiness).

It is necessary to properly take rest breaks in order to reduce visual fatigue due to VDT tasks. Safety guidelines on visual work recommend regular breaks for prolong visual display tasks. For example, Korea's guidelines for VDT tasks state that workers need proper rest breaks during the work time (Korea Ministry of Emplyoment and Labor, 2004), and England's guidelines advise workers to take rest breaks periodically (U.K. Health and Safety Executive, 1992). Specifically, New Zealand's guidelines advise 5-10 minutes of rest per hour (NewZealand Accident Compensations Corporation, 2010), Occupational Safety and Health Administration recommends 10 minutes of rest after continuous work for 1 or 2 hours (OSHA, 1997), and guidelines of National Institute for Occupational Safety and Health (NIOSH) also recommend 15 minutes of rest after 1 hour of high visually demanding work or after 2 hours of moderate visually demanding work (Murray, 1981).

According to the previous researches, periodic rests increase work efficiency and decrease body discomfort including visual discomfort (Balci & Aghazadeh, 2003; Galinsky, Swanson, Sauter, Hurrell, & Schleifer, 2000; Henning, Jacques, Kissel, Sullivan, & Alteras-Webb, 1997). Henning et al. (1997) showed that short and frequent rests and simple stretching increased physical comfort including less visual fatigue and enhanced worker productivity. Galinsky et al. (2000) showed that a supplementary work-rest schedule with an additional 20 minutes of rest during a total of 8.5 hours of work was more effective than a conventional work-rest schedule in terms of physical discomfort, visual fatigue, and work performance. Balci and Aghazadeh (2003) also showed that micro breaks (30 s - 3 min) after 15 minutes of work than 10 minutes of rest after 60 minutes of work or 5 minutes of rest after 30 minutes of work showed lower physical discomfort, while 5 minutes of rest after 30 minutes of work provided the lowest visual fatigue. In addition, higher physical discomfort and lower visual fatigue resulted from mental arithmetic tasks compared to data entry tasks. However, in reality, it is difficult that VDT workers take rests during the work due to various reasons [e.g. psychosocial factors (Carayon, 1993), work incentive (Schleifer & Amick, 1989), skipping rests in favor of continuously concentrated work (Henning et al., 1997)]. In addition, the time to the onset of visual fatigue can vary as visual fatigue is affected by various factors such as type of work, VDT task environment, and personal characteristics (Howarth & Bullimore, 2005; Sullivan, 2008). Therefore, it is expected that real-time notice of the time to rest will be more effective to reduce visual fatigue.

Recently display products with various curvatures have been released in the market. Curved displays provide more benefits over flat displays. Curved displays are deemed to provide relatively similar viewing distance and wider viewing angle than flat displays, and alleviate letter distortion and glare (Ahn, Jin, Kwon, & Yun, 2014; Shupp, Andrews, Dickey-Kurdziolek, Yost, & North, 2009). Moreover, curved displays improve legibility (Jeong, Na, & Suk, 2015; Park et al., unpublished-a; Park, Choi, Yi, Lee, & Kyung, unpublished-b), and reduce visual fatigue compared to flat ones (Lee & Kim, 2015; Park et al., unpublished-a; Park et al., unpublished-b).

Previously, studies on curved display were done in various ways. Especially, there are some studies on visual display with convex curvature. Regarding reading the visual stimuli printed on A4 paper, Lin, Lin, Hwang, Jeng, and Liao (2009) examined the effects of surface treatment, ambient light (200lx, 1500lx, 8000lx) and curvature (-100mm, +100mm, flat; + for convex) on visual fatigue. They found the effects of surface treatment and ambient light on visual fatigue, but no curvature effect was found. Similarly, Wang, Hwang, and Kuo (2012) studied the effects of display curvature (-100mm,

+100mm, flat; + for convex) and ambient light (50lx, 500lx, 6000lx, 12000lx) on the visual performance of two age groups (Younger: 20-29 yrs, Older: 60-69 yrs), using printed text on A4 paper as visual stimuli. The younger group's visual performance was not affected by ambient light or curvature. The older group's visual performance was enhanced at the 50lx light with the 100mm curvature, the 500lx light with the 100mm, and the 500lx light with the flat curvature. Häkkinen, Pölönen, Salmimaa, and Hautanen (2008)'s study, participants read texts on curved plastic (-60mm, -80mm, +60mm, +80mm, flat; + for convex). They found that text reading was easier when the display curvature was perpendicular to visual stimuli, and the concave curvature was better if it was made in the text reading direction. Mustonen, Kimmel, Hakala, and Häkkinen (2015) studied the effects of curvature (50mm, 100mm, flat) and direction (concave, convex) on the visual searching task performance using a 4.5" flexible AMOLED display. The 50mm curvatures negatively affected the visual task performance, and more so in the 50mm convex curvature case. In terms of work efficiency and visual fatigue, Shupp et al. (2009) compared the target search task performance between flat and curved arrangements (radius = 30") of multi-monitors which consisted of 1 or 12 or 24 monitors. A better work performance was observed at the curved arrangement. Park et al. (unpublished-a) studied about the effects of curvature (400mm, 600mm, 1200mm, flat), task duration, and display zone on the legibility and visual fatigue during visual searching tasks on a 50" multi-monitor comprised of 5 flat monitors. The 600mm curvature showed the best legibility and the lowest visual fatigue. In addition, Park et al. (unpublished-b) studied the effects of curvature (600mm, 1140mm, 2000mm, 4000mm, flat) and task duration (0 min, 15 min, 30 min, 45 min, 60 min) on legibility, visual fatigue, workload, visual discomfort, and satisfaction. The 600mm curvature resulted in better legibility, lower visual fatigue and lower mental workload than the flat condition. Lee and Kim (2015) examined the effect of curvature (1000mm, 2000mm, 3000mm, 4000mm, flat) on user's visual fatigue while doing 6 different types of task for 30 minutes. The 1000mm curvature was better in terms of visual fatigue. Other attempts were made to find optimal curvatures. Jeong et al. (2015) considered two experiments using 27" bendable plates to compare readability and find out preferred curvatures. The first experiment compared sentence reading time between curved and flat displays, and the second experiment measured users' preferred curvature using 6 different screen images. Reading speed at a curved display was faster than at a flat display, and participants preferred curved displays. Choi et al. (2015) researched users' preferred curvature while looking at 6 different task screens using a 27" bendable tin plate which had two handles for bending. They discovered that users preferred a larger radius of curvature when looking scenery images and the smallest radius of curvature when looking game images. Moreover, it was expected that a smaller radius of curvature would be preferred in the situation where more interactions with the computer screen were needed. In addition, they stated that the optimal curvature for 6 works was 561mm and it might relate to the viewing distance, 600mm. In Ahn et al. (2014)'s study on the effect of display curvature on user satisfaction, curved displays showed statistically higher satisfaction than flat displays.

Physiological evaluations by measuring functional changes in the visual system (accommodation and convergence) after visual tasks, degradation of visual performance (visibility, and eye movement), and subjective evaluation using questionnaires (Chi & Lin, 1998; Kwon et al., 2012; Lin et al., 2009; Murata et al., 2001; Park et al., unpublished-a; Saito et al., 1994; Sheedy et al., 2003; Steenstra et al., 2009; Uetake et al., 2000) are used to assess visual fatigue. In the ophthalmological area, BUT (tear breakup time), ocular protection index, bulbar conjunctival redness, maximum enduring time without eye blinking, temperature of eye surface, VEP (visual evoked potential) were used to measure visual fatigue (Kwon et al., 2012; Suh et al., 2010). In addition to these measures, pupil diameter (Chi & Lin, 1998; Murata et al., 2001; Saito et al., 1994; Uetake et al., 2000), eye movements (Chi & Lin, 1998), eye blinks (Patel, Henderson, Bradley, Galloway, & Hunter, 1991), accommodation amplitude (Chi & Lin, 1998; Lin et al., 2008a; Ostberg, 1980; Saito et al., 1994), accommodation speed (Saito et al., 1994), near point of accommodation (NPC, Murata et al., 1996), dark focus (Jaschinski-Kruza, 1991), dark convergence (Jaschinski-Kruza, 1991), CFF threshold (Chi & Lin, 1998; Lin et al., 2008a; Murata et al., 1996; Saito et al., 1994), visual acuity (Chi & Lin, 1998; Lin et al., 2008a), and electroencephalogram (EEG, Chen et al., 2014) were available for assessing visual fatigue due to VDT tasks. To assess the effects of VDT task on daily cumulated visual fatigue, Murata et al. (1996) measures visual fatigue in terms of VEP, NPC and CFF, between VDT workers and non-VDT workers. Workers' visual fatigue increased throughout the day, and VDT workers showed larger changes in VEP, NPC and CFF than non-VDT workers. Saito et al. (1994) measured accommodation amplitude, accommodation speed, pupil diameter, CFF threshold and perceived visual fatigue in order to find out the impact of 5 hours of VDT task with 1 hour of rest on visual fatigue. The result of the experiment showed decrement of accommodation amplitude, accommodation speed, pupil diameter, CFF threshold and increment of perceived visual fatigue along 2 hours of VDT task. One hour of rest afterward recovered accommodation amplitude and pupil diameter. Yoo, Yoon, and Kim (1992) studied the effects of 90 minutes of proofreading task on accommodative constriction, near point accommodation, accommodation amplitude, and Ar/As (accommodative response / accommodative stimulus ratio). The 90 minutes of proofreading task caused a significant increment of accommodative constriction time and a decrement of accommodation amplitude. In addition, 30 minutes of rest after the task recovered accommodation functions. Lin et al. (2008a) showed that time-based factors such as scanning speed, target presentation rate, and work time had significant effects on visual acuity, CFF threshold and accommodation amplitude, and environment-based factors such as screen type and viewing distance had significant effects on visual acuity, CFF threshold, accommodation amplitude, and reaction time. The results showed that visual acuity, CFF threshold, and accommodation amplitude decreased (7.4%, 2.4%, 4.7%; respectively) after VDT task.

Some attempts have been made to predict visual fatigue. Many existing researches predicted visual fatigue by selecting and combining disparity's spatiotemporal characteristic that occurred while watching 3D image (Choi, Yun, Kim, & Kim, 2012; Kim & Sohn, 2010, 2011). Choi et al. (2012) made a visual fatigue prediction model (R^2 = 0.70 ~ 0.73) using a linear combination of 8 disparity's spatiotemporal characteristics. Visual fatigue was also predicted using a linear combination of horizontal disparity and vertical disparity was also done (r = 0.71 ~ 0.85) (Kim & Sohn, 2010, 2011). Oh and Lee (2012) made a visual fatigue prediction model including disparity's spatiotemporal characteristics (depth, spatial frequency, motion) and a human factor characteristic (zone of comfort). Li, Barkowsky, and Callet (2013) studied on the inter relationship of 3D image characteristics (relative disparity, disparity amplitude, velocities for planar and in-depth motion), visual discomfort, and blinking rate. They used each characteristic to make objective eye blinking rate models (R^2 = 0.38 ~ 0.88). Their models were highly correlated with visual discomfort (r = 0.53 ~ 0.99). Murata et al. (2001) measured the width of focal accommodation, speed of focal accommodation, pupil diameter, and perceived visual fatigue during 3 consecutive 20-min VDT tasks. A regression model for predicting visual fatigue was proposed using the above measurements (R^2 = 0.78). However, there are some limitations when applying the results of previous studies to the real-time prediction model because 3D characteristics of 3D image cannot be applied to general VDT task (2D image), and researchers used measures which are difficult to obtain in real time or require high-cost equipment.

Various methods such as PCR (Principal component regression), and ANN (Artificial neural network) are also used to propose prediction models. PCR is the method based on Principal Component Analysis, which converts a set of correlated variables into a linearly uncorrelated variables, the principal component (Liu, Kuang, Gong, & Hou, 2003). ANN is used to predict and approximate a non-linear relationship between input data set and output data set (Hsu, Gupta, & Sorooshian, 1995). Neurons with mathematical arithmetic capacity in ANN are interconnected, and run by proper learning algorithms. Learning of ANN have a series of procedures as follows. Neurons from each layer of multi-layer perceptron, composed with input layer, hidden layer, and output layer, calculate sum of n inputs using weight by transfer function (also known as activation function), and the results are transferred to the next layer. (Lee, Ahn, Lee, & Kim, 2009; Lee, Jung, Lee, & Park, 2011). There are various types of learning algorithm for ANN. The backpropagation algorithm is most widely used, and this method finds a proper function by renewing weight of each layer using error between target output and output which is a result of input (Kim et al., 2013). The expectation-maximization algorithm (EM algorithm) is a repetitive algorithm finding parameters which have maximum likelihood (Kim & Lee, 2012). Other algorithms for learning include gene expression programming (Ferreira, 2006), and simulated annealing (Da & Xiurun, 2005).

1.2. Research purpose

The purpose of this research was first to examine visual ergonomic issues in VDT tasks on curved displays performed by younger and older individuals. This research used pupil and conjunctiva related data which can be relatively easily obtained during the daily use of display to measure visual fatigue. In addition, the current study was aimed to develop real-time visual fatigue prediction models using pupil and conjunctiva related data and individual characteristic data. In order to predict visual fatigue better, regression models and an artificial neural network model were compared in terms of predictive accuracy.

1.3. Research hypotheses

The following experiment was to examine the effects of VDT task duration, display curvature and age groups on physiological visual fatigue, perceived visual fatigue, and satisfaction of display. The following were the hypotheses to study how task duration (0min, 15min, 30min, 45min, 60min), display curvature (600mm, 1140mm, 4000mm, flat) and age group (younger and older group) affected users' visual fatigue and display satisfaction.

(1) Pupil diameters are affected by task duration, display curvature, and age group.

(2) Bulbar conjunctival redness is affected by task duration, display curvature, and age group.

(3) CFF threshold is affected by task duration, display curvature, and age group.

(4) Perceived visual fatigue is affected by task duration, display curvature, and age group.

(5) Satisfaction of display is affected by task duration, display curvature, and age group.

(6) Pupil diameters are influenced by the interaction effects of task duration, display curvature, and age group.

(7) Bulbar conjunctival redness is influenced by the interaction effects of task durations, display curvatures, and age groups.

(8) CFF threshold is influenced by the interaction effects of task durations, display curvatures, and age groups.

(9) Perceived visual fatigue is influenced by the interaction effects of task durations, display curvatures, and age groups.

(10) Satisfaction of display is influenced by the interaction effects of task durations, display curvatures, and age groups.

(11) Real-time prediction of visual fatigue is feasible using physiological measures and individual characteristics data.

1.4. Thesis outline

The current thesis is comprised of 5 sections. First of all, research backgrounds, literature studies, research hypotheses, and thesis outline are included in Section 1. Section 2 explains research methods such as participants, experimental design, experimental environment, experimental apparatus, experimental procedure, and data analysis methods. Section 3 is about experimental results. Section 4 deals with in-depth data analysis and explains similarity and difference between the current study and the previous studies, and also considers several prediction techniques to find a better real-time prediction model for visual fatigue using physiological data and individual characteristics data. Section 5 is about conclusions, and future studies.

II. METHODS

2.1. Participants

Two age groups, comprised of 32 younger individuals with the age range of 20-35yrs and 32 older individuals with the age range of 45-60yrs, took part in the current study. The mean (SD) age of each group was 24.1 (4.8) yrs and 50.5 (6.0) yrs, respectively. Before the experiment, each participant filled out the presbyopia questionnaire to determine whether they had presbyopia or not (Kazuhiro, 2013). To ensure homogeneity within the group, a visual acuity test (Kee, Lee, & Lee, 2006), an eye dominance test using the Dolman method (Cheng, Yen, Lin, Hsia, & Hsu, 2004) and the Ishihara test for color blindness (Ishihara, 1943) were conducted. The visual acuity of younger and older participants was 1.0 (0.26) and 1.1 (0.23), respectively. Older participants only had presbyopia. No participant showed color weakness or color blindness. Participants were asked to have a sufficient sleep, not to take alcoholic or caffeinated drinks, and not to do an excessive visual task before the experiment. All participants consented procedures approved by the UNIST institutional review board (IRB).

2.2. Experimental design

Each participant repeated a 15-min VDT task 4 times. The VDT task was the comparison proofreading with a dead copy on the left side and a live copy on the right side of the screen (Anderson, 1990; Figure 1). Participants were instructed to mark different parts on the live copy compared to the dead copy using the computer mouse. The visual stimuli used in the experiment, were sampled from online articles provided by Naver Cast (Choi, 2014; Choi & Kim, 2012a, 2012b, 2012c, 2013a, 2013b; Han, 2015; Hwang, 2014a, 2014b; Hwang, 2011, 2012a, 2012b, 2012c, 2012d, 2012e; Jang, 2012; Jo, 2010; Jung, 2013; Lee, 2015; Lee, 2014a; Lee, 2014b; Lee, 2012a, 2012b, 2012c; Nam, 2014; Oh, 2013a; Oh, 2013b; Park, 2013; Yim, 2014; Yim, 2011a, 2011b, 2011c, 2011d, 2011e, 2011f; Yoon, 2015). The typeface used in the experiment was the Malgun Gothic font (Park, Lee, Kang, & Lee, 2007). According to Park et al. (2007), both younger and older groups could read 94% of characters when the font size was 14-pt with the viewing distance of 50cm. The current study used a 16.8-pt font and a 60cm viewing distance, 20% increase in both dimensions.

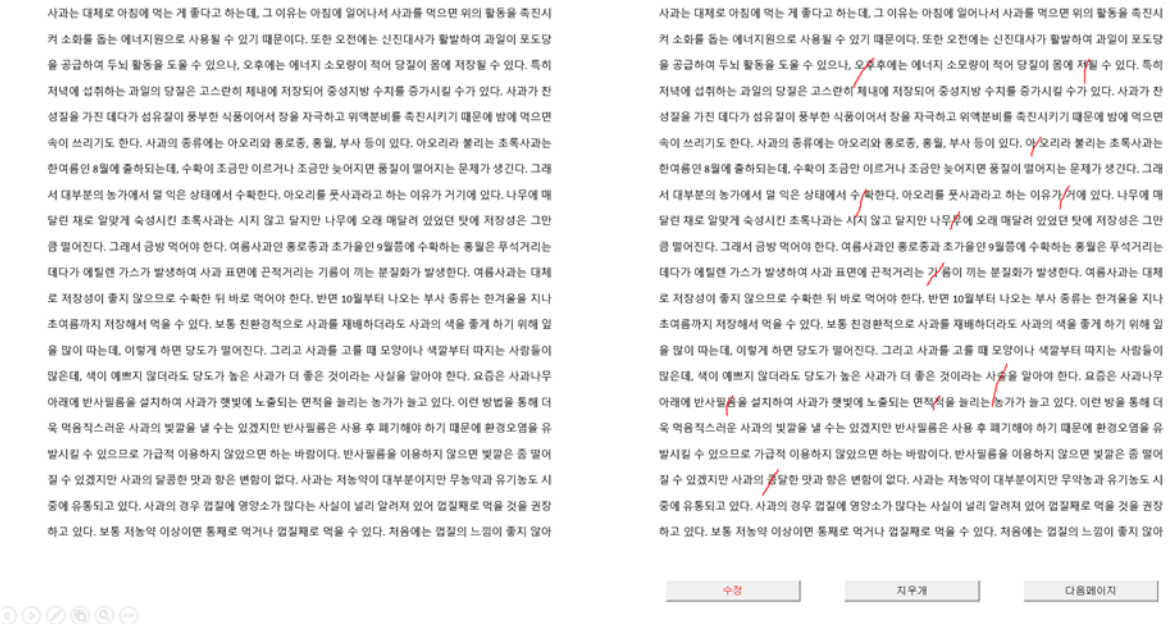


Figure 1. Comparison proofreading

The current study incorporated 3 independent variables and 5 dependent variables. Independent variables used in the study were task duration (TD; 0min, 15min, 30min, 45min, 60min), display curvature (CV; 600mm, 1140mm, 4000mm, Flat), and age group (YO; 20-35yrs, 45-60yrs). Dependent variables were pupil diameter (PD, physiological visual fatigue), bulbar conjunctival redness (CR, physiological visual fatigue), critical fusion frequency threshold (CFF, physiological visual fatigue), eye complaint questionnaire (ECQ, perceived visual fatigue) and satisfaction of display (ST). Task duration was a within-subject factor while display curvature and age group were between-subject factors. Pupil diameters were measured continuously during the VDT task. To assess bulbar conjunctival redness eye pictures were taken before and after each 15-min task (Suh et al., 2010). CFF thresholds were measured before and after the entire 60-min task. Subjective ratings on perceived visual fatigue and satisfaction were obtained after every 15-min task (Table 1).

Table 1. Summary of dependent variables

Measures	0 min (Pre-task)	15 min	30 min	45 min	60 min (Post-task)
Pupil diameter (mm)	○†	○	○	○	○
Bulbar conjunctival redness (10-100)	○	○	○	○	○
CFF (Hz)	○	-	-	-	○
ECQ (0-100)	○	○	○	○	○
Display Satisfaction (0-100)	-	○	○	○	○

† The means of the first 1-min data of proofreading task

2.3. Experimental environment

The experimental setting was 27” curved rear screens, each with 4 different curvatures, a beam projector (EB-4950WU, EPSON, Japan), and the Warpalizer® software (Univisual Technologies Nordic AB, Sweden) which can correct image distortion on the curved screens (Figures 2 and 3). Four curvatures used were 600mm, 1140mm, 4000mm and flat. The 600mm display curvature was equal to the viewing distance used in the current study. Relatively similar viewing distances across a screen can minimize ocular accommodation, potentially resulting in lower visual fatigue. The 1140mm curvature corresponds to a 30° effective visual angle that requires only eye movements for faster visual information processing (Hatada, Sakata, & Kusaka, 1980). The 4000mm curvature is a display curvature adopted by a commercial product (SE591C, Samsung, Korea), and the flat curvature was selected as a control condition.

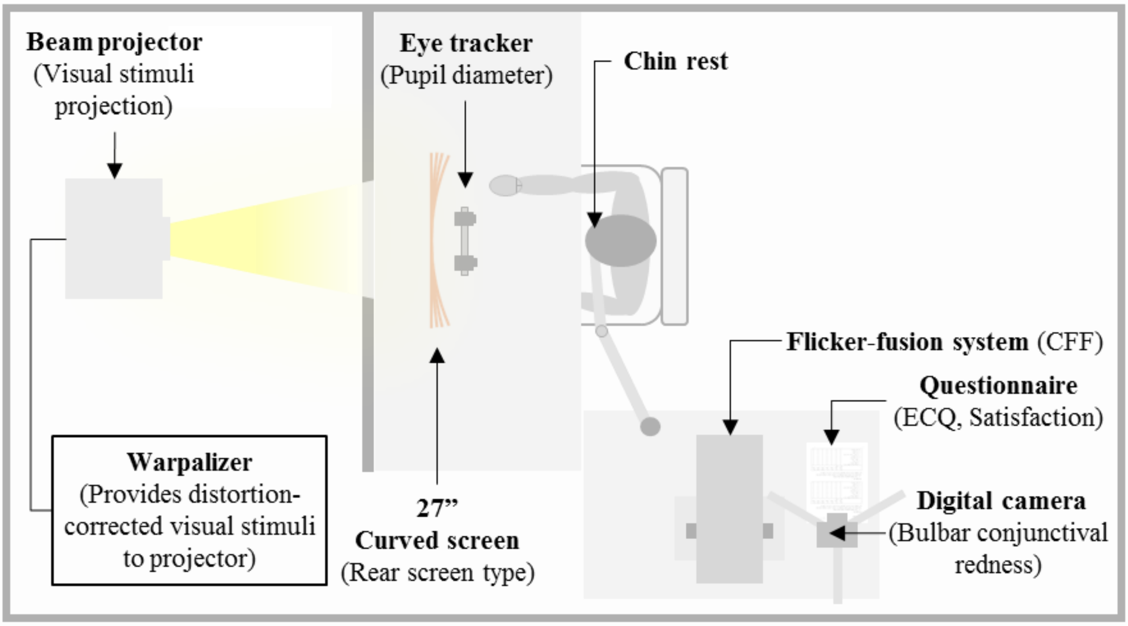


Figure 2. Experimental environment and apparatus

(a)

(b)

Figure 3. Before (a) and after (b) applying the Warpalizer software

Visual fatigue can be affected by many factors such as viewing distance, display height, illumination, temperature, and humidity. In order to avoid confounding effects from such factors, the experimental setting was referred to ergonomic recommendations for VDT workspace. According to the guidelines of OSHA on Working Safely with Video Display Terminals, the viewing distance to the display was set to 60cm, and was controlled using a chin rest (Occupational Safety and Health Administration, 1997). In addition, a height adjustable chair was provided to help the subject maintain the vertical viewing angle at 15° to 20° from the screen center, and the display was tilted 5° rearward (Kim, Kang, & Cho, 1997). 450-500lx of illumination, 20-60% of humidity and 20-24℃ of room temperature were maintained in accordance with the OSHA's guidelines on office indoor air quality (Occupational Safety and Health Administration, 1999). All the walls in the laboratory room were covered with black cloth to prevent light reflection. An air conditioner and a humidifier were used to control temperature and humidity.

2.4. Experimental apparatus

The following are the experimental apparatuses used to measure visual fatigue before and after the experiment. Using the FaceLAB™ (Seeingmachines, Australia) eye-tracking system, pupil diameters were sampled at 60Hz during the proofreading task. To measure and analyze pupil data, FaceLAB™ (v5, Seeingmachines, Australia) software and WorldView (v2.3, Seeingmachines, Australia) software were used. Bulbar conjunctival redness was measured by inspecting the pictures of participants' dominant eye. The pictures were taken using a digital camera (D5000, Nikon Co., Japan) before and after each 15min proofreading task under 500lx luminance. Before and after the entire 60-min experiment, CFF threshold was measured using a Flicker fusion system (Model 12021A, Lafayette Instrument Company, USA; Figure 4). Subjective ratings were used to measure perceived visual fatigue and satisfaction of display. The self-reporting questionnaire consists of 10 eye-complaint items

(Steenstra et al., 2009) and 1 display satisfaction item.

Figure 4. Flicker fusion system

2.5. Experimental procedure

The experimental session per participant lasted about two hours. The experimental procedure is as follows (Figure 5). 1) A brief explanation about the study was provided and the participant's personal demographic information (name, sex, and age) was collected. 2) For 5 minutes, the visual acuity test, the color blindness test, and the eye dominance test were performed. 3) Verbal instructions about how to fill out the questionnaire and a training session for the experimental apparatus (flicker fusion system) were provided, and the eye tracking system was calibrated for 15 minutes. 4) A 10-min practice of proofreading was performed. 5) After the practice, another 10-min break was provided to relieve visual fatigue due to the practice. 6) Right before the proofreading task, the participant's bulbar conjunctiva was photographed, and their perceived visual fatigue and CFF threshold were measured. 7) The participant performed the proofreading task for 15 minutes while pupil diameters were continuously measured. 8) After the 15 min task, the participant's bulbar conjunctiva was photographed again. After that, their perceived visual fatigue and display satisfaction were measured. 9) After steps 7 and 8 were repeated 4 times, the CFF threshold was measured again.

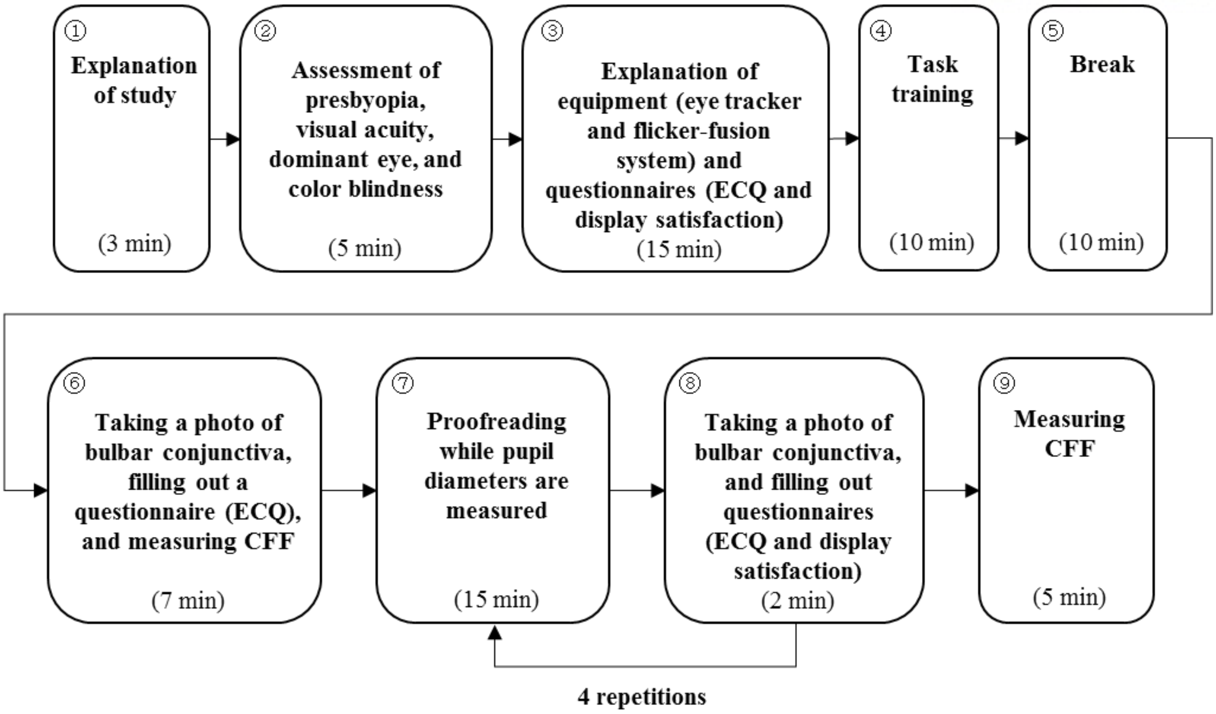
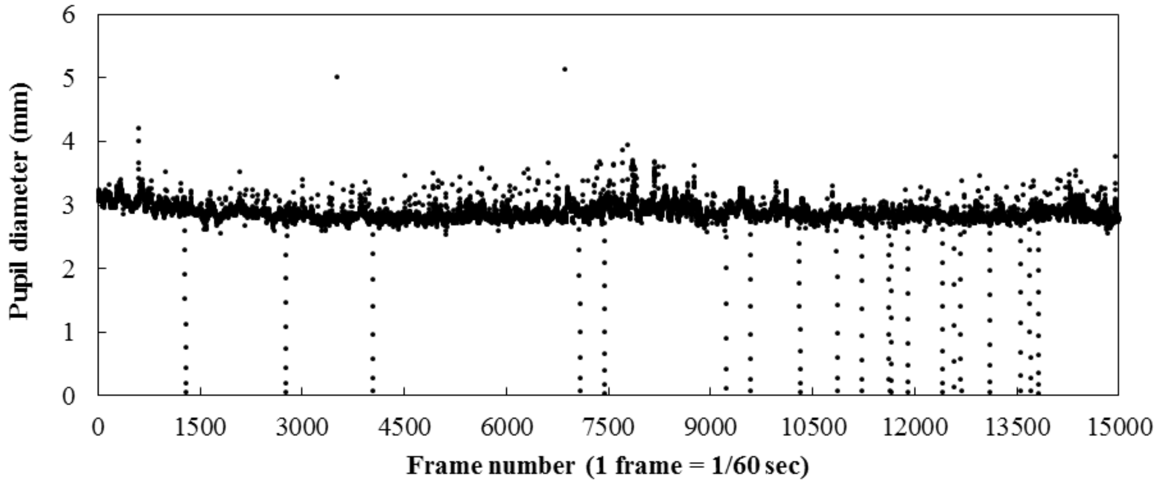


Figure 5. Experimental procedure

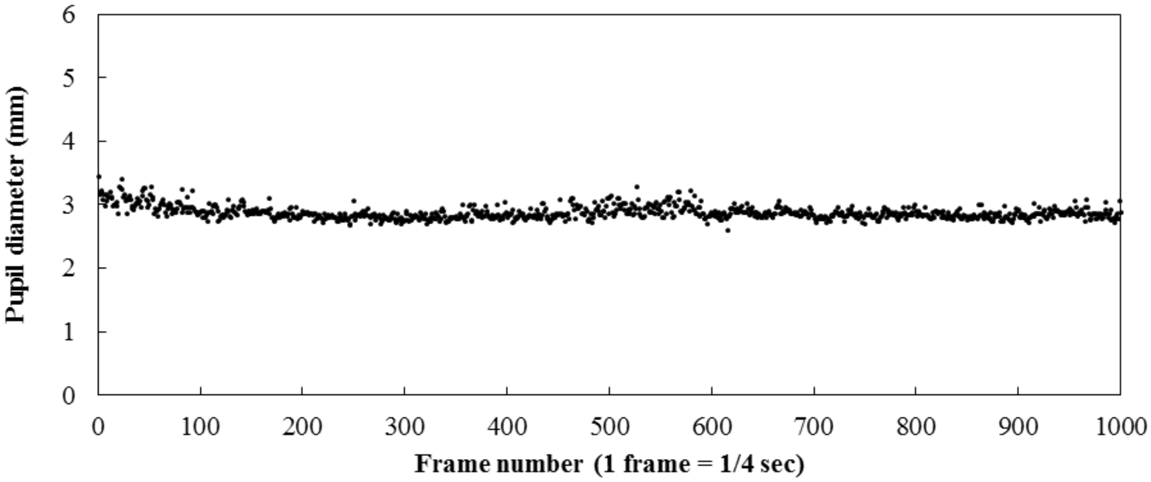
2.6. Method for data analysis

In the current research, pupil diameter, bulbar conjunctival redness, and CFF threshold were obtained from the dominant eye. The pupil diameter was defined as the horizontal width of the pupil. Outliers in pupil diameter data were removed by the Hampel filter Hampel filter (Pearson, 2002), and then down-sampled from 60Hz to 4Hz. The mean of these preprocessed values was used for the data analysis (Figure 6). The means of the first 1-min data was used as a reference. There was no difference in initial pupil diameters between the four groups in each age group ($p \geq 0.38$). Bulbar conjunctiva was photographed before the 60-min experiment and right after each 15-min task to assess bulbar conjunctival redness. Bulbar conjunctiva is the part of the conjunctiva covering the anterior surface of the sclera, the white of the eye. One Human Factors professional and two Human Factors graduate students rated bulbar conjunctiva photos on the scale of 10 to 100 (Schulze, Jones, & Simpson, 2007; Figure 7). Each rater evaluated the same photo 5 times. The grand mean of three raters' means was used as the final score for bulbar conjunctival redness. Intraclass correlation coefficient (ICC) between raters or between each rater's evaluations (5 sets) were calculated to see their reliability. ICCs between raters and between each rater's evaluations were > 0.9 ($p<0.0001$). CFF thresholds were measured 3 times before and after the entire 60-min experiment (Kawashima, Okamoto, Ishikawa, & Negishi, 2013). For the analysis, the mean of 3 CFF thresholds was used. The participant rated their perceived visual fatigue on the 10 items of the Eye Complaint Questionnaire (ECQ). Each item had a

7-point scale from 'not at all' to 'very much' (0-6), and the final ECQ score was converted to a percent value (Sum of 10-item scores / 60 × 100) (Bergqvist & Knave, 1994; Heuer, Hollendiek, Kroger, & Romer, 1989; Steenstra et al., 2009). Overall satisfaction of display during the 15-min task was rated on a 100mm visual analog scale (0, not at all – 100, totally satisfied).



(a)



(b)

Figure 6. Example of pupil diameter data
(before (a) and after (b) removing outliers and down-sampling)

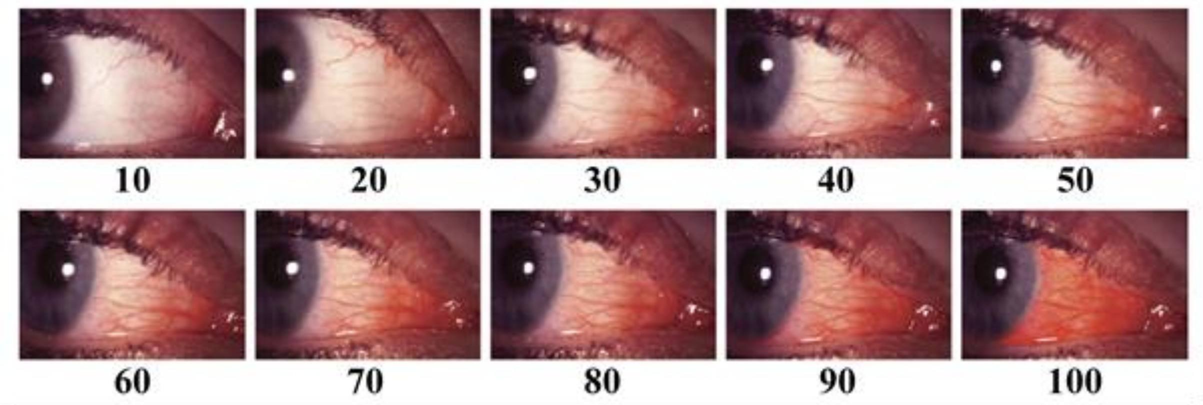


Figure 7. Bulbar conjunctival redness scale (Schulze et al., 2007)

Statistical analyses and calculations were done using JMP 12 (SAS Institute Inc. USA) and MATLAB® 2011 (The MathWorks Inc. USA). The statistical significance level (α) was set to 0.05. 3-way ANOVAs were used 1) to examine the effects of task duration (5 levels), curvature (4 levels) and age groups (2 levels) on pupil diameter, bulbar conjunctival redness, and perceived visual fatigue, 2) to examine the effects of task duration (4 levels), curvature (4 levels) and age groups (2 levels) on display satisfaction, and 3) to examine the effects of task duration (2 levels), curvature (4 levels) and age groups (2 levels) on CFF threshold. Tukey's HSD test was performed when ANOVA was significant. Associations between the measures by each age group were analyzed using a trend line and the coefficient of determination. In addition, prediction models for visual fatigue were developed using 4 methods such as multiple linear regression, polynomial regressions and ANN. Prediction models for display satisfaction were also proposed. The models' explanatory power and accuracy were compared. Prediction models using multiple linear regression and polynomial regression were made using 85% of the entire data and the rest 15% of data were used for accuracy while 70% of the entire data were used for training the ANN model, and 15% for validation, and the remaining 15% for prediction. Among diverse training algorithms, the backpropagation was used as a training algorithm. Tangent sigmoid functions and linear functions were used as transfer functions respectively for the hidden layer and output layer. The ANN model was trained for 1000 epochs until training errors < 0.01. The principal component regression was considered, but was excluded due to weak associations between variables that comprised one principal component ($R^2 < 0.15$). RMSE (Root Mean Square Error) and MAPE (Mean Absolute Percentage Error) were used to compare predictive accuracy of the prediction models. RMSE and MAPE were calculated as follows.

$$\mathbf{RMSE} = \sqrt{\frac{\sum(\boldsymbol{y_t} - \boldsymbol{\hat{y}_t})^2}{\boldsymbol{n}}} \qquad \mathbf{(1)}$$

$$\mathbf{MAPE} = \frac{\sum|(\boldsymbol{y_t} - \boldsymbol{\hat{y}_t})\ /\ \boldsymbol{y_t}|}{\boldsymbol{n}} \times \mathbf{100}\ (\boldsymbol{y_t} \neq \mathbf{0}) \qquad \textbf{(2)}$$

In the equations (1) and (2), y_t is the observed value, $\hat{y}_t$ is the predicted value, and n is the number of observations.

III. RESULTS

3.1. Pupil diameter

Pupil diameters (mean ± SE, mm) significantly decreased with task duration (p<0.0001). The mean pupil diameter was the largest at the beginning (3.33±0.11), and gradually reduced to 3.22 (±0.11) after 15 min, 3.18 (±0.11) after 30 min, 3.17 (±0.11) after 45 min, and 3.16 (±0.11) after 60 min. From the post-hoc test, the task duration was divided into three groups (0 min; 15 min; 30 min, 45 min, 60 min) with the first group showing the largest pupil diameter (3.33; 3.22; 3.16-3.18). There was no significant difference in the mean pupil diameters from 30 min to 60min (Figure 8).

Pupil diameters were significantly different according to display curvature (p=0.0019). The mean diameter was the greatest at the 1140mm curvature (3.55±0.11), and got smaller in the order of display curvature of 600 mm (3.23±0.11), Flat (3.08±0.11), and 4000 mm (2.93±0.12). From the post-hoc test, the curvature group was divided into two (1140 mm, 600 mm; 600 mm, flat, 4000 mm), with the first group showing larger mean pupil diameters (3.23-3.55 vs. 2.93-3.23). However, the effect of age groups (p=0.18) or the interaction effect (p≥0.31) was not statistically significant (Figure 8).

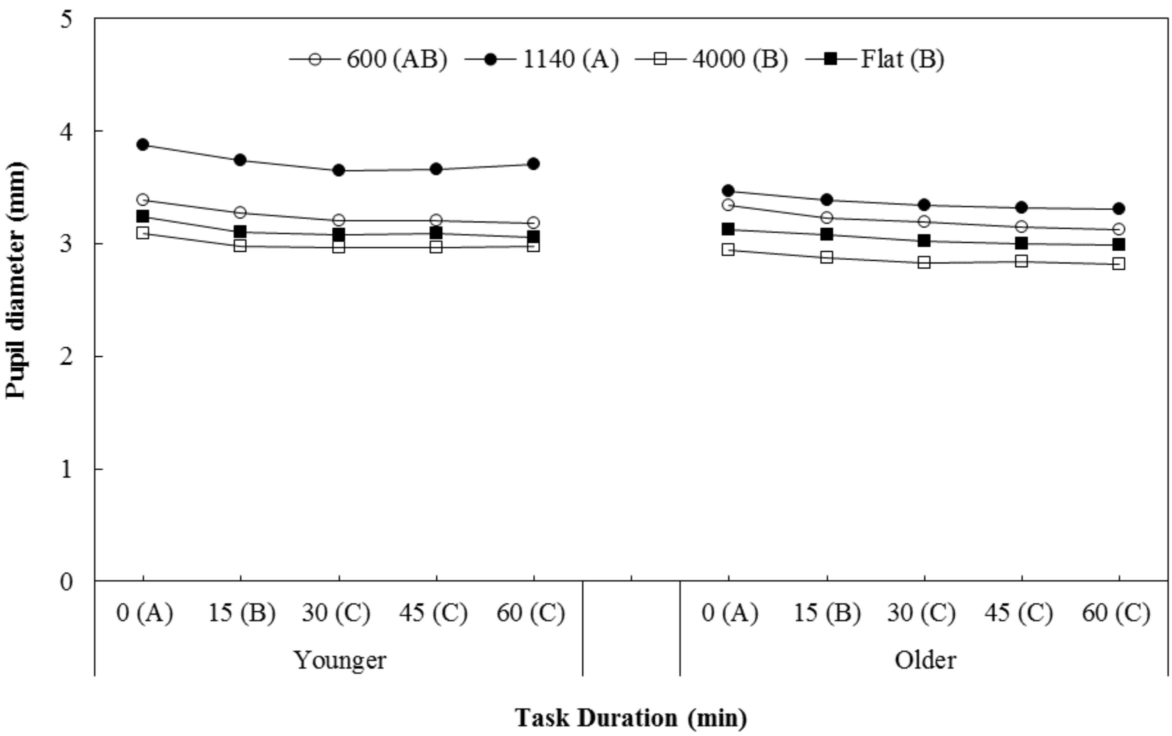


Figure 8. Effects of task duration, display curvature, and presbyopia on pupil diameter (Tukey HSD grouping in parenthesis; Ranges of SE = 0.05 ~ 0.25)

3.2. Bulbar conjunctival redness

Bulbar conjunctival redness significantly increased with task duration ($p<0.0001$). The mean bulbar conjunctival redness was the lowest at the beginning (27.6±0.46), and gradually increased to 31.4 (±0.46) after 15 min, 31.5 (±0.46) after 30 min, 31.7 (±0.46) after 45 min, and 32.8 (±0.46) after 60 min. From the post-hoc test, the task duration was divided into two groups (0 min; 15 min, 30 min, 45 min, 60 min), with the first group showing lower bulbar conjunctival redness (27.6 vs. 31.4-32.8). There was no significant difference in the mean bulbar conjunctival redness from 15 min to 60 min. However, effects of display curvatures ($p=0.84$), age groups ($p=0.97$), and the interaction effects ($p\geq0.10$) were not statistically significant (Figure 9).

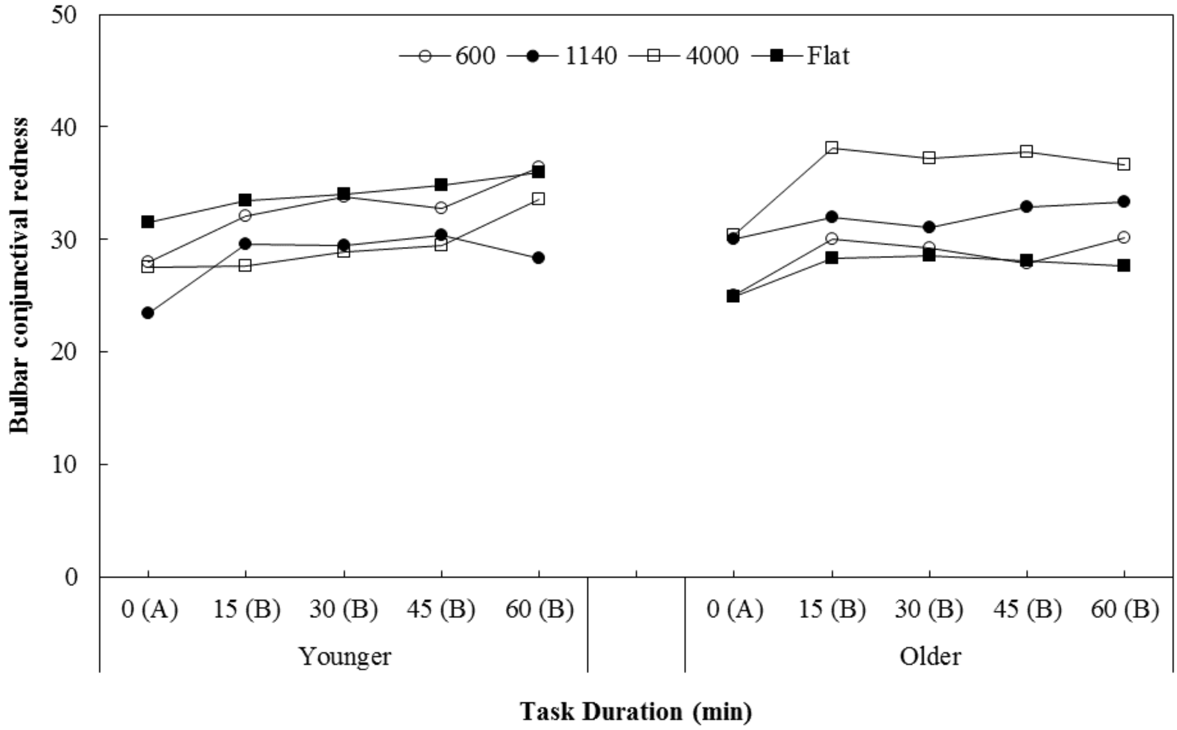


Figure 9. Effects of task duration, display curvature, and presbyopia on bulbar conjunctival redness (Tukey HSD grouping in parenthesis; Ranges of SE = 2.00 ~ 5.64)

3.3. Critical Fusion Frequency (CFF)

The effect of task duration on CFF threshold (Hz) was statistically significant ($p=0.0016$). The mean CFF threshold measured after the task (42.0 ± 0.09) was significantly lower than before the task (42.4 ± 0.09). However, the effects of display curvatures ($p=0.98$), age groups ($p=0.16$), and interaction effects ($p\geq0.23$) were not statistically significant (Figure 10).

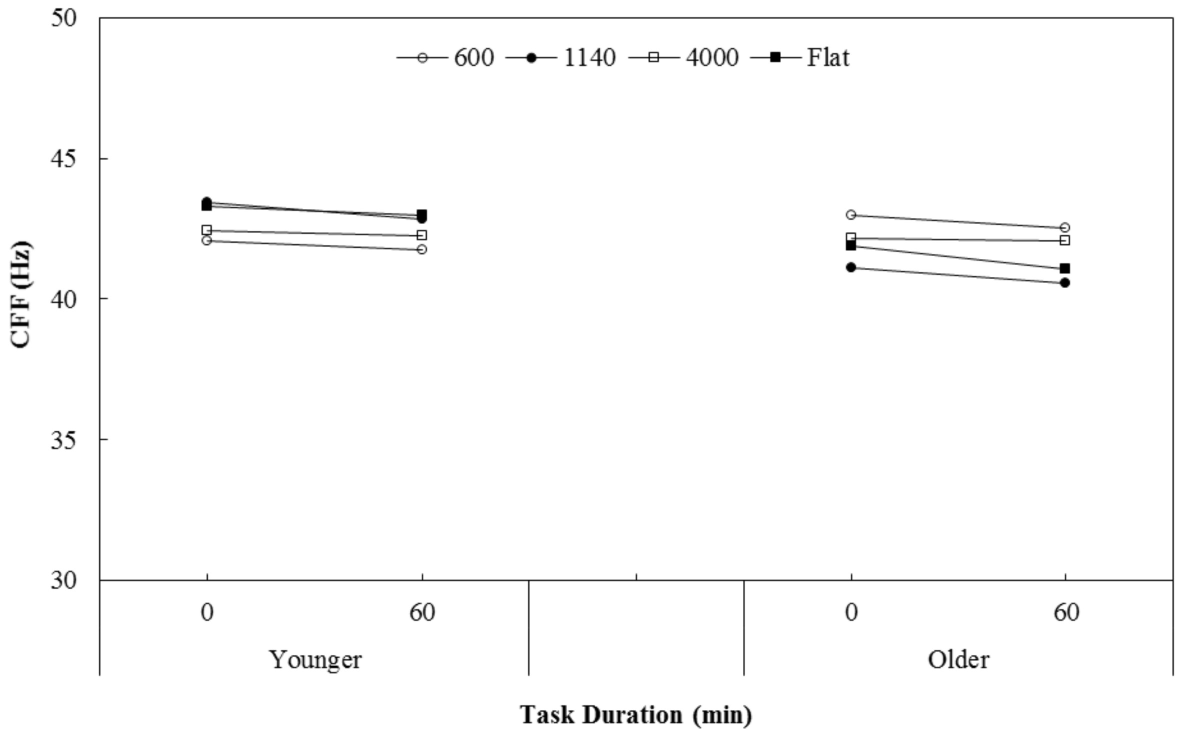


Figure 10. Effects of task duration, display curvature, and presbyopia on critical fusion frequency (Ranges of SE = 0.39 ~ 1.56)

3.4. Eye Complaint Questionnaire (ECQ)

ECQ scores significantly increased with task duration (p<0.0001). The mean ECQ score was the lowest at the beginning (9.71±1.13), and gradually increased to19.0 (±1.13) after 15 min, 22.9 (±1.13) after 30 min, 26.8 (±1.13) after 45 min, and 29.8 (±1.13) after 60 min. The post-hoc test showed that the task duration was divided into four groups (0 min; 15 min, 30 min; 30 min, 45 min; 45 min, 60 min), with the first group showing the lowest perceived visual fatigue (9.71; 19.0-22.9; 22.9-26.8; 26.8-29.8). However, effects of display curvatures (p=0.37), age groups (p=0.80), and their interaction effects (p≥0.25) were not statistically significant (Figure 11).

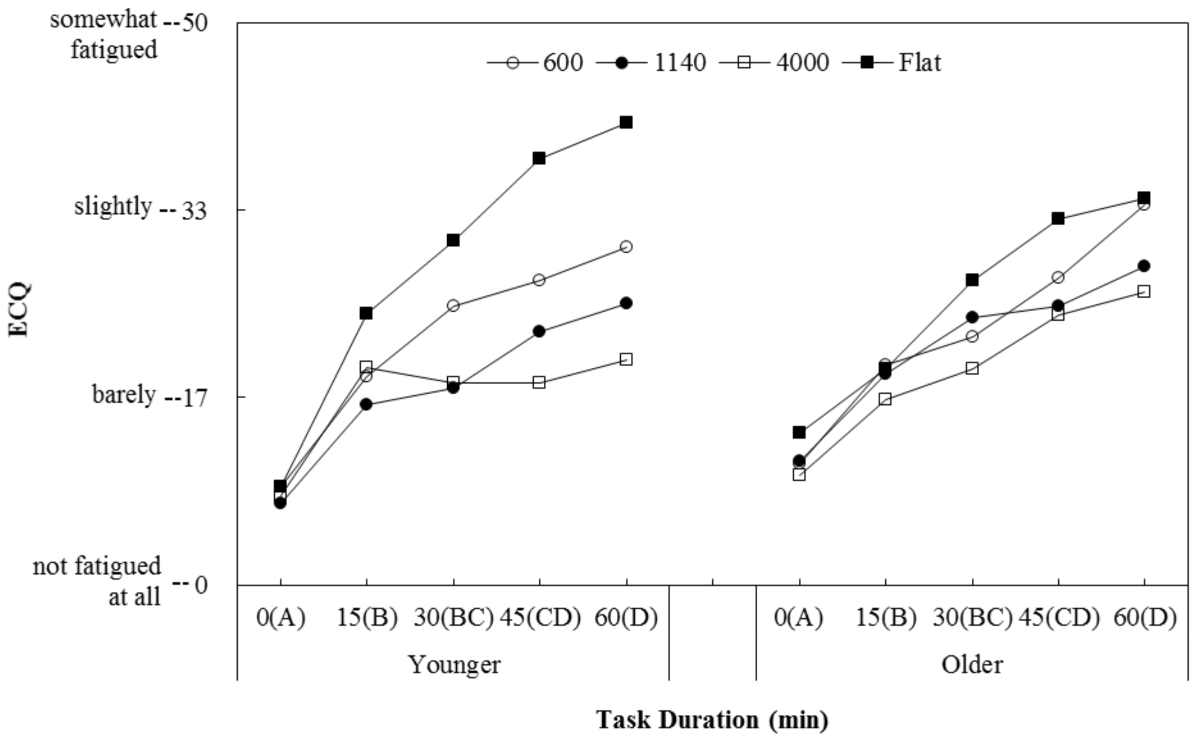


Figure 11. Effects of task duration, display curvature, and presbyopia on Eye Complain Questionnaire scores (Tukey HSD grouping in parenthesis; Ranges of SE = 1.30 ~ 11.13)

3.5. Display satisfaction

There was no main or interaction effect on display satisfaction ($p \geq 0.06$). Display satisfaction, though not significant ($p = 0.06$), was affected by the interaction effect of task duration × curvature. There was a gradual increment of display satisfaction after 30 min at the 1140mm curvature (Figure 12).

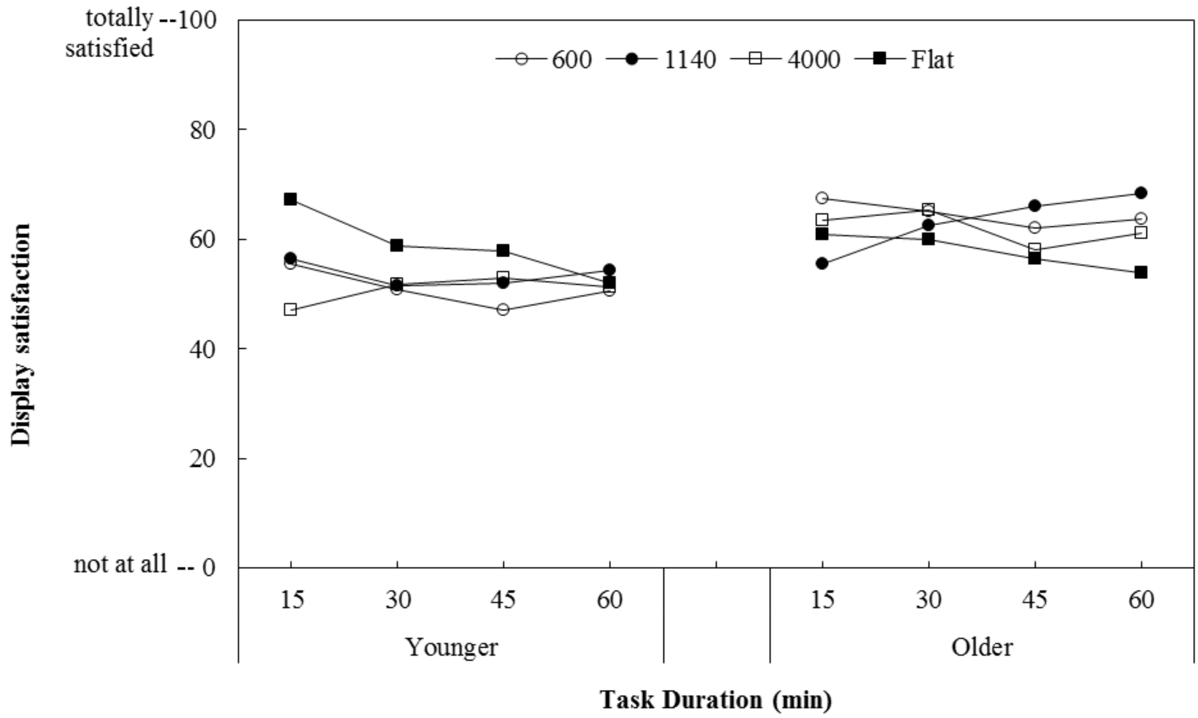


Figure 12. Effects of task duration, display curvature, and presbyopia on display satisfaction (Ranges of SE = 3.51 ~ 11.26)

IV. DISCUSSION

Regarding visual ergonomic issues involved in VDT tasks on curved displays, this study analyzed how visual fatigue and display satisfaction were different by task duration, curvature, and age group. In this section, the current research outcomes are compared with previous studies. In addition, associations between the measures by each age group are analyzed. Moreover, the prediction models for visual fatigue and display satisfaction were developed by using multiple linear regression, polynomial regressions, and ANN. The most suitable model for predicting real-time visual fatigue was selected in terms of explanatory power and predictive accuracy.

4.1. Pupil diameter

Pupil diameters shrink with visual fatigue (Murata et al., 2001; Saito et al., 1994). Near reflex occurs in combination of convergence, accommodation and pupil miosis. These factors complement each other (Levin et al., 2011). If visual fatigue is caused by short-distance VDT work, it results in shortage of accommodation and convergence. As a result, pupils contract more to obtain clear images. In this study, there were differences in pupil diameters by task duration and display curvature. Similar to previous studies, pupil diameters in this study decreased as task duration increased. Compared to the baseline (at 0 min), pupil diameters reduced by 2.9% (15 min), 4.0% (30 min), 4.2% (45 min) and 4.2% (60 min), respectively. Pupil diameters significantly decreased after 15 min and 30 min of task duration. However, there was no significant difference during 30 minutes - 60 minutes of proofreading task. Also, pupil diameters were the only measure in this work that was affected by display curvature, indicating pupil diameters were the most sensitive to visual fatigue. With regard to curvature, pupil diameters were the largest at the 1140mm curvature and the smallest at the flat and 4000mm curvatures, indicating that the 1140mm curvature was advantageous in terms of visual fatigue over the 4000mm or flat curvature. Based on these results, optimal curvatures are expected to exist around 1140mm. To find optimal curvatures, curvature radii around 1140mm should be further investigated.

4.2. Bulbar conjunctival redness

Dry eye is accompanied by redness of the eye (Lee & Park, 2011). Eye blink rates reduce during VDT tasks (Patel et al., 1991; Yaginuma, Yamada, & Nagai, 1990), and as a result, stability of the tear film decreases and people feel dry eyes and visual fatigue (Blehm et al., 2005). Consequently, bulbar conjunctival redness increases with visual fatigue. Bulbar conjunctival redness is an indicator of physiological visual fatigue. In this study, bulbar conjunctival redness significantly increased with task duration. The increment of bulbar conjunctival redness was 16.6% (15 min), 17.2% (30 min), 17.1% (45 min) and 21.4% (60 min), relative to the baseline (at 0 min). Though bulbar conjunctival redness between 0 min and 15 min was significantly different, there was no change of bulbar conjunctival redness from 15 minutes and 60 minutes. In Suh et al. (2010)'s study, there was no difference in bulbar conjunctival redness during 1-hr VDT tasks. Such discrepancy may be due to differences in the task [proofreading task (this study) vs. typing game] and/or the number of subjects (64 people vs. 15 people).

4.3. Critical Fusion Frequency (CFF)

According to Sullivan (2008), reduction of CFF threshold with visual fatigue is due to the declined ability to distinguish two separate pulses of light caused by fatigue of the central nervous system. In this study, CFF threshold decreased 0.4Hz after 60 minutes of VDT task. This was similar to the result of Lin et al. (2008a)'s study where CFF threshold decreased by 0.12Hz after 1-hr tracking task. Saito et al. (1994) showed a 0.9Hz decrement in CFF threshold after 1-hr data entry task. Wu (2012) showed that CFF threshold decreased by 1.2Hz after 40 minutes of proofreading task and video watching task. Park et al. (unpublished-a) showed a 0.3Hz of decrement in CFF threshold after 15 minutes of visual searching task. However, in the current study, because measuring CFF thresholds could affect pupil diameters, CFF threshold was measured only pre and post the entire 60-min task. Therefore, the exact time to onset of visual fatigue could not be explained by CFF threshold.

4.4. ECQ (Perceived visual fatigue)

In this study, perceived visual fatigue increased over task duration. The perceived visual fatigue after 15 minutes and 1-hr was 2.0 and 3.1 times higher than the baseline (at 0 min). In the Murata et al. (2001)'s study, perceived visual fatigue increased by about 15.6 times after 60 minutes of VDT task. The difference between the previous study and this study may be caused by task difference [Murata et al. (2001) used two displays at different viewing distances vs. this study was conducted on a single display condition] and the difference in measurements for visual fatigue [the previous study used a single question vs. this study used 10 questions by Steenstra et al. (2009)]. Saito et al. (1994) showed that after 5 hours of task, perceived visual fatigue increased 2.2 times. However, it is difficult to compare this research with the current study, because the previous study included an 1-hr break during 5 hours task to relieve visual fatigue. Kwon et al. (2012) showed that watching 2D TV and 3D TV for 2 hours increased perceived visual fatigue 1.9, and 2.8 times. According to Jaschinski-Kruza (1988, 1991), longer viewing distance caused less visual fatigue. Kwon et al. (2012) used a 5000mm viewing distance vs. this study used a 600mm viewing distance. Therefore, watching TV at a 5000mm distance may have led to less visual fatigue.

4.5. Display satisfaction

In this study, there was no significant effect of task duration, curvature, and age group on display satisfaction. A potential reason is because display satisfaction depends on individual differences such as previous experiences on display and expectations for the products (Churchill & Surprenant, 1982). Though the interaction effect of task duration and curvature was not significant (p=0.06), display satisfaction increased after 30 minutes at the 1140mm curvature. And also, even though the interaction effect of curvature and age group was not significant (p=0.79), there was a gradual increment of display satisfaction in the older group at the 1140mm. From this point, the 1140mm curvature could be especially beneficial for older individuals.

4.6. Association between measures

Some previous studies showed that as visual fatigue increased, pupil diameters decreased (Murata et al., 2001; Saito et al., 1994; Uetake et al., 2000), bulbar conjunctival redness increased (Kwon et al., 2012; Suh et al., 2010), CFF threshold decreased (Chi & Lin, 1998; Lin et al., 2008a; Murata et al., 1996; Saito et al., 1994), and perceived visual fatigue increased (Steenstra et al., 2009). Based on these, bulbar conjunctival redness likely has a positive correlation with visual fatigue while pupil diameter and CFF threshold have a negative correlation with visual fatigue.

Since there was no effect of age group on visual fatigue and satisfaction of display, association between measures by each age group was additionally analyzed. Figure 13 shows correlations between ECQ and other measures for each age group. Equations on the Table 2 were derived by substituting x and y in Figure 13. For both groups, ECQ decreased as pupil diameters increased. Also, the slope of the trend line was steeper for the younger group (younger group: -303.03, older group: -208.33), consistent with the previous studies (Murata et al., 2001; Saito et al., 1994; Uetake et al., 2000), and the older group showed less change in perceived visual fatigue with the same change of pupil diameter compared to the younger group, indicating that the older group's visual fatigue is insensitive to change of pupil diameter. In addition, in the case of the older group their pupil diameters have low variations due to the aging of eyes (Winn, Whitaker, Elliott, & Phillips, 1994). Thus it would be relatively harder to check visual fatigue of older individuals using their pupil diameter compared to younger individuals. For both younger and older groups, their ECQ increased as bulbar conjunctival redness increased. There was a greater increment for the older group (younger group: 8.58, older group: 169.49). However, in the case of the older group, there was no correlation between perceived visual fatigue and bulbar conjunctival redness (p=0.88). This is because as people age, blood vessels lose flexibility and are hard to contract. Thus, bulbar conjunctival redness could not well represent visual fatigue of older individuals. ECQ of both age groups decreased as CFF threshold increased, in consistent with the previous results (Chi & Lin, 1998; Lin et al., 2008a; Murata et al., 1996; Saito et al., 1994). There was less change of ECQ in the older group with the change of CFF threshold (younger group: -65.79, older group: -41.69). This shows that visual fatigue of the older group is insensitive to the change of CFF threshold. This may be due to homeostasis of perceived fatigue for older individuals (Kyung & Nussbaum, 2013). In fact, pain perception and reported pain decrease as people ages (Gibson & Helme, 2001). Therefore, it will be ineffective to check the visual fatigue of older individuals using CFF threshold. ECQ decreased for both groups as display satisfaction increased. Thus, satisfaction of display and visual fatigue are negatively correlated.

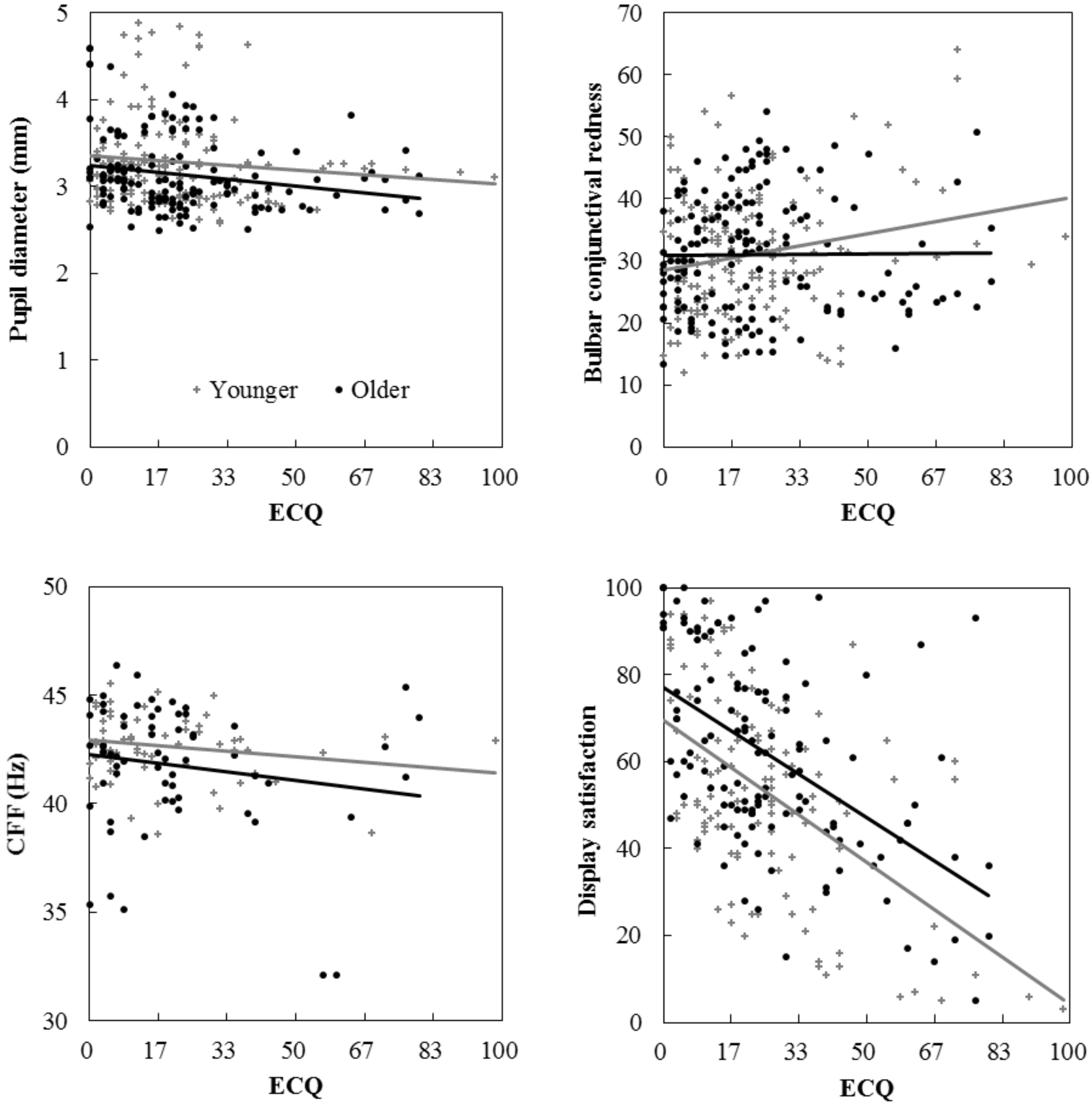


Figure 13. Correlations between ECQ and other variables by age group

Table 2. Regressions of physiological and subjective measures on visual fatigue (ECQ) by age group, coefficients of determination (R^2), and correlation coefficients (r)

Measures	Younger			Order		
	Equation	R^2 (r)	p	Equation	R^2 (r)	p
Pupil diameter	y = -303.03x + 1014.64	0.01 (-0.11)	0.16	y = -208.33x + 676.06	0.04 (-0.17)	0.04
Bulbar conjunctival redness	y = 8.58x - 245.04	0.04 (0.21)	0.01	y = 169.49x - 5223.22	0.0001 (0.01)	0.88
CFF	y = -65.79x + 2823.49	0.04 (-0.19)	0.14	y = -41.67x + 1761.96	0.03 (-0.13)	0.32
Satisfaction	y = -1.53x + 106.29	0.28 (-0.51)	<.0001	y = -1.67x + 128.60	0.28 (-0.51)	<.0001

Figure 14 shows correlations between satisfaction of display and other measures by each age group. Equations on the Table 3 were derived by substituting x and y shown in Figure 14. First of all, for both groups, display satisfaction increased as pupil diameter increased, and the change rate for the younger group was larger (younger group: 400, older group: 344.83). As bulbar conjunctival redness increased, display satisfaction of both groups increased, and the change rate for the younger group was larger (younger group: 13.97, older group: 10.33). As CFF threshold increased, display satisfaction increased for the younger group and decreased for the older group (younger group: 70.42, older group: -51.02). However, the correlation between display satisfaction and CFF threshold for the older group was very weak (r = -0.09).

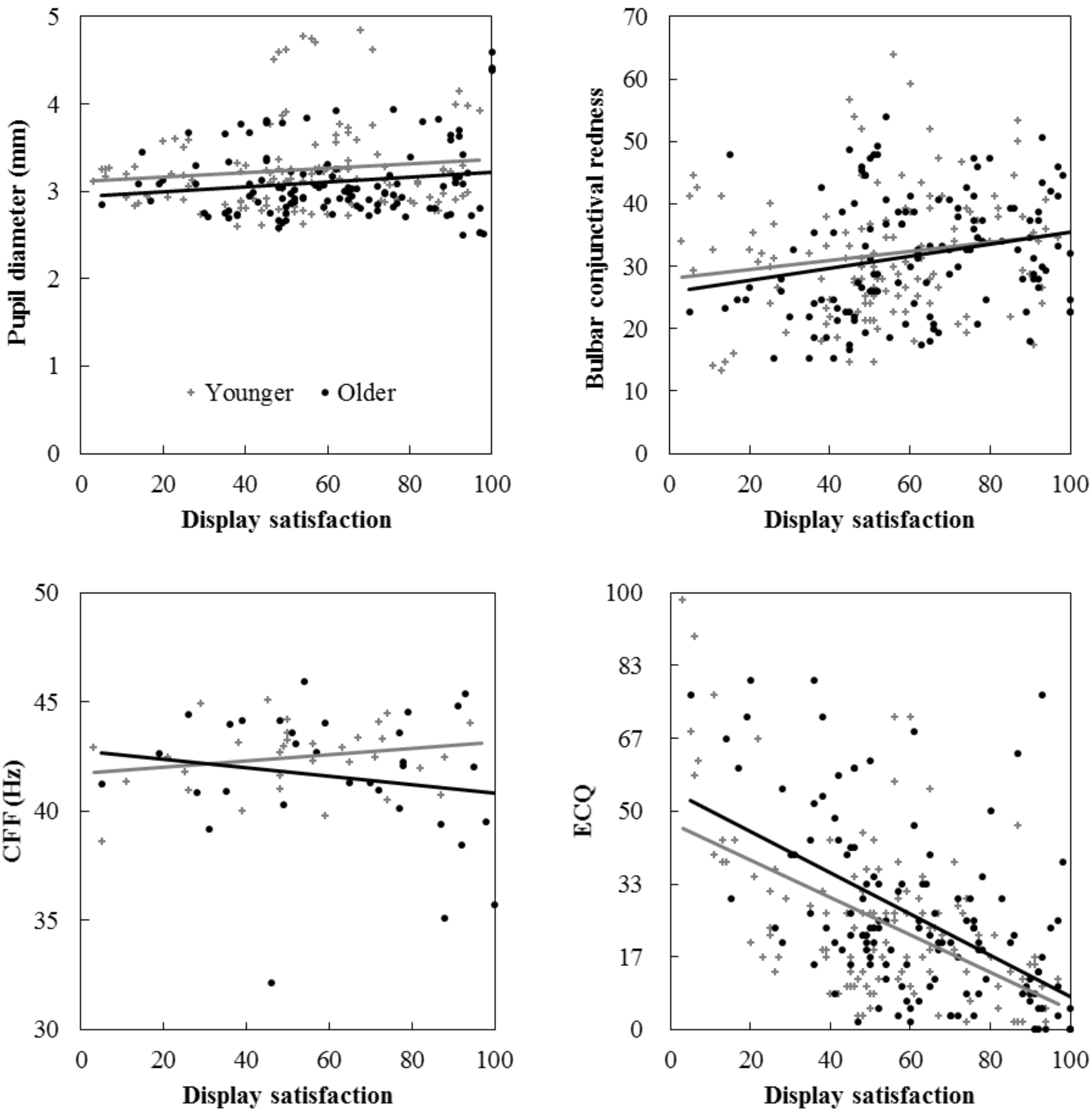


Figure 14. Correlations between display satisfaction and other variables by age group

Table 3 Regressions of physiological and subjective measures on display satisfaction by age group, coefficients of determination (R^2), and correlation coefficients (r)

Measures	Younger			Older		
	Equation	R^2 (r)	p	Equation	R^2 (r)	p
Pupil diameter	y = 400x - 1244.96	0.01 (0.11)	0.20	y = 344.83x - 1011.97	0.02 (0.15)	0.09
Bulbar conjunctival redness	y = 13.97x - 391.89	0.03 (0.13)	0.15	y = 10.33x - 266.63	0.05 (0.21)	0.02
CFF	y = 70.42x - 2938.17	0.05 (0.17)	0.19	y = -51.02x + 2181.89	0.03 (-0.09)	0.48
ECQ	y = -2.34x + 110.67	0.28 (-0.51)	<.0001	y = -2.11x + 115.72	0.28 (-0.51)	<.0001

To sum up, in the case of the younger group, pupil diameters had no relationship with perceived visual fatigue and satisfaction of display ($p = 0.16$, $p = 0.20$; respectively). However, for the older group, pupil diameter and perceived visual fatigue had a weak negative correlation ($r = -0.17$, $p = 0.04$), and although not significant, showed a weak positive correlation with satisfaction of display ($r = 0.15$, $p = 0.09$). Bulbar conjunctival redness showed a positive correlation with the younger group's perceived visual fatigue ($r = 0.21$, $p = 0.01$), and showed a positive correlation with the older group's display satisfaction ($r = 0.21$, $p = 0.02$). In the case of CFF threshold, there was no significant correlation between perceived visual fatigue and display satisfaction for both age groups. Perceived visual fatigue and display satisfaction showed a clear negative correlation for both age groups ($r = -0.51$, $p < 0.0001$; $r = -0.51$, $p < 0.0001$), respectively. To predict the younger group's visual fatigue, bulbar conjunctival redness and display satisfaction should be used, and to predict the older group's visual fatigue, pupil diameter and display satisfaction are expected to be effective. Similarly to predict the younger group's display satisfaction, perceived visual fatigue should be used, and to predict the older group's display satisfaction, pupil diameter, bulbar conjunctival redness and perceived visual fatigue should be considered.

4.7. Prediction models for visual fatigue

Murata et al. (2001) made a multiple linear regression model that predicts visual fatigue using accommodation width, accommodation speed, pupil diameter, and perceived visual fatigue. The current study used the multiple linear regression, the quadratic polynomial regression, and the 3rd degree polynomial regression to predict visual fatigue and display satisfaction. Variables used in the multiple linear regression model were task duration (TD), curvature (CV), age group (YO), pupil diameter (PD), bulbar conjunctival redness (CR), display satisfaction (ST), dominant eye visual acuity

(DV), and gender (SX). The regression equations are as follows. The multiple linear regression model consisted of 1 constant term, 5 first degree terms, 10 2-way interaction terms, and 10 3-way interaction terms. The coefficient of determination (adjusted R^2) was 0.71 ($p<0.0001$), indicating about 71% of visual fatigue can be explained by this model.

$$
\begin{aligned}
ECQ = {} & 0.11 \times TD + 5.58 \times YO - 13.13 \times PD - 0.45 \times ST - 4.34 \times SX + (CV - 26330.67) \times ((YO - 0.48) \times -0.0002) + (CV - 26330.67) \times ((PD - 3.18) \\
& \times -0.0003) + (CV - 26330.67) \times ((CR - 32.02) \times 0.00001) + (CV - 26330.67) \times ((SX - 0.42) \times -0.0003) + (PD - 3.18) \times ((ST - 57.74) \times \\
& 0.49) + (CR - 32.02) \times ((ST - 57.74) \times 0.01) + (CR - 32.02) \times ((DV - 1.01) \times -0.86) + (CR - 32.02) \times ((SX - 0.42) \times 0.7) + (ST - 57.74) \times \\
& ((SX - 0.42) \times 0.41) + (DV - 1.01) \times ((SX - 0.42) \times 28.38) + (TD - 37.5) \times ((CR - 32.02) \times ((ST - 57.74) \times -0.001)) + (TD - 37.5) \times ((CR - \\
& 32.02) \times ((DV - 1.01) \times -0.06)) + (CV - 26330.67) \times ((YO - 0.48) \times ((PD - 3.18) \times 0.001)) + (CV - 26330.67) \times ((ST - 57.74) \times ((SX - 0.42) \\
& \times 0.00001)) + (YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times - 51.14)) + (PD - 3.18) \times ((CR - 32.02) \times ((DV - 1.01) \times -7.31)) + (PD - 3.18) \times \\
& ((ST - 57.74) \times ((DV - 1.01) \times 4)) + (PD - 3.18) \times ((DV - 1.01) \times ((SX - 0.42) \times -50.1)) + (CR - 32.02) \times ((ST - 57.74) \times ((DV - 1.01) \times -0.09)) \\
& + (CR - 32.02) \times ((DV - 1.01) \times ((SX - 0.42) \times 3.30)) + 81.98
\end{aligned}
\tag{3}
$$

The quadratic polynomial regression model was composed of 1 constant term, 5 first degree terms, 1 second degree term, 9 2-way interaction terms, and 11 3-way interaction terms. The coefficient of determination (adjusted R^2) of this model was 0.69 ($p<0.0001$).

$$
\begin{aligned}
ECQ = {} & 0.10 \times TD + 0.00004 \times CV -7.69 \times PD - 0.42 \times ST + (DV -1.01) \times ((DV -1.01) \times 24.77) -7.50 \times SX + (TD - 37.5) \times ((ST - 57.74) \times -0.004) \\
& + (CV - 26330.67) \times ((YO - 0.48) \times -0.0002) + (CV - 26330.67) \times ((CR - 32.02) \times 0.00001) + (CV - 26330.67) \times ((SX - 0.42) \times -0.0003) + (PD \\
& - 3.18) \times ((ST - 57.74) \times 0.39) + (CR - 32.02) \times ((ST - 57.74) \times 0.02) + (CR - 32.02) \times ((SX - 0.42) \times 0.76) + (ST - 57.74) \times ((SX - 0.42)\times 0.28) \\
& + (DV - 1.01) \times ((SX - 0.42) \times 19.7) + (TD - 37.5) \times ((CV - 26330.67) \times ((PD - 3.18) \times -0.00001)) + (TD - 37.5) \times ((CR - 32.02) \times ((ST - \\
& 57.74) \times -0.0004)) + (TD - 37.5) \times ((CR - 32.02) \times ((DV - 1.01) \times - 0.06)) + (CV - 26330.67) \times ((YO - 0.48) \times ((PD - 3.18) \times 0.001)) + (CV \\
& - 26330.67) \times ((PD - 3.18) \times ((ST - 57.74) \times -0.00001)) + (CV - 26330.67) \times ((ST - 57.74) \times ((SX - 0.42) \times 0.00001)) + (YO - 0.48) \times \\
& ((CR - 32.02) \times ((DV - 1.01) \times -5.2)) + (PD - 3.18) \times ((CR - 32.02) \times ((DV - 1.01) \times -6.34)) + (PD - 3.18) \times ((ST - 57.74) \times ((DV - 1.01) \times \\
& 2.82)) + (PD - 3.18) \times ((DV - 1.01) \times ((SX - 0.42) \times -79.98)) + (CR - 32.02) \times ((ST - 57.74) \times ((DV -1.01) \times -0.04)) + 65.63
\end{aligned}
\tag{4}
$$

The 3rd degree polynomial regression model consisted of 1 constant term, 6 first degree terms, 1 third degree term, 7 2-way interaction terms, and 12 3-way interaction terms. In addition, the coefficient of determination (adjusted R^2) was 0.66 ($p<0.0001$).

$$ECQ = 0.0001 \times CV + 11.20 \times YO - 5.29 \times PD - 0.41 \times CR - 0.58 \times ST - 38.92 \times DV + (DV - 1.01) \times ((DV - 1.01) \times ((DV - 1.01) \times 304.76)) + (TD - 37.5) \times ((CR - 32.02) \times 0.01) + (TD - 37.5) \times ((ST - 57.74) \times -0.01) + (CV - 26330.67) \times ((YO - 0.48) \times -0.0002) + (CV - 26330.67) \times ((DV - 1.01) \times 0.0004) + (CV - 26330.67) \times ((SX - 0.42) \times -0.0003) + (PD - 3.18) \times ((CR - 32.02) \times -0.7) + (ST - 57.74) \times ((SX - 0.42) \times 0.39) + (TD - 37.5) \times ((CV - 26330.67) \times ((PD - 3.18) \times -0.00001)) + (TD - 37.5) \times ((CR - 32.02) \times ((DV - 1.01) \times -0.05)) + (CV - 26330.67) \times ((YO - 0.48) \times ((PD - 3.18) \times 0.001)) + (CV - 26330.67) \times ((PD - 3.18) \times ((CR - 32.02) \times -0.00003)) + (CV - 26330.67) \times ((PD - 3.18) \times ((ST - 57.74) \times -0.00001)) + (YO - 0.48) \times ((CR - 32.02) \times ((DV - 1.01) \times -3.37)) + (YO - 0.48) \times ((CR - 32.02) \times ((SX - 0.42) \times -2.78)) + (YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -86.49)) + (PD - 3.18) \times ((CR - 32.02) \times ((DV - 1.01) \times -12.49)) + (PD - 3.18) \times ((ST - 57.74) \times ((DV - 1.01) \times 3.66)) + (CR - 32.02) \times ((ST - 57.74) \times ((DV - 1.01) \times -0.07)) + (ST - 57.74) \times ((DV - 1.01) \times ((SX - 0.42) \times 1.44)) + 118.45 \tag{5}$$

Next, variables used in the multiple linear regression model to predict satisfaction of display were task duration (TD), curvature (CV), age group (YO), pupil diameter (PD), bulbar conjunctival redness (CR), perceived visual fatigue (EQ), dominant eye visual acuity (DV), and gender (SX). The regression equations are as follows. The multiple linear regression model had 1 constant term, 3 first degree terms, 6 2-way interaction terms, and 11 3-way interaction terms. And the coefficient of determination (adjusted R^2) of this model was 0.67 ($p<0.0001$).

$$Satisfaction = 0.0001 \times CV + 0.45 \times CR - 0.45 \times EQ + (TD - 37.5) \times ((PD - 3.18) \times 0.37) + (CV - 26330.67) \times ((CR - 32.02) \times -0.00001) + (CV - 26330.67) \times ((EQ - 24.76) \times 0.00001) + (CV - 26330.67) \times ((DV - 1.01) \times 0.001) + (CV - 26330.67) \times ((SX - 0.42) \times 0.0004) + (CR - 32.02) \times ((EQ - 24.76) \times 0.03) + (TD - 37.5) \times ((CV - 26330.67) \times ((CR - 32.02) \times -0.0000003)) + (TD - 37.5) \times ((PD - 3.18) \times ((EQ - 24.76) \times 0.02)) + (TD - 37.5) \times ((CR - 32.02) \times ((DV - 1.01) \times -0.09)) + (TD - 37.5) \times ((DV - 1.01) \times ((SX - 0.42) \times 1.02)) + (CV - 26330.67) \times ((YO - 0.48) \times ((DV - 1.01) \times -0.002)) + (CV - 26330.67) \times ((YO - 0.48) \times ((SX - 0.42) \times 0.0004)) + (CV - 26330.67) \times ((PD - 3.18) \times ((DV - 1.01) \times 0.001)) + (CV - 26330.67) \times ((EQ - 24.76) \times ((SX - 0.42) \times 0.00002)) + (YO - 0.48) \times ((EQ - 24.76) \times ((SX - 0.42) \times 0.67)) + (PD - 3.18) \times ((CR - 32.02) \times ((DV - 1.01) \times 4.26)) + (PD - 3.18) \times ((DV - 1.01) \times ((SX - 0.42) \times -199.29)) + 51.71 \tag{6}$$

The quadratic polynomial regression model was composed of 1 constant term, 4 first degree terms, 2 second degree terms, 8 2-way interaction terms, and 10 3-way interaction terms. The coefficient of determination (adjusted R^2) of this model was 0.68 ($p<0.0001$).

$$\begin{aligned} Satisfaction = {} & 0.0001 \times CV + (PD - 3.18) \times ((PD - 3.18) \times 10.51) + 0.6 \times CR \\ & - 0.73 \times EQ + (DV - 1.01) \times ((DV - 1.01) \times 54.86) - 15.50 \times SX \\ & + (TD - 37.5) \times ((PD - 3.18) \times 0.37) + (CV - 26330.67) \times ((CR - 32.02) \times -0.00001) \\ & + (CV - 26330.67) \times ((DV - 1.01) \times 0.001) + (YO - 0.48) \times ((EQ - 24.76) \times 0.46) \\ & + (PD - 3.18) \times ((SX - 0.42) \times -28.32) + (CR - 32.02) \times ((EQ - 24.76) \times 0.01) \\ & + (CR - 32.02) \times ((SX - 0.42) \times 0.48) + (EQ - 24.76) \times ((SX - 0.42) \times -0.31) \\ & + (TD - 37.5) \times ((PD - 3.18) \times ((EQ - 24.76) \times 0.02)) + (TD - 37.5) \times ((CR - 32.02) \times ((DV - 1.01) \times -0.09)) \\ & + (TD - 37.5) \times ((DV - 1.01) \times ((SX - 0.42) \times 1.24)) + (CV - 26330.67) \times ((YO - 0.48) \times ((PD - 3.18) \times 0.001)) \\ & + (CV - 26330.67) \times ((YO - 0.48) \times ((DV - 1.01) \times -0.001)) + (CV - 26330.67) \times ((YO - 0.48) \times ((SX - 0.42) \times 0.0004)) \\ & + (CV - 26330.67) \times ((PD - 3.18) \times ((DV - 1.01) \times 0.003)) + (YO - 0.48) \times ((EQ - 24.76) \times ((SX - 0.42) \times 1.01)) \\ & + (YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -54.69)) + (PD - 3.18) \times ((DV - 1.01) \times ((SX - 0.42) \times -146.05)) + 52.93 \end{aligned} \tag{7}$$

The 3rd degree polynomial regression model was composed of 1 constant term, 4 first degree terms, 3 second degree terms, 2 third degree term, 5 2-way interaction terms, and 12 3-way interaction terms. The coefficient of determination (adjusted R^2) was 0.72 ($p<0.0001$).

$$\begin{aligned} Satisfaction = {} & 0.0001 \times CV + (PD - 3.18) \times ((PD - 3.18) \times 24.09) + (PD - 3.18) \times ((PD - 3.18) \times ((PD - 3.18) \times -11.79)) + 0.57 \times CR \\ & - 0.39 \times EQ + (EQ - 24.76) \times ((EQ - 24.76) \times 0.02) + (EQ - 24.76) \times ((EQ - 24.76) \times ((EQ - 24.76) \times -0.0003)) \\ & + (DV - 1.01) \times ((DV - 1.01) \times 89.82) - 9.84 \times SX + (TD - 37.5) \times ((PD - 3.18) \times 0.39) \\ & + (CV - 26330.67) \times ((DV - 1.01) \times 0.001) + (CV - 26330.67) \times ((SX - 0.42) \times 0.0001) \\ & + (CR - 32.02) \times ((DV - 1.01) \times 2.45) + (EQ - 24.76) \times ((DV - 1.01) \times -1.05) \\ & + (TD - 37.5) \times ((PD - 3.18) \times ((EQ - 24.76) \times 0.02)) + (TD - 37.5) \times ((CR - 32.02) \times ((DV - 1.01) \times -0.09)) \\ & + (TD - 37.5) \times ((DV - 1.01) \times ((SX - 0.42) \times 1.58)) + (CV - 26330.67) \times ((YO - 0.48) \times ((DV - 1.01) \times -0.001)) \\ & + (CV - 26330.67) \times ((PD - 3.18) \times ((DV - 1.01) \times 0.002)) + (CV - 26330.67) \times ((EQ - 24.76) \times ((SX - 0.42) \times 0.00002)) \\ & + (CV - 26330.67) \times ((DV - 1.01) \times ((SX - 0.42) \times -0.001)) + (YO - 0.48) \times ((EQ - 24.76) \times ((DV - 1.01) \times 1.09)) \\ & + (YO - 0.48) \times ((EQ - 24.76) \times ((SX - 0.42) \times 1.40)) + (YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -68.41)) \\ & + (PD - 3.18) \times ((CR - 32.02) \times ((DV - 1.01) \times 5.55)) + (PD - 3.18) \times ((DV - 1.01) \times ((SX - 0.42) \times -102.96)) + 41.16 \end{aligned} \tag{8}$$

The above results can be used when developing a system which diagnoses display users' visual fatigue in real time using pupil-related and conjunctiva-related data. Variables except for display satisfaction that cannot be measured in real time, were used for the regression model that predicts visual fatigue [task duration (TD), curvature (CV), age group (YO), pupil diameter (PD), bulbar conjunctival redness (CR), dominant eye visual acuity (DV), and gender (SX)]. The multiple linear regression model consisted of 1 constant term, 3 first degree terms, 5 2-way interaction terms, 5 3-way interaction terms, and 4 4-way interaction terms. The coefficient of determination (adjusted R^2) was 0.43 ($p<0.0001$). In addition, the standardized coefficient (β) of first degree term was larger for task duration (0.39) than for curvature (0.23) and for age group (0.25), which means task duration is more influential to visual fatigue.

$$ECQ = 0.34 \times TD + 0.0001 \times CV + 9.29 \times YO + (TD - 30) \times ((CV - 26330.67) \times 0.000002) + (CV - 26330.67) \times ((DV - 1.01) \times -0.001) + (CV - 26330.67) \times ((SX - 0.42) \times -0.0002) + (YO - 0.48) \times ((PD - 3.21) \times 8.52) + (YO - 0.48) \times ((DV - 1.01) \times 16.94) + (CV - 26330.67) \times ((YO - 0.48) \times ((PD - 3.21) \times 0.001)) + (CV - 26330.67) \times ((YO - 0.48) \times ((CR - 31.14) \times 0.00001)) + (CV - 26330.67) \times ((YO - 0.48) \times ((DV - 1.01) \times 0.001)) + (YO - 0.48) \times ((PD - 3.21) \times ((DV - 1.01) \times 55.3)) + (YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -89.34)) + (TD - 30) \times ((YO - 0.48) \times ((CR - 31.14) \times ((DV - 1.01) \times -0.07))) + (CV - 26330.67) \times ((YO - 0.48) \times ((CR - 31.14) \times ((DV - 1.01) \times 0.0001))) + (CV - 26330.67) \times ((YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -0.004))) + (YO - 0.48) \times ((PD - 3.21) \times ((CR - 31.14) \times ((DV - 1.01) \times -8.35))) + 3.57 \quad \textbf{(9)}$$

Table 4. Coefficients, standardized beta, and VIF of multiple linear regression

Term	Coefficients	p	Standardized beta	VIF
Intercept	3.57	0.05	0.00	
TD	0.34	<.0001	0.39	1.00
CV	0.00010	<.0001	0.23	1.30
YO	9.29	<.0001	0.25	1.38
TD×CV	0.0000021	0.02	0.10	1.03
CV×DV	-0.00080	<.0001	-0.40	1.63
CV×SX	-0.00022	<.0001	-0.25	1.28
YO×PD	8.52	0.04	0.11	1.48
YO×DV	16.94	0.03	0.11	1.34
CV×YO×PD	0.00082	<.0001	0.37	2.46
CV×YO×CR	0.000010	0.02	0.12	1.51
CV×YO×DV	0.0012	<.0001	0.31	2.00
YO×PD×DV	55.30	0.01	0.13	1.36
YO×DV×SX	-89.34	<.0001	-0.30	1.56
TD×YO×CR×DV	-0.070	0.02	-0.11	1.08
CV×YO×CR×DV	0.000094	0.0001	0.26	2.31
CV×YO×DV×SX	-0.0039	<.0001	-0.47	2.03
YO×PD×CR×DV	-8.35	0.0003	-0.20	1.63

The quadratic polynomial regression model was composed of 1 constant term, 2 first degree terms, 2 second degree terms, 3 2-way interaction terms, 5 3-way interaction terms, and 2 4-way interaction terms. The coefficient of determination (adjusted R^2) was 0.43 ($p<0.0001$). Moreover, standardized coefficient (β) of first degree term was larger for task duration (0.38) than for age group (0.23), which means task duration is more influential than age group to visual fatigue.

$$ECQ = 0.33 \times TD + (TD - 30) \times ((TD - 30) \times -0.01) + 8.49 \times YO + (DV - 1.01) \times ((DV - 1.01) \times -29.09) + (CV - 26330.67) \times ((DV - 1.01) \times -0.001) + (CV - 26330.67) \times ((SX - 0.42) \times -0.0002) + (PD - 3.21) \times ((DV - 1.01) \times 22.983) + (CV - 26330.67) \times ((YO - 0.48) \times ((PD - 3.21) \times 0.0004)) + (CV - 26330.67) \times ((YO - 0.48) \times ((DV - 1.01) \times 0.001)) + (CV - 26330.67) \times ((PD - 3.21) \times ((CR - 31.14) \times -0.00002)) + (YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -66.57)) + (CR - 31.14) \times ((DV - 1.01) \times ((SX - 0.42) \times 3.34)) + (CV - 26330.67) \times ((YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -0.001))) + (YO - 0.48) \times ((PD - 3.21) \times ((CR - 31.14) \times ((DV - 1.01) \times -6.09))) + 9.99 \quad \textbf{(10)}$$

Table 5. Coefficients, standardized beta and, VIF of quadratic polynomial regression

Term	Coefficients	p	Standardized beta	VIF
Intercept	9.99	<.0001	0.00	
TD	0.33	<.0001	0.38	1.00
TD×TD	-0.0050	0.02	-0.10	1.01
YO	8.49	<.0001	0.23	1.30
DV×DV	-29.09	0.01	-0.14	1.45
CV×DV	-0.00068	<.0001	-0.34	1.84
CV×SX	-0.00023	<.0001	-0.26	1.26
PD×DV	22.98	0.03	0.11	1.28
CV×YO×PD	0.00050	<.0001	0.23	1.63
CV×YO×DV	0.00091	<.0001	0.23	1.52
CV×PD×CR	-0.000024	<.0001	-0.24	1.31
YO×DV×SX	-66.57	<.0001	-0.22	1.42
CR×DV×SX	3.34	<.0001	0.23	1.36
CV×YO×DV×SX	-0.0014	0.002	-0.18	1.65
YO×PD×CR×DV	-6.09	0.01	-0.15	1.84

The 3rd degree polynomial regression model consisted of 1 constant term, 4 first degree terms, 2 second degree terms, 1 third degree term, 6 2-way interaction terms, 7 3-way interaction terms, and 4 4-way interaction terms. In addition, the coefficient of determination (adjusted R^2) was 0.53 ($p<0.0001$).

Also, by taking a look at standardized coefficient (β) of the first degree term of the 3rd degree polynomial regression, visual acuity (0.57) of the dominant eye was more influential to visual fatigue than other variables such as task duration (0.39), curvature (0.20), and age group (0.19).

$$
\begin{aligned}
ECQ = {} & 0.34 \times TD + (TD - 30) \times ((TD - 30) \times -0.01) + 0.0001 \times CV + 7.06 \times \\
& YO - 41.75 \times DV + (DV - 1.01) \times ((DV - 1.01) \times -44.84) + (DV - 1.01) \times \\
& ((DV - 1.01) \times ((DV - 1.01) \times 178)) + (TD - 30) \times ((CV - 26330.67) \times \\
& 0.000002) + (CV - 26330.67) \times ((DV - 1.01) \times -0.001) + (YO - 0.48) \times \\
& ((DV - 1.01) \times -19.098) + (YO - 0.48) \times ((SX - 0.42) \times 9.25) + (PD - \\
& 3.21) \times ((CR - 31.14) \times 0.96) + (DV - 1.01) \times ((SX - 0.42) \times 17.18) + \\
& (CV - 26330.67) \times ((YO - 0.48) \times ((PD - 3.21) \times 0.001)) + (CV - \\
& 26330.67) \times ((YO - 0.48) \times ((SX - 0.42) \times 0.0003)) + (CV - 26330.67) \times \\
& ((PD - 3.21) \times ((SX - 0.42) \times 0.001)) + (YO - 0.4) \times ((PD - 3.21) \times ((CR \\
& - 31.14) \times 1.25)) + (YO - 0.48) \times ((CR - 31.14) \times ((DV - 1.01) \times -3.08)) \\
& + (YO - 0.48) \times ((DV - 1.01) \times ((SX - 0.42) \times -85.48)) + (CR - 31.14) \times \\
& ((DV - 1.01) \times ((SX - 0.42) \times 1.85)) + (TD - 30) \times ((YO - 0.48) \times ((CR - \\
& 31.14) \times ((DV - 1.01) \times -0.06))) + (CV - 26330.67) \times ((YO - 0.48) \times \\
& ((PD - 3.21) \times ((DV - 1.01) \times -0.002))) + (CV - 26330.67) \times ((YO - 0.48) \\
& \times ((DV - 1.01) \times ((SX - 0.42) \times -0.003))) + (YO - 0.48) + ((PD - 3.21) \times \\
& ((CR - 31.14) \times ((DV - 1.01) \times -7.40)) + 51.75
\end{aligned}
\tag{11}
$$

Table 6. Coefficients, standardized beta and, VIF of 3rd degree polynomial regression

Term	Coefficient	p	Standardized beta	VIF
Intercept	51.75	<.0001	0.00	
TD	0.34	<.0001	0.39	1.00
TD×TD	-0.0057	0.004	-0.12	1.02
CV	0.000084	<.0001	0.20	1.53
YO	7.06	0.0001	0.19	1.55
DV	-41.75	<.0001	-0.57	8.66
DV×DV	-44.84	0.0005	-0.21	2.31
DV×DV×DV	178.00	0.0003	0.48	10.78
TD×CV	0.0000021	0.01	0.10	1.03
CV×DV	-0.0011	<.0001	-0.55	2.44
YO×DV	-19.09	0.01	-0.13	1.60
YO×SX	9.25	0.01	0.12	1.34
PD×CR	0.96	<.0001	0.21	1.59
DV×SX	17.18	0.01	0.12	1.37
CV×YO×PD	0.00077	<.0001	0.35	2.51
CV×YO×SX	0.00038	<.0001	0.21	1.40
CV×PD×SX	0.00066	<.0001	0.30	1.99
YO×PD×CR	1.25	0.006	0.14	1.62
YO×CR×DV	-3.08	0.0005	-0.22	2.57
YO×DV×SX	-85.48	<.0001	-0.29	2.61
CR×DV×SX	1.85	0.03	0.13	2.27
TD×YO×CR×DV	-0.06	0.02	-0.10	1.09
CV×YO×PD×DV	-0.0024	<.0001	-0.25	1.95
CV×YO×DV×SX	-0.0031	<.0001	-0.38	2.23
YO×PD×CR×DV	-7.40	0.004	-0.18	2.50

The results of the principal component regression are as follows. First of all, by the principal component analysis, 7 variables [task duration (TD), curvature (CV), age group (YO), pupil diameter (PD), bulbar conjunctival redness (CR), dominant eye visual acuity (DV), and gender (SX)] were classified into 4 principal components that explain 72.7% of variance (the first principal component: YO, SX; the second principal component: CR, DV; the third principal component: TD, PD; the fourth principal component: CV). The regression model that predicts visual fatigue using 4 principal components is as follows. The coefficient of determination (adjusted R^2) was 0.14.

$$ECQ = -0.79\times PC_1 + 0.09\times PC_2 + 6.97\times PC_3 - 0.81\times PC_4 + 21.55 \qquad \textbf{(12)}$$

Next, display users' visual fatigue was predicted by ANN. The result was drawn using 7 variables [task duration (TD), curvature (CV), age group (YO), pupil diameter (PD), bulbar conjunctival redness (CR), dominant eye visual acuity (DV), and gender (SX)] which were used as the input layer's neurons. Visual fatigue was used as the output layer's neuron. The number of the hidden layer's neurons changed from 5, 10, 15, and 20. The following table (Table 7) shows the correlation coefficient between visual fatigues observed (by ECQ score) and predicted by the models with a different number of neurons in their hidden layer. When 15 neurons were used for the hidden layer, the correlation coefficient was the highest.

Table 7. Correlation between predicted and reported ECQ scores

Number of neurons in the hidden layer	Training (70% of data used)	Validation (15% of data used)	Prediction (15% of data used)	All data used
5	0.49	0.37	0.15	0.43
10	0.80	0.53	0.62	0.72
15	0.83	0.76	0.88	0.83
20	0.70	0.45	0.43	0.62

Except for the principal component regression model with the lowest explanatory power, 4 models (the multiple linear regression model, the quadratic polynomial regression model, the 3rd degree polynomial regression model, and the ANN model with 15 neurons in the hidden layer) were compared in terms of correlation coefficient, RMSE, and MAPE. The ANN model was the best in terms of all three criteria (Table 8). Three regression models were comparable in terms of RMSE. In terms of MAPE, the 3rd degree polynomial regression model showed the highest accuracy among three regression models.

Table 8. Comparison of prediction models in terms of RMSE, MAPE, and correlation coefficient

Prediction model	RMSE	MAPE (%)	r
Multiple linear regression	11.20	130.82	0.68
Quadratic polynomial regression	11.17	126.49	0.68
3rd degree polynomial regression	12.11	111.30	0.68
Artificial neural network	10.29	87.44	0.83

4.8. Limitations

No age effect was found in this study. This can be influenced by the font size used in this work. The font size 16.8pt used in the experiment was larger than generally used for the proofreading task in the previous studies (10 – 14pt) (Chan & Ng, 2012; Chan, Tsang, & Ng, 2014; Piepenbrock, Mayr, & Buchner, 2014). Task performance was not taken into account in the current study. Hence, a further study that incorporates task performance is needed for better ergonomic evaluation of curved display (Lin et al., 2008a; Piepenbrock, Mayr, Mund, & Buchner, 2013). According to Park et al. (unpublished-a), task performance (accuracy and speed) was better at the 600mm and 1200mm curvatures than the flat display during visual searching tasks at a 500mm viewing distance. Combined with the results of the current study, it seems possible to find optimal curvatures around the range of 600mm and 1140mm for VDT tasks in terms of visual fatigue and task performance. The visual fatigue prediction models developed in the current study assumed that pupil diameters and bulbar conjunctival redness could be measured in real time, thus a further study on evaluating bulbar conjunctival redness in real time should be done. In addition, this study used the lateral area of the sclera to assess bulbar conjunctival redness, which is rarely exposed while using a display. Therefore, a further study on developing an algorithm that evaluates bulbar conjunctival redness using frontal images of the eye is needed. In this study, only two physiological measures, pupil diameter and bulbar conjunctival redness, were used to predict real-time visual fatigue. Other measures related to visual fatigue such as eye blink rate and PERCLOS (percentage of eye closure) can be additionally considered.

V. CONCLUSIONS

Task duration made significant effects on perceived visual fatigue and physiological visual fatigue, but not on display satisfaction. Even if a 15 minute proofreading task was thought to be short, there was a significant increment of visual fatigue. Therefore, taking frequent short breaks can be effective to relieve visual fatigue (Blehm et al., 2005). Actually, seeing distant objects at least twice an hour helps prevent visual fatigue (Cheu, 1998). Display curvatures had a significant effect only on pupil diameters and low visual fatigue was observed at the 1140mm curvature. The 4000mm curvature had no difference with the flat display in terms of visual fatigue. Lastly, there was no statistically significant effect of age groups on visual fatigue and display satisfaction.

Display tasks other than proofreading, longer-term task durations, and measures of task performance should be additionally considered in the future work. Moreover, it seems possible to develop a prediction system that diagnoses visual fatigue in real time by using viewers' pupil and bulbar conjunctival redness data. Among the real-time visual fatigue prediction model, the ANN model and the 3rd degree polynomial regression model showed the best and the second best accuracy. In order to develop the real-time visual fatigue diagnosing system in this way, however, a technique of measuring bulbar conjunctival redness in real time is required. In addition, a more sensitive prediction of older individuals' visual fatigue using bulbar conjunctival redness is needed. Finally, this study can be improved further in two ways - 1) developing an algorithm that can assess bulbar conjunctival redness using the frontal image rather than the side image of the eye, and 2) finding out other real-time ocular-related measurements to improve predictive accuracy of visual fatigue.

RERERENCES

Ahn, S., Jin, B., Kwon, S., & Yun, M. (2014). A research on curved display comparing to flat display regarding posture, tilt angle, focusing area and satisfaction. *Journal of the Ergonomics Society of Korea, 33*(3), 191-202. Retrieved from http://www.dbpia.co.kr/Article/NODE02431648

Anderson, L. K. (1990). *Handbook for proofreading*. Chicago, IL: NTC Business Books.

Balci, R., & Aghazadeh, F. (2003). The effect of work-rest schedules and type of task on the discomfort and performance of VDT users. *Ergonomics, 46*(5), 455-465. doi:10.1080/0014013021000047557

Bergqvist, U. O., & Knave, B. G. (1994). Eye discomfort and work with visual display terminals. *Scand J Work Environ Health, 20*(1), 27-33.

Blehm, C., Vishnu, S., Khattak, A., Mitra, S., & Yee, R. W. (2005). Computer vision syndrome: a review. *Surv Ophthalmol, 50*(3), 253-262. doi:10.1016/j.survophthal.2005.02.008

Carayon, P. (1993). Effect of Electronic Performance Monitoring on Job Design and Worker Stress: Review of the Literature and Conceptual Model. *Hum Factors, 35*(3), 385-395. doi:10.1177/001872089303500301

Chan, A. H. S., & Ng, A. W. Y. (2012). Effects of display factors on Chinese proofreading performance and preferences. *Ergonomics, 55*(11), 1316-1330. doi:10.1080/00140139.2012.714472

Chan, A. H. S., Tsang, S. N. H., & Ng, A. W. Y. (2014). Effects of line length, line spacing, and line number on proofreading performance and scrolling of Chinese text. *Hum Factors, 56*(3), 521-534.

Chen, C., Wang, J., Li, K., Wu, Q., Wang, H., Qian, Z., & Gu, N. (2014). Assessment visual fatigue of watching 3DTV using EEG power spectral parameters. *Displays, 35*(5), 266-272. doi:10.1016/j.displa.2014.10.001

Cheng, C. Y., Yen, M. Y., Lin, H. Y., Hsia, W. W., & Hsu, W. M. (2004). Association of ocular dominance and anisometropic myopia. *Invest Ophthalmol Vis Sci, 45*(8), 2856-2860. doi:10.1167/iovs.03-0878

Cheu, R. A. (1998). Good vision at work. *Occup Health Saf, 67*(9), 20-24.

Chi, C. F., & Lin, F. T. (1998). A comparison of seven visual fatigue assessment techniques in three data-acquisition VDT tasks. *Hum Factors, 40*(4), 577-590.

Choi, B., Lee, S., Lee, J. E., Hong, S., Lee, J., & Kim, S. (2015). A study on the optimum curvature for the curved monitor. *Journal of Information Display, 16*(4), 217-223. doi:10.1080/15980316.2015.1111847

Choi, H. (2014). Chrome cast. Retrieved from http://navercast.naver.com/contents.nhn?rid=122&contents_id=56744&leafId=122

Choi, J., & Kim, Y. (2012a). All rounder, fruits. Retrieved from http://navercast.naver.com/contents.nhn?rid=202&contents_id=17705&leafId=202

Choi, J., & Kim, Y. (2012b). Fresh and vitality food, vegetables. Retrieved from http://navercast.naver.com/contents.nhn?rid=202&contents_id=17337&leafId=202

Choi, J., & Kim, Y. (2012c). Nutrient richness, grain. Retrieved from http://navercast.naver.com/contents.nhn?rid=202&contents_id=17215&leafId=202

Choi, J., & Kim, Y. (2013a). Food for preventing influenza. Retrieved from http://navercast.naver.com/contents.nhn?rid=202&contents_id=19186&leafId=202

Choi, J., & Kim, Y. (2013b). Milk goods. Retrieved from http://navercast.naver.com/contents.nhn?rid=202&contents_id=18673&leafId=202

Choi, J., Yun, M., Kim, A., & Kim, J. (2012, 15-17 Oct. 2012). *Visual comfort measurement for 2D/3D converted stereo video sequence.* Paper presented at the 3DTV-Conference: The True Vision - Capture, Transmission and Display of 3D Video (3DTV-CON), Zurich: IEEE.

Choi, S. (2004). *Industrial safety great dictionary*. Seoul: Gold.

Churchill, G. A., Jr., & Surprenant, C. (1982). An Investigation into the Determinants of Customer Satisfaction. *Journal of Marketing Research*, *19*(4), 491-504. doi:10.2307/3151722

Colby, S. L., & Ortman, J. M. (2015). *Projections of the Size and Composition of the U.S. Population: 2014 to 2060*. Washington, D.C.: U.S. Department of Commerce Economics and Statistics Administration U.S. Census Bureau.

Da, Y., & Xiurun, G. (2005). An improved PSO-based ANN with simulated annealing technique. *Neurocomputing*, *63*, 527-533. doi:10.1016/j.neucom.2004.07.002

Dainoff, M. J., Happ, A., & Crane, P. (1981). Visual fatigue and occupational stress in VDT operators. *Hum Factors*, *23*(4), 421-437.

Ferreira, C. (2006). Designing Neural Networks Using Gene Expression Programming. In A. Abraham, B. de Baets, M. Köppen, & B. Nickolay (Eds.), *Applied Soft Computing Technologies: The Challenge of Complexity* (Vol. 34, pp. 517-535). Berlin Heidelberg: Springer

Galinsky, T. L., Swanson, N. G., Sauter, S. L., Hurrell, J. J., & Schleifer, L. M. (2000). A field study of supplementary rest breaks for data-entry operators. *Ergonomics*, *43*(5), 622-638. doi:10.1080/001401300184297

Gibson, S. J., & Helme, R. D. (2001). Age-related differences in pain perception and report. *Clin Geriatr Med*, *17*(3), 433-456.

Gratton, I., Piccoli, B., Zaniboni, A., Meroni, M., & Grieco, A. (1990). Change in visual function and viewing distance during work with VDTs. *Ergonomics*, *33*(12), 1433-1441. doi:10.1080/00140139008925344

Häkkinen, J., Pölönen, M., Salmimaa, M., & Hautanen, J. (2008). Reading experience with curved hand-held displays. *Journal of the Society for Information Display, 16*(11), 1099-1103. doi:10.1889/JSID16.11.1099

Han, C. (2015). Instruction for using smartphone camera. Retrieved from http://navercast.naver.com/contents.nhn?rid=46&contents_id=79359

Hatada, T., Sakata, H., & Kusaka, H. (1980). Psychophysical Analysis of the "Sensation of Reality" Induced by a Visual Wide-Field Display. *SMPTE Journal, 89*(8), 560-569. doi:10.5594/j01582

Hedman, L. R., & Briem, V. (1984). Short-term changes in eyestrain of VDU users as a function of age. *Hum Factors, 26*(3), 357-370.

Henning, R. A., Jacques, P., Kissel, G. V., Sullivan, A. B., & Alteras-Webb, S. M. (1997). Frequent short rest breaks from computer work: effects on productivity and well-being at two field sites. *Ergonomics, 40*(1), 78-91. doi:10.1080/001401397188396

Heuer, H., Hollendiek, G., Kroger, H., & Romer, T. (1989). Rest position of the eyes and its effect on viewing distance and visual fatigue in computer display work. *Z Exp Angew Psychol, 36*(4), 538-566.

Howarth, P. A., & Bullimore, M. A. (2005). Vision and visual work. In J. R. Wilson & N. Corlett (Eds.), *Evaluation of Human Work* (3rd ed., pp. 573-604). Boca Raton, FL: CRC Press.

Hsu, K.-l., Gupta, H. V., & Sorooshian, S. (1995). Artificial Neural Network Modeling of the Rainfall-Runoff Process. *Water Resources Research, 31*(10), 2517-2530. doi:10.1029/95WR01955

Hwang, I. (2014a). Drink too much water is not good for your health. Retrieved from http://navercast.naver.com/contents.nhn?rid=239&contents_id=53261&leafId=239

Hwang, I. (2014b). Prevention is the best way for influenza. Retrieved from http://navercast.naver.com/contents.nhn?rid=239&contents_id=44586&leafId=239

Hwang, K. (2011). Asan opuntia humifusa. Retrieved from http://navercast.naver.com/contents.nhn?rid=43&contents_id=7049&leafId=43

Hwang, K. (2012a). Hadong asian clam. Retrieved from http://navercast.naver.com/contents.nhn?rid=43&contents_id=7879&leafId=43

Hwang, K. (2012b). Seosan rockfish. Retrieved from http://navercast.naver.com/contents.nhn?rid=43&contents_id=7770&leafId=43

Hwang, K. (2012c). Seosan shepherd's purse. Retrieved from http://navercast.naver.com/contents.nhn?rid=43&contents_id=7681&leafId=43

Hwang, K. (2012d). Seoul seolleongtang. Retrieved from http://navercast.naver.com/contents.nhn?rid=43&contents_id=8386&leafId=43

Hwang, K. (2012e). Wando abalone. Retrieved from http://navercast.naver.com/contents.nhn?rid=43&contents_id=7204&leafId=43

Ishihara, S. (1943). *Ishihara tests for colour blindness* (1st ed.). Sydney: Shepherd and Newman.

Jang, J. (2012). Class of excellent tea. Retrieved from http://navercast.naver.com/contents.nhn?rid=173&contents_id=12179&leafId=173

Jaschinski-Kruza, W. (1988). Visual strain during VDU work: the effect of viewing distance and dark focus. *Ergonomics, 31*(10), 1449-1465. doi:10.1080/00140138808966788

Jaschinski-Kruza, W. (1991). Eyestrain in VDU users: viewing distance and the resting position of ocular muscles. *Hum Factors, 33*(1), 69-83.

Jeong, K., Na, N., & Suk, H. (2015). Readability Performance and Subjective Appraisal of Curved Monitor. *SID Symposium Digest of Technical Papers, 46*(1), 130-133. doi:10.1002/sdtp.10314

Jo, T. (2010). Principle of magic. Retrieved from http://navercast.naver.com/contents.nhn?rid=102&contents_id=3974&leafId=102

Jung, B. (2013). Bitcoin. Retrieved from http://navercast.naver.com/contents.nhn?rid=122&contents_id=35725&leafId=122

Kawashima, K., Okamoto, J., Ishikawa, K., & Negishi, K. (2013). Parameter Comparison of Assessing Visual Fatigue Induced by Stereoscopic Video Services. In R. Shumaker (Ed.), *Virtual Augmented and Mixed Reality. Designing and Developing Augmented and Virtual Environments* (Vol. 8021, pp. 175-183). Berlin Heidelberg: Springer

Kazuhiro, H. (2013). *Recover presbyopia*. Seoul: About a Book.

Kee, S., Lee, S., & Lee, Y. (2006). Thicknesses of the fovea and retinal nerve fiber layer in amblyopic and normal eyes in children. *Korean J Ophthalmol, 20*(3), 177-181.

Kim, D., & Sohn, K. (2010, 19-23 July 2010). *Depth adjustment for stereoscopic image using visual fatigue prediction and depth-based view synthesis.* Paper presented at the Multimedia and Expo (ICME), 2010 IEEE International Conference on, Suntec City: IEEE.

Kim, D., & Sohn, K. (2011). Visual Fatigue Prediction for Stereoscopic Image. *Circuits and Systems for Video Technology, IEEE Transactions on, 21*(2), 231-236. doi:10.1109/TCSVT.2011.2106275

Kim, J., Hong, J., Byun, Y., Jung, E., Seo, S., & Chun, B. (2013). Development of Improvement Effect Prediction System of C.G.S Method based on Artificial Neural Network. *Journal of the Korean Geoenvironmental Society, 14*(9), 31-37. Retrieved from http://www.dbpia.co.kr/Article/NODE02228454

Kim, J., Kang, K., & Cho, Y. (1997). The influence of the vertical location of VDT screen on the ocular dryness. *Journal of the Korean Ophthalmological Society, 38*(8), 1328-1335. Retrieved from http://kiss.kstudy.com/search/detail_page.asp?key=1965712

Kim, J., & Lee, J. (2012). Adaptive Threshold Detection Using Expectation-Maximization Algorithm for MultiLevel Holographic Data Storage. *The Journal of The Korean Institute of*

Communication Sciences, 39(10), 809-814. Retrieved from http://www.dbpia.co.kr/Article/NODE02010739

Knave, B. G., Wibom, R. I., Voss, M., Hedstrom, L. D., & Bergqvist, U. O. (1985). Work with video display terminals among office employees. I. Subjective symptoms and discomfort. *Scand J Work Environ Health, 11*(6), 457-466.

Korea Ministry of Emplyoment and Labor. (2004). *Working guidelines for VDT workers*. Sejong: Korea Ministry of emplyoment and labor.

Krupinski, E. A., & Berbaum, K. S. (2009). Measurement of visual strain in radiologists. *Acad Radiol, 16*(8), 947-950. doi:10.1016/j.acra.2009.02.008

Kwon, J., Kang, S., Kim, K., Suh, Y., Oh, J., Kim, S., & Kim, H. S., Jongsuk. (2012). The Ocular Fatigue of Watching Three-Dimensional (3D) Images. *Journal of the Korean Ophthalmological Society, 53*(7), 941-946. doi:10.3341/jkos.2012.53.7.941

Kyung, G., & Nussbaum, M. A. (2013). Age-related difference in perceptual responses and interface pressure requirements for driver seat design. *Ergonomics, 56*(12), 1795-1805. doi:10.1080/00140139.2013.840391

Lambooij, M., Fortuin, M., Heynderickx, I., & Ijsselsteijn, W. (2009). Visual Discomfort and Visual Fatigue of Stereoscopic Displays: A Review. *Journal of Imaging Science and Technology, 53*(3), 30201-30201-30201-30214. doi:10.2352/J.ImagingSci.Technol.2009.53.3.030201

Lee, B. (2015). Drone. Retrieved from http://navercast.naver.com/contents.nhn?rid=2878&contents_id=79489&leafId=2878

Lee, C., Ahn, J., Lee, J., & Kim, T. (2009). Prediction of scour depth using incorporation of cluster analysis into arficial neural networks. *JOURNAL OF THE KOREAN SOCIETY OF CIVIL ENGINEERS B, 29*(2B), 111-120. Retrieved from http://www.dbpia.co.kr/Article/NODE01240068

Lee, H., & Kim, S. (2015). *Effect of Curved Monitor for Reduction on Asthenopia*. Paper presented at the Annual Meeting of the Korean Ophthalmological Society, Goyang: The Korean Ophthalmological Society.

Lee, H., & Park, H. (2011). Development of telephone consultation algorithm for patient discharged with ophthalmic disease. *Journal of Korean Academy of Nursing Administration, 17*(3), 336-348. Retrieved from http://kiss.kstudy.com/search/detail_page.asp?key=3037227

Lee, S. (2014a). UHDTV. Retrieved from http://navercast.naver.com/contents.nhn?rid=122&contents_id=55443&leafId=122

Lee, S., Jung, S., Lee, W., & Park, K. (2011). A predictive model for urban temperature using the artificial neural network. *Journal of the Korea Planning Association, 46*(1), 129-142. Retrieved from http://www.dbpia.co.kr/Article/NODE01604371

Lee, W. (2014b). Dyslexia. Retrieved from http://navercast.naver.com/contents.nhn?rid=23&contents_id=45813&leafId=23

Lee, Y. (2012a). How to make a good steak? Retrieved from http://navercast.naver.com/contents.nhn?rid=117&contents_id=14913&leafId=117

Lee, Y. (2012b). Ice cream. Retrieved from http://navercast.naver.com/contents.nhn?rid=117&contents_id=15134&leafId=117

Lee, Y. (2012c). Taro soup. Retrieved from http://navercast.naver.com/contents.nhn?rid=117&contents_id=13150&leafId=117

Levin, L. A., Nilsson, S. F. E., Hoeve, J. V., Wu, S., Kaufman, P. L., & Alm, A. (2011). *Adler's Physiology of the Eye* (11th ed.). Philadelphia, PA: Elsevier Health Sciences.

Li, J., Barkowsky, M., & Callet, P. L. (2013). *Visual discomfort is not always proportional to eye blinking rate: Exploring some effects of planar and in-depth motion on 3DTV QOE.* Paper presented at the International Workshop on Video Processing and Quality Metrics for Consumer Electronics, Scottsdale, AZ.

Li, J., Barkowsky, M., & Le Callet, P. (2014). Visual discomfort of stereoscopic 3D videos: Influence of 3D motion. *Displays, 35*(1), 49-57. doi:10.1016/j.displa.2014.01.002

Lin, D. Y. M., & Yeh, L. C. (2010, 25-28 July 2010). *Impacts of TFT-LCD polarity, font size and line space on visual performance with age-difference considerations.* Paper presented at the Computers and Industrial Engineering (CIE), 2010 40th International Conference on, Awaji: IEEE.

Lin, Y. H., Chen, C. Y., Lu, S. Y., & Lin, Y. C. (2008a). Visual fatigue during VDT work: Effects of time-based and environment-based conditions. *Displays, 29*(5), 487-492. doi:10.1016/j.displa.2008.04.003

Lin, Y. T., Lin, P. H., Hwang, S. L., & Jeng, S. C. (2008b). Surface treatment, reflectance, and age effects on electronic-paper reading performance. *Journal of the Society for Information Display, 16*(10), 1051-1062. doi:10.1889/JSID16.10.1051

Lin, Y. T., Lin, P. H., Hwang, S. L., Jeng, S. C., & Liao, C. C. (2009). Investigation of legibility and visual fatigue for simulated flexible electronic paper under various surface treatments and ambient illumination conditions. *Applied Ergonomics, 40*(5), 922-928. doi:10.1016/j.apergo.2009.01.003

Liu, R. X., Kuang, J., Gong, Q., & Hou, X. L. (2003). Principal component regression analysis with spss. *Computer Methods and Programs in Biomedicine, 71*(2), 141-147. doi:10.1016/S0169-2607(02)00058-5

Lockhart, T. E., & Shi, W. (2010). Effects of age on dynamic accommodation. *Ergonomics, 53*(7), 892-903. doi:10.1080/00140139.2010.489968

Mourant, R. R., Lakshmanan, R., & Chantadisai, R. (1981). Visual fatigue and cathode ray tube display terminals. *Hum Factors, 23*(5), 529-540.

Murata, A., Uetake, A., Otsuka, M., & Takasawa, Y. (2001). Proposal of an Index to Evaluate Visual Fatigue Induced During Visual Display Terminal Tasks. *International Journal of Human-Computer Interaction, 13*(3), 305-321. doi:10.1207/S15327590IJHC1303_2

Murata, K., Araki, S., Yokoyama, K., Yamashita, K., Okumatsu, T., & Sakou, S. (1996). Accumulation of VDT work-related visual fatigue assessed by visual evoked potential, near point distance and critical flicker fusion. *Ind Health, 34*(2), 61-69.

Murray, W. E. (1981). *Potential health hazards of video display terminals*. Cincinnati, Ohio: National Institute for Occupational Safety and Health, Division of Biomedical and Behavioral Science.

Mustonen, T., Kimmel, J., Hakala, J., & Häkkinen, J. (2015). Visual Performance With Small Concave and Convex Displays. *Hum Factors, 57*(6), 1029-1050. doi:10.1177/0018720815570090

Nam, D. (2014). Olympic, Titanic, Britannic. Retrieved from http://navercast.naver.com/contents.nhn?rid=107&contents_id=77687&leafId=107

NewZealand Accident Compensations Corporation. (2010). *Guidelines for using computers*. Wellington: NewZealand Accident Compensations Corporation.

Occupational Safety and Health Administration. (1997). *Working safely with video display terminals*. Washington, D.C.: U.S. Department of Labor Occupational Safety and Health Administration Retrieved from https://books.google.co.kr/books?id=LLZH7cxRpJoC.

Occupational Safety and Health Administration. (1999). *Indoor air quality investigation*. Washington, D.C.: U.S. Department of Labor Occupational Safety and Health Administration Retrieved from https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_2.html#5.

Oh, G. (2013a). Dead skin. Retrieved from http://navercast.naver.com/contents.nhn?rid=21&contents_id=21741&leafId=21

Oh, H., & Lee, S. (2012, 15-17 Oct. 2012). *Prediction of visual fatigue from spatiotemporal characteristics in stereoscopic video*. Paper presented at the 3DTV-Conference: The True Vision - Capture, Transmission and Display of 3D Video (3DTV-CON), 2012, Zurich: IEEE.

Oh, W. (2013b). BitTorrent. Retrieved from http://navercast.naver.com/contents.nhn?rid=122&contents_id=23660&leafId=122

Ostberg, O. (1980). Accommodation and visual fatigue in display work. *Displays, 2*(2), 81-85. doi:10.1016/0141-9382(80)90052-9

Park, S. (2013). Sort of whale. Retrieved from http://navercast.naver.com/contents.nhn?rid=24&contents_id=33443&leafId=24

Park, S., Choi, D., Yi, J., Lee, S., Choi, B., Lee, S., & Kyung, G. (unpublished-a). *Effects of display curvature, display zone, and task duration on legibility and visual fatigue: Determining* *ergonomic display curvatures for 50" displays*.

Park, S., Choi, D., Yi, J., Lee, S., & Kyung, G. (unpublished-b). *The influence of the display curvature and task duration on visual task performance, visual fatigue, workload and satisfaction*.

Park, S., Lee, J., Kang, D., & Lee, H. (2007). *Legibility evaluation for the letter sizing of an electronic product.* Paper presented at the Ergonomics Society of Korea Spring Conference: Eromonomics Society of Korea.

Patel, S., Henderson, R., Bradley, L., Galloway, B., & Hunter, L. (1991). Effect of visual display unit use on blink rate and tear stability. *Optom Vis Sci, 68*(11), 888-892.

Pearson, R. K. (2002). Outliers in process modeling and identification. *Control Systems Technology, IEEE Transactions on, 10*(1), 55-63. doi:10.1109/87.974338

Piepenbrock, C., Mayr, S., & Buchner, A. (2014). Smaller pupil size and better proofreading performance with positive than with negative polarity displays. *Ergonomics, 57*(11), 1670-1677. doi:10.1080/00140139.2014.948496

Piepenbrock, C., Mayr, S., Mund, I., & Buchner, A. (2013). Positive display polarity is advantageous for both younger and older adults. *Ergonomics, 56*(7), 1116-1124. doi:10.1080/00140139.2013.790485

Rambold, H., Neumann, G., Sander, T., & Helmchen, C. (2006). Age-related changes of vergence under natural viewing conditions. *Neurobiol Aging, 27*(1), 163-172. doi:10.1016/j.neurobiolaging.2005.01.002

Saito, S., Sotoyama, M., Saito, S., & Taptagaporn, S. (1994). Physiological indices of visual fatigue due to VDT operation: pupillary reflexes and accommodative responses. *Ind Health, 32*(2), 57-66.

Saito, S., Taptagaporn, S., & Salvendy, G. (1993). Visual comfort in using different VDT screens. *International Journal of Human-Computer Interaction, 5*(4), 313-323. doi:10.1080/10447319309526071

Schleifer, L. M., & Amick, B. C. (1989). System response time and method of pay: Stress effects in computer-based tasks. *International Journal of Human-Computer Interaction, 1*(1), 23-39. doi:10.1080/10447318909525955

Schulze, M. M., Jones, D. A., & Simpson, T. L. (2007). The development of validated bulbar redness grading scales. *Optom Vis Sci, 84*(10), 976-983. doi:10.1097/OPX.0b013e318157ac9e

Sheedy, J. E., Hayes, J. N., & Engle, J. (2003). Is all asthenopia the same? *Optom Vis Sci, 80*(11), 732-739.

Shupp, L., Andrews, C., Dickey-Kurdziolek, M., Yost, B., & North, C. (2009). Shaping the display of the future: The effects of display size and curvature on user performance and insights. *Human-Computer Interaction, 24*(1-2), 230-272. doi:10.1080/07370020902739429

Smith, M. J., Cohen, B. G., & Stammerjohn, L. W., Jr. (1981). An investigation of health complaints and job stress in video display operations. *Hum Factors, 23*(4), 387-400.

Statistics Korea. (2011). *Projections of the Korea population: 2010 to 2060*. Daejeon: Statistics Korea.

Steenstra, I. A., Sluiter, J. K., & Frings-Dresen, M. H. (2009). The eye-complaint questionnaire in a visual display unit work environment: internal consistency and test-retest reliability. *Ergonomics, 52*(3), 334-344. doi:10.1080/00140130802376083

Suh, Y., Kim, K., Kang, S., Kim, S., Oh, J., Kim, H., & Song, J. (2010). The Objective Methods to Evaluate Ocular Fatigue Associated With Computer Work. *Journal of the Korean Ophthalmological Society, 51*(10), 1327-1332. doi:10.3341/jkos.2010.51.10.1327

Sullivan, J. M. (2008). *Visual fatigue and the driver* (UMTRI-2008-50). Retrieved from http://deepblue.lib.umich.edu/bitstream/handle/2027.42/61186/100999.pdf?sequence=1

Takeda, Y., Sugai, M., & Yagi, A. (2001). Eye fixation related potentials in a proof reading task. *Int J Psychophysiol, 40*(3), 181-186.

Turville, K. L., Psihogios, J. P., Ulmer, T. R., & Mirka, G. A. (1998). The effects of video display terminal height on the operator: a comparison of the 15 degree and 40 degree recommendations. *Appl Ergon, 29*(4), 239-246.

U.K. Health and Safety Executive. (1992). *Working with display screen equipment (DSE)*. London: U.K. Health and Safety Executive.

U.N. Department of Economic and Social Affairs. (2015). *World population prospects 2015*. New York City: United Nations.

Uetake, A., Murata, A., Otsuka, M., & Takasawa, Y. (2000, 2000). *Evaluation of visual fatigue during VDT tasks*. Paper presented at the Systems, Man, and Cybernetics, 2000 IEEE International Conference, Nashville, TN: IEEE.

Wang, A. H., Hwang, S. L., & Kuo, H. T. (2012). Effects of bending curvature and ambient illuminance on the visual performance of young and elderly participants using simulated electronic paper displays. *Displays, 33*(1), 36-41. doi:10.1016/j.displa.2011.12.002

Westman, M., & Liinamaa, M. J. (2012). Relief of asthenopic symptoms with orthoptic exercises in convergence insufficiency is achieved in both adults and children. *Journal of Optometry, 5*(2), 62-67. doi:10.1016/j.optom.2012.03.002

Winn, B., Whitaker, D., Elliott, D. B., & Phillips, N. J. (1994). Factors affecting light-adapted pupil size in normal human subjects. *Invest Ophthalmol Vis Sci, 35*(3), 1132-1137.

Wolf, E., & Schraffa, A. M. (1964). Relationship between critical flicker frequency and age in flicker perimetry. *Arch Ophthalmol, 72*, 832-845.

Wu, H. C. (2012). Visual fatigue and performances for the 40-min mixed visual work with a projected screen. *The Ergonomics Open Journal, 5*, 10-18.

Yaginuma, Y., Yamada, H., & Nagai, H. (1990). Study of the relationship between lacrimation and blink in VDT work. *Ergonomics, 33*(6), 799-808. doi:10.1080/00140139008927186

Yamamoto, S. (1987). Visual, musculoskeletal and neuropsychological health complaints of workers using videodisplay terminal and an occupational health guideline. *Japanese journal of ophthalmology, 31*(1), 171-183. Retrieved from http://europepmc.org/abstract/MED/3626175

Yim, J. (2014). Evolution of the mouth. Retrieved from http://navercast.naver.com/contents.nhn?rid=21&contents_id=48165&leafId=21

Yim, S. (2011a). Architecture of enlightenment. Retrieved from http://navercast.naver.com/contents.nhn?rid=121&contents_id=5736

Yim, S. (2011b). Baroque architecture of France. Retrieved from http://navercast.naver.com/contents.nhn?rid=121&contents_id=5518

Yim, S. (2011c). Gothic architecture of Germany. Retrieved from http://navercast.naver.com/contents.nhn?rid=121&contents_id=4735

Yim, S. (2011d). Gothic architecture of Italy. Retrieved from http://navercast.naver.com/contents.nhn?rid=121&contents_id=4741

Yim, S. (2011e). Late Baroque architecture. Retrieved from http://navercast.naver.com/contents.nhn?rid=121&contents_id=5459

Yim, S. (2011f). Late Gothic architecture. Retrieved from http://navercast.naver.com/contents.nhn?rid=121&contents_id=4731

Yoo, J., Yoon, J., & Kim, J. (1992). Influence of VDT work on accommodative function. *J Korean Ophthalmological Society, 33*(7), 693-697. Retrieved from http://kiss.kstudy.com/search/detail_page.asp?key=1967641

Yoon, S. (2015). Adults ADHD. Retrieved from http://navercast.naver.com/contents.nhn?rid=23&contents_id=79457&leafId=23

Yu, R. F., & Yang, L. D. (2014). Age-related changes in visual lobe shape characteristics and their relationship to visual search performance. *Ergonomics, 57*(9), 1300-1314. doi:10.1080/00140139.2014.921328

APPENDICES

A. Checklist for presbyopia (Kazuhiro, 2013)

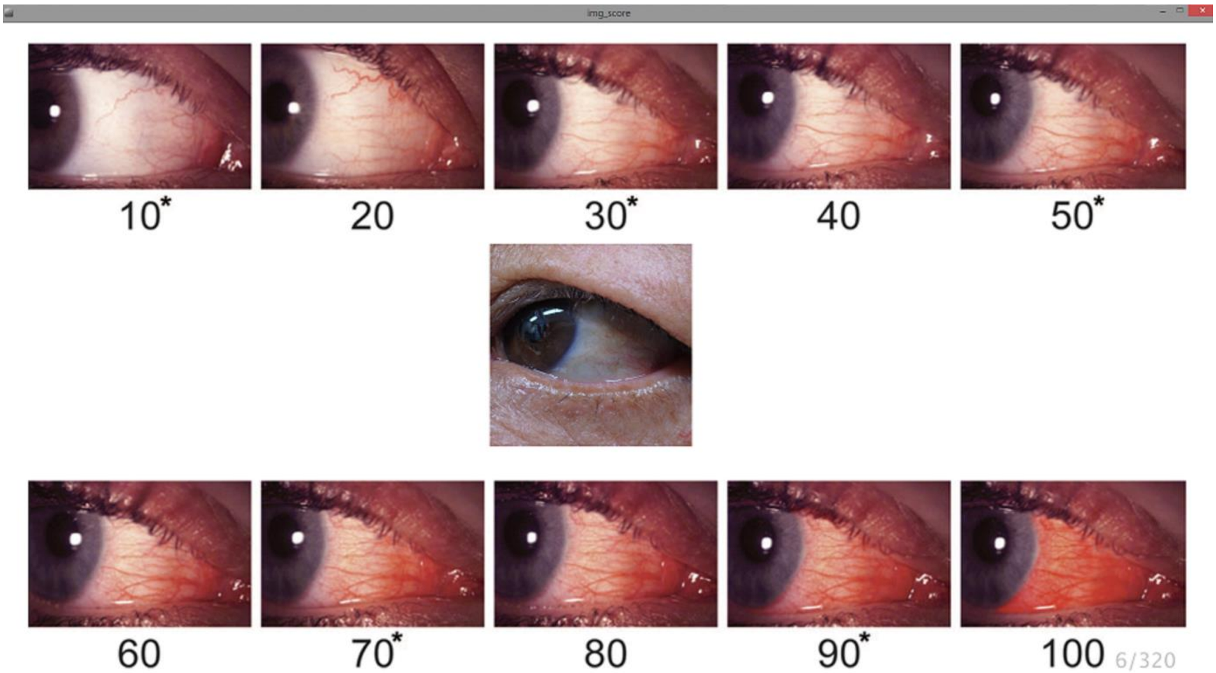
노안체크리스트

다음의 항목을 읽고 해당되는 곳에 체크표시를 합니다.

해당되는 항목이 세 개 이상이면 눈의 노화가 진행되고 있다고 봅니다.

- ☐ 자신도 모르게 책이나 신문을 눈에서 멀리 하고 읽는다.
- ☐ 휴대전화 문자 메시지를 확인하기 어렵다.
- ☐ 미간과 이마에 눈에 띄는 주름이 생긴다.
- ☐ 어깨가 자주 결린다.
- ☐ 방안이 예전보다 어둡게 느껴진다.
- ☐ 안개가 낀 것처럼 눈앞이 뿌옇게 보여 눈을 자주 비빈다.
- ☐ 세제나 화장품 용기에 붙어 있는 제품 설명이 잘 보이지 않는다.
- ☐ 바닥의 높이가 조금만 달라도 발을 헛디뎌 넘어진다.
- ☐ 숫자나 글자를 잘못 읽는 경우가 늘었다.
- ☐ 밤거리의 불빛이 괜히 눈부시다.
- ☐ 책을 읽다가 갑자기 먼 곳을 보면 초점이 잘 맞지 않는다.
- ☐ 책을 조금만 읽어도 쉽게 눈이 피로하고 머리가 아프다.
- ☐ 최근 들어 눈의 피로가 부쩍 심하다.
- ☐ 바늘구멍에 실을 꿰기가 어렵다.
- ☐ 안경을 벗으면 오히려 눈이 잘 보이는 것 같다.
- ☐ 낮에는 괜찮은데, 아침이나 밤에는 신문이나 책 읽기가 어렵다.
- ☐ 세밀한 작업을 오래 계속하기 싫다.
- ☐ 책이나 서류를 집중해서 읽다 보면 속이 메슥거린다.

B. Bulbar conjunctival redness comparing software for grading



C. Questionnaires for subjective measures on visual discomfort and satisfaction

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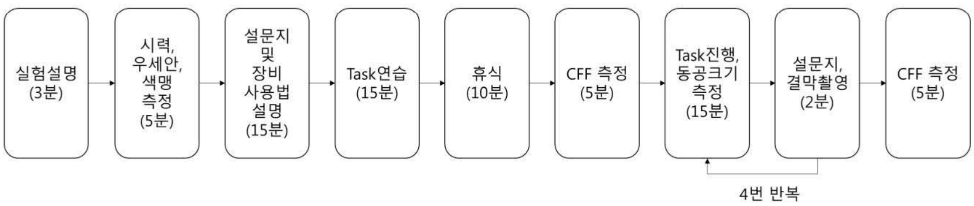
눈의 상태와 관련된 설문조사

안녕하십니까? 바쁘신 와중에도 실험에 참여해주셔서 감사합니다.
저는 울산과학기술원 인간 및 시스템공학과 ixlab의 대학원생입니다.

본 실험은 곡면 모니터 사용시 노안 및 비 노안간 시각피로도 연구를 위해 진행되며, 주어질 작업으로 교정작업이 포함되어 있습니다.
본 설문지는 귀하와 관련된 일반적 특성에 대한 질문과, 실험 전, 실험 중, 실험 후 귀하의 눈의 상태 (경미한 통증이나 피로감)에 대한 질문의 두 가지 영역으로 구성되어 있습니다.
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 참여해주셔서 감사합니다.



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일반적 특성

●귀하와 관련된 일반적 특성에 대한 질문입니다. 아래 질문에 답해 주시기 바랍니다.

0. 이름: ( )

1. 성별: □ 남 □ 여

2. 연령: 만 ( ) 세

●눈과 관련된 검사가 진행됩니다.

0. 시력 (검사 후 기입): 좌 ( ) 우 ( ),
   시력 보정기구 ( )

1. 우세안: ( )

2. 색맹유무 (검사 후 기입): ( )

3. 현재 본인의 눈 건강 상태에 대해 서술해 주십시오 (과거에 앓았던 질병이나, 최근 눈에 문제가 있어 병원에 갔었다 등의 의견을 구체적으로 서술해 주십시오)

※ 신분증과 통장을 준비해주시기 바랍니다.

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측정 (1) – 연습

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 주변에 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈이 건조하다	☐	☐	☐	☐	☐	☐	☐

피험자 번호 ___ **날짜 2015. . .**

2. 눈의 불편함 (Visual Discomfort)

문서 교정 작업을 진행하는 동안 눈은 얼마나 불편함을 느꼈나요?

(0) (100)

전혀 불편하지 않음 매우 불편

3. 만족도 (Satisfaction)

전체적으로 문서 교정 작업을 수행하는 동안 어느 정도의 만족감을 느꼈나요?

(0) (100)

전혀 만족하지 않음 매우 만족

피험자 번호 ___ 날짜 2015. . .

측정 (2) – 0min

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 주변에 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈이 건조하다	☐	☐	☐	☐	☐	☐	☐

피험자 번호 ___ 날짜 2015. . .

측정 (3) – 15min

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 주변에 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈이 건조하다	☐	☐	☐	☐	☐	☐	☐

피험자 번호 ___ 날짜 2015. . .

2. 눈의 불편함 (Visual Discomfort)

문서 교정 작업을 진행하는 동안 눈은 얼마나 불편함을 느꼈나요?

(0) (100)

전혀 불편하지 않음 매우 불편

3. 만족도 (Satisfaction)

전체적으로 문서 교정 작업을 수행하는 동안 어느 정도의 만족감을 느꼈나요?

(0) (100)

전혀 만족하지 않음 매우 만족

피험자 번호 ___　　　　　　　　　　　　　　날짜 2015. . .

측정 (4) – 30min

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 주변에 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈이 건조하다	☐	☐	☐	☐	☐	☐	☐

피험자 번호 ___　　　　　　　　　　　　　　　　　　　　　날짜 2015. . .

2. 눈의 불편함 (Visual Discomfort)

문서 교정 작업을 진행하는 동안 눈은 얼마나 불편함을 느꼈나요?

(0) 전혀 불편하지 않음 ———————— (100) 매우 불편

3. 만족도 (Satisfaction)

전체적으로 문서 교정 작업을 수행하는 동안 어느 정도의 만족감을 느꼈나요?

(0) 전혀 만족하지 않음 ———————— (100) 매우 만족

피험자 번호 ___ 날짜 2015. . .

측정 (5) – 45min

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 주변에 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈이 건조하다	☐	☐	☐	☐	☐	☐	☐

피험자 번호 ___ **날짜 2015. . .**

2. 눈의 불편함 (Visual Discomfort)

문서 교정 작업을 진행하는 동안 눈은 얼마나 불편함을 느꼈나요?

(0) (100)

전혀 불편하지 않음 매우 불편

3. 만족도 (Satisfaction)

전체적으로 문서 교정 작업을 수행하는 동안 어느 정도의 만족감을 느꼈나요?

(0) (100)

전혀 만족하지 않음 매우 만족

피험자 번호 ___ 날짜 2015. . .

측정 (6) – 60min

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 주변에 이상한 느낌이 든다	☐	☐	☐	☐	☐	☐	☐
8. 눈이 가렵다	☐	☐	☐	☐	☐	☐	☐
9. 눈이 빨갛다	☐	☐	☐	☐	☐	☐	☐
10. 눈이 건조하다	☐	☐	☐	☐	☐	☐	☐

피험자 번호 ___ **날짜 2015. . .**

2. 눈의 불편함 (Visual Discomfort)

문서 교정 작업을 진행하는 동안 눈은 얼마나 불편함을 느꼈나요?

(0) (100)

전혀 불편하지 않음 매우 불편

3. 만족도 (Satisfaction)

전체적으로 문서 교정 작업을 수행하는 동안 어느 정도의 만족감을 느꼈나요?

(0) (100)

전혀 만족하지 않음 매우 만족

실험이 모두 종료 되었습니다.
참여해주셔서 감사합니다.