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Principles for the comfortable viewing of stereoscopic three-dimensional television (3DTV) images

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REPORT ITU-R BT.2293-1

Principles for the comfortable viewing of stereoscopic three-dimensional television (3DTV) images

(2013-2014)

Foreword

With the increasing interest in stereoscopic three-dimensional (3D) content services, concerns have been raised about the comfort and safety of viewing stereoscopic images. These concerns have been recognized as part of the bottleneck preventing the proliferation of stereoscopic 3DTV content services into the mass market. As a result, it has become important that adequate information and guidance is available to producers of stereoscopic 3DTV content in order to assist with the production of programmes that are comfortable to watch. The aim of this Report is to collate the available information and to highlight some of the concerns that have been expressed about viewing 3D images, especially to younger viewers[1].

Summary

3D viewing safety is of primary importance for the popularization of 3D content. In the 1950s, stereoscopic content won commercial success in Hollywood for a short time. However, strong headaches and visual discomfort caused by excessive binocular disparity and the crudeness of the production equipment were reported, and the market literally died until the early 21st century. Visual discomfort was one of the primary reasons cited for the loss of interest in stereoscopic images. Therefore, safety guidelines for the production, distribution and viewing of 3DTV programmes are vital to the success of commercializing 3DTV broadcasting especially if producers expect to achieve long hours of continuous viewing.

Now that 3DTV services are available in the home, the home viewing environment has become a critical factor to be taken into account when assessing how comfortable a stereoscopic 3DTV programme is to watch. Very few broadcasters or administrations however, make information available to help viewers get the best experience from these services.

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[1] Further general information on the subject of 3DTV can be found in Report ITU-R BT.2160-4.

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1 Principles for comfortable viewing of stereoscopic three-dimensional images

1.1 Composite factors in perception of stereoscopic 3D images

A stereoscopic 3D system expresses depth by presenting video that has disparity[2] with respect to the left and right eyes of the viewer. The perception of depth depends on factors such as the programme production techniques, the display devices, the 3D glasses (if required), the viewing conditions, and the viewer's physical characteristics. Any visual fatigue associated with the viewing of stereoscopic 3DTV programmes will be, to a greater or lesser extent, dependent on these as well as other factors such as spatial distortion.

NOTE – Section 5 of Annex 4 describes a spatial distortion prediction system for 3DTV that calculates the spatial distortion of a reproduced stereoscopic image and predicts the extent of the puppet-theatre and cardboard effects, excessive binocular parallax, and excessive parallax distribution.

1.2 Measures to enable comfortable viewing of stereoscopic three-dimensional images

The complexity of the end-to-end broadcast chain, which now involves many different organizations, processes and technologies (from capture, through post-production, mastering, broadcast, reception and display) means no single organization can exercise an overall control of end-to-end quality of a programme.

All parties concerned with stereoscopic 3DTV systems should take the characteristics of stereoscopic 3D systems, described in § 1.1, into account when manufacturing equipment, producing programmes and displaying 3D images and pay particular attention to how the programmes may be viewed by the intended audience. It is not reasonable to expect that solely regulating the amount of parallax in 3DTV programmes is enough to ensure viewer comfort.

1.2.1 Programme production

It is important to identify measures to help avoid the inadvertent creation of material for transmission on broadcast television that could induce visual fatigue and other possible health hazards.

Measures should be proportionate to the risks and should not place undue burdens on broadcasting organizations or programme producers. The impact of measures on broadcasters or programme producers may vary with their programme genres and the intended target age range of the audience.

On occasions, programme production is beyond the control of the broadcaster especially during live broadcasts such as sport or music concerts; therefore broadcasting organizations should be encouraged to raise awareness among programme producers of the risks of creating stereoscopic television images that may induce visual fatigue.

This awareness could range from simple information pamphlets and on-line training through to detailed instruction and practical (hands on) training courses.

Training should be designed to give producers of 3DTV programmes the understanding of the characteristics of stereoscopic 3D images and the impact to the viewer of 3D video techniques.

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[2] Disparity describes the actual shift between the same two points in the stereo pair. Thus the disparity would always remain the same irrespective of screen size.

1.2.2 Viewing environments and display devices

It must be recognized that home viewing environments and display devices have an impact on the likelihood of visual problems and that these viewing conditions will differ between households, reflecting the style of living. It is therefore important that viewers are also well informed of requirements for satisfactory viewing of stereoscopic 3D images.

1.2.3 Examples of safety guidelines

In 2010, a liaison statement (see Annex 9) was sent to the WHO requesting information on potential impact on health of 3D. In their reply, they stated that they could not give any direct information from their own files, as they presently do not have a project on this topic.

Some administrations have therefore issued their own guidance. For examples of such guidance given by some national bodies see:

Annex 1: Example of safety guidelines – Japan

Annex 2: Examples of safety guidelines – Korea (Republic of)

Annex 3: Examples of safety guidelines – Italian Health Ministry

2 Psychophysical aspects of viewing stereoscopic images

2.1 Psychophysical aspects

It is necessary to gain a full understanding of the results of psychophysical studies before attempting to implement new broadcast schemes, in order to fully understand the effects to which the viewer is subjected and the performance that is required of the main equipment in these systems. There are a number of issues to be studied before the effects of viewing three-dimensional images on human perception and visual functions can be fully understood.

Section 1 of Annex 4 "**Psychophysical studies on three dimensional television systems"** identifies some key study items on the psychophysical aspects of stereoscopic television systems. It also includes the results of studies related to the naturalness and unnaturalness of stereoscopic video, the evaluation of visual comfort based on an analysis of parallax distributions within certain frames, and the visual fatigue by viewing stereoscopic video.

A major disadvantage of current implementations of stereoscopic television is the presentation of the stereoscopic images on a single surface (the display screen). There is evidence that this can give rise to a potential conflict between "vergence" (the eye movement to target both eyes to the same point on the screen) and "accommodation" (the action by which the "lens" in the viewer's eye focuses on that point). It has been documented in medical literature that this conflict can cause viewer's discomfort, eye fatigue, headache and possibly other health hazards notably if the viewing continues for an extended period of time[3, 4].

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[3] See for instance: K. Ukai and P.A. Howarth "Visual fatigue caused by viewing stereoscopic motion images: background, theories and observations" – Elsevier B:V., 2007, which states, *inter alia*, "Viewers should be careful to avoid viewing stereoscopic images for extended durations because visual fatigue might be accumulated. They should be ready to stop immediately if fusion difficulties are experienced".

[4] Masaki Emoto, Takahiro Niida, and Fumio Okano – "Repeated Vergence Adaptation Causes the Decline of Visual Functions in Watching Stereoscopic Television", Journal of Display Technology, Vol. 1, No. 2, December 2005.

Such effects have been noticed in some trial broadcasts. For example, one of the terrestrial broadcasters in the Republic of Korea, SBS (Seoul Broadcasting System), broadcast South Africa World Cup Soccer Games in 3D from 11th June 2010. In a survey of nearly 100 viewers, 75% expressed satisfaction with the trial 3DTV broadcasting service. However, the survey showed that 30% of the viewer felt dizziness, double image and eye fatigue.

Factors that affect 3D viewing comfort also include inter-pupillary distance, intra-scene disparity range, and the speed of depth change of objects in the scene. In addition, rapid cuts between shots of differing depths and changing depths with zoom or pans are known to cause viewer discomfort. Some of these techniques are commonly used to make 2D production more engaging but when applied to 3D programmes, might cause discomfort to the 3D viewer. Similarly, applying 3D production techniques tends to create a 2D programme that might be considered by 2D viewers as boring. It is for this reason that many 3D productions to date have been different from the 2D productions of the same event or release. It is widely known that current 3D movie releases are editorially different from the 2D releases.

Parallax is affected by the programme production technique, display device, viewing conditions, and viewer characteristics (such as inter-pupil distance). Accordingly, all parties concerned with stereoscopic 3D systems should take this characteristic of stereoscopic 3D systems into account.

2.1.1 Geometrical relationships and naturalness

The reproduction of depth information is essential for people to gain a realistic sense of three-dimensionality from a stereoscopic image. Depth distortion in the stereoscopic image can create an unnatural impression when the image is viewed.

In stereoscopic imaging, the object is imaged using two cameras. The arrangement of these two cameras can be classified into;

- parallel configurations, where the optical axes of the two cameras are parallel with each other, and
- intersecting “toed-in” configurations where the two optical axes are made to intersect.

A parallel configuration will produce a stereoscopic image with no spatial distortion when the gap between the centre of each camera lens is set equal to the gap between the pupils, the horizontal offset of the left and right images projected on the screen is equal to the gap between the pupils, and the camera’s angle of view is equal to the expected viewing angle of the display. In such cases, the image is said to be viewed under orthostereoscopic (distortion-free) conditions. However when actual programme production and viewing conditions are taken into consideration, it is difficult to ensure that distortion-free conditions are always satisfied. If these conditions are not met the spatial distortion of the stereoscopic image can cause unnatural effects such as the “puppet theatre” effect where the stereoscopic images of foreground objects appear unnaturally small, and the “cardboard” effect, where the stereoscopic image of an object appears unnaturally thin.

Section 2 of Annex 4 presents a geometric analysis of reproduced stereoscopic image spaces and discusses the results and their relationship to the distortion of reproduced stereoscopic image spaces. The results of subjective evaluation tests that support these findings are also shown. The discussion relates to how the reproduced stereoscopic image space is affected by parameters such as the camera configuration (parallel or toed-in), display screen size, and viewing distance.

2.1.2 Visual comfort and discomfort in viewing stereoscopic images

Finding a way to make the visual comfort of stereoscopic images a measurable physical factor is arguably one of the key issues in stereoscopic imaging research. As has been stated, stereoscopic images convey depth information to the viewer by making use of the parallax between the images presented to the left and right eyes. If we could ascertain how the magnitude and distribution characteristics of this parallax relate to the visual comfort of the image, this information would be very useful for the production of stereoscopic images.

How these parameters relate to the subjective visual comfort was studied by focusing on the average and range of the parallax distributions. It was shown that they both have a correlation with the visual comfort of stereoscopic images and that the range of parallax distributions in stereoscopic images appraised as visually comfortable was almost 60 pixels in HDTV image. It was also suggested that stereoscopic images tend to become more visually comfortable when the average value of the parallax distribution approaches zero (i.e. at apparent positions closer to the display screen).

In a stereo 3D system the presentation of two images to the respective left and right eyes forms a binocular 3D image. If discrepancies arise between these images due to the systems used for production, storage, transmission or display, they can cause psychophysical stress, and in some cases 3D viewing can fail. For example, when shooting and displaying stereoscopic 3DTV programmes, there can be geometrical distortions, such as size inconsistency, vertical shift, and rotation error, between left and right images. It is important that such geometrical distortions should be suppressed. Similarly stereoscopic image cross-talk, where the images "leak" and can be partially seen by the opposite eye, can also result in discomfort for the viewer and equipment, especially display equipment (including 3D glasses) should be designed to minimize this effect. Detection and tolerance limits of evaluating visual discomfort in terms of cross-talk were reported to be highly dependent on image content and display contrast, and cross talk must be reduced on high contrast displays.

Section 3 of Annex 4 presents some results of subjective evaluation tests with regard to visual comfort in viewing stereoscopic images. The results indicate that stereoscopic image having an excessive range of parallax distribution can be evaluated as uncomfortable to view. The research results on visual discomfort caused by discrepancies between left and right images are also shown. The results indicate the detection and tolerance limit of discrepancies with regard to visual discomfort in viewing stereoscopic images.

2.1.3 Visual fatigue in viewing stereoscopic images

Two of the major factors that cause visual fatigue are:

- The difficulty in fusing left and right retinal images with large binocular parallax. This demands an increased viewer fusion effort. Fusion effort is based on two factors: the principle of stereoscopic image display (defined by horizontal binocular parallax, inevitable in stereoscopic systems), and issues emanating from the display hardware itself (leading to differences between views of left and right images).
- A dissociation of vergence and accommodation due to the difference in visual functions between viewing real objects and viewing stereoscopic images. The vergence point is positioned within the depth of field when viewing a real object. On the other hand, the vergence point is sometimes outside the depth of field when binocular parallax is large in viewing stereoscopic images. Temporal discontinuous changes in dissociation can also lead to visual fatigue.

2.1.4 Assessment methodology

It is understood that traditional testing methodologies such as PSNR, might not be indicative of the effect of artefacts, and that new metrics will need to be considered. Development of appropriate assessment methodology, in conjunction with a common set of reference source material is therefore of the utmost importance for evaluating 3DTV systems.

The ITU details a method for the subjective assessment of image quality and depth quality in Recommendation ITU-R BT.1438 – Subjective assessment of stereoscopic television pictures.

Recommendation ITU-R BT.2021 – Subjective methods for the assessment of stereoscopic 3DTV systems, details the recommended methodology for the assessment of 3D image quality.

Recommendation ITU-R BT.2021 Annex 1 details sets of criteria that should be considered when assessing visual comfort;

> "Primary perceptual dimensions" are "visual comfort", "picture quality" and depth quality".
>
> "Additional perceptual dimensions" are "sense of presence", sensation of reality and "naturalness".

It is important that these criteria are used to assess the impact on the comfort of viewing 3DTV programmes through the entire broadcast process including the effects of bandwidth reduction used for contribution and eventual distribution of stereoscopic programmes. Allowances should also be made for the duration of a stereoscopic programme (the length of time a viewer will be watching in 3D), as production techniques that are acceptable for short programmes might cause discomfort if applied over a long period of time.

2.2 Visual discomfort induced by disparity and motion magnitude of stereoscopic video

It has been known that the motion and depth characteristics of 3D content are central determinants of visual discomfort during stereoscopic 3DTV viewing. In order to investigate the influence of these motion and depth characteristics on visual comfort, subjective visual comfort assessments were conducted using visual stimuli with various disparities, motion velocities, and motion directions. In addition, subjects were given a questionnaire in order to investigate some of the physical symptoms accompanied by the perceived visual discomfort.

The experimental results showed that an increase in velocity of horizontal, vertical, and depth motion induced more visual discomfort. A questionnaire accompanying the test reveals that the subjects felt focusing difficulties due to fast spatial and temporal changes of disparity in stereoscopic 3D content. In addition, subjects reported a higher degree of visual discomfort as the binocular disparity increased. Overall symptoms of visual discomfort can become severe and are often encountered as focusing difficulty and eyestrain. The results of subjective visual comfort assessments for motion and disparity magnitude of 3D content are given in Annex 5.

2.3 The influence of stereopsis and abnormal binocular vision on ocular and systemic discomfort while watching 3D television

2.3.1 Introduction

Stereopsis refers to an awareness of the distances of objects from the observer and binocular vision is necessary to perceive stereopsis. The term stereopsis is often used synonymously with binocular depth perception. Image processing is essential to the perception of stereopsis and many components of stereopsis such as retina disparity, eye movement, primary perception of brain and image processing functions are important therefore people with abnormal binocular vision (ABV), including strabismus, amblyopia, and anisometropia, may vary in their ability to perceive 3D images according to their degree of stereopsis.

In a study carried out by the Republic of Korea (see Annex 6 for full details), 98 people with ABV and 32 normal binocular vision subjects were enrolled to evaluate the degree of 3D perception and ocular and systemic discomfort (3D fatigue) in people with ABV and their relationship to stereo acuity while watching a 3D television.

2.3.2 Methodology and results

Best corrected visual acuity, refractive errors, angle of strabismus, and stereopsis were measured. After watching 3D television for 20 minutes, a survey was given to each subject to evaluate the degree of 3D perception and 3D fatigue while watching 3DTV. The participants with ABV showed a lower degree of 3D perception. However, the amount of 3D fatigue did not differ from normal participants. According to the degree of stereopsis, the study compared the subjects of normal stereo acuity with those of abnormal stereo acuity. Subjects with normal stereo acuity reported more 3D fatigue, although they perceived 3D better. People with ABV who had a high degree of stereopsis felt more 3D fatigue than normal participants. Those with exotropia reported 3D fatigue most frequently.

Section 4 of Annex 6 presents some experimental results of subjective evaluation with regard to visual fatigue in viewing stereoscopic images. The results indicate that inconsistencies between vergence and accommodation can cause visual fatigue.

2.4 The impact of Parkinson's Disease on discomfort while watching 3D television

People with Parkinson's disease often experience the degeneration of dopamine-generating cells in the brain, have retina problems, eyeball movement problems and visual perception problems. Dopamine is a chemical messenger for light adaptation, and it controls the flow of information through cone circuits and rod circuits in the retina, Parkinson's disease sufferers are known to perceive visual stimuli poorly.

A study carried out in the Republic of Korea concluded there was no significant difference in dynamic 3D perception between those with Parkinson's disease to a control group. The study also concluded there was no difference in 3D fatigue between the two groups.

Further details of research can be found in Annex 7.

2.5 Influence of Alzheimer's Dementia on dynamic 3D perception and fatigue[5]

As has been said, image processing is essential to the perception of stereopsis. This information processing system is used to watch 3DTV and some people with dementia may have problems perceiving a 3DTV image.

A further study carried out in the Republic of Korea, conducted with people suffering from Alzheimer's dementia has shown that 3D perception is significantly lower. In terms of safety, the components of 3D discomfort did not differ between the control group and those with Alzheimer's dementia.

Further details on this research can be found in Annex 10.

2.6 3D viewing and refractive errors in children

Due to its high prevalence, reported up to 96.5% in Asia, myopia is a major public health problem. Close up working or "near-work", is a well-established environmental factor related to the development and progression of myopia. Near-working induces accommodation, and after prolonged accommodation, transient myopic shifts can be observed even after the work has ceased. This near-work induced myopia can be considered a possible environmental myopigenic factor.

Watching 3D video requires more accommodation than watching 2D video. If unnecessary accommodation induces more transient myopic shift, it might lead to the development and progression of permanent myopia.

To assess the role of 3DTV in terms of refractive errors in children the following questions need to he answered:

[5] All test subjects were volunteers able to understand and sign a consent pro forma and all tests were conducted under the guidance of the Institutional Review Board (IRB).

1) Are there any refractive changes such as a transient myopic shift after watching 3DTV?

2) Do myopes or exotropes show more myopic shift?

3) Do changing refractive errors persist after 10 minutes of rest in subjects who showed myopic shift?

In order to fully understand these issues, a study carried out in the Republic of Korea found the following.

Watching properly made 3D content on a 3DTV for 50 minutes at 2.8 metres did not influence the refractive errors of myopic or exotropic subjects more than for other subjects nor did it lead to refractive errors in children.

The mean refractive error of subjects with myopic shift returned to a baseline value after 10 minutes of rest without producing any residual near-work induced myopia.

To prevent myopic shifts after watching 3DTV, the following factors were controlled:

- Allowing for properly produced 3D content (image disparity within ±1 degree).
- A watching duration of less than 50 minutes.
- A viewing distance of more than 2.8 metres.
- 10 minutes of rest after 50 minutes of watching.

These observations should be considered when developing viewing safety guidelines.

A full report of the study can be found in Annex 11.

3 Points to consider for broadcasters to provide comfortable 3DTV broadcasting

Positive disparity, negative disparity, depth budget, and depth motion cause inconsistency of accommodation and vergence in the creation of stereoscopic 3D content. They also differ in terms of binocular disparity, which is the positional difference of two images delivered to human eyes, and therefore the visual fatigue caused by binocular disparity while watching 3D images requires a study in terms of content. Annex 8 gives further detail of visual discomfort induced by the binocular disparity of stereoscopic video and guidance to minimize such discomfort.

Broadcasters who are commissioning and distributing 3D programmes should be able to give advice to those producing the 3D programmes on techniques that should ensure they can be comfortably viewed. This advice includes (but is not limited too) the following areas.

3.1 Preparation

Because 3D images based on binocular disparity have a risk of causing discomfort to viewers if conventional 2D production techniques are used, it is important that all staff involved with 3D production should fully understand the characteristics of the 3D image technology.

It is advisable to continual update the training to the staff engaged in the production on the fundamentals of 3D image technology, psychophysical effects of 3D images, and characteristics and operations of 3D cameras and other related devices, by referring to the latest information from case examples and academic publications.

3.2 Shooting (acquisition) and editing

Currently, it is preferable to assign a stereographer (a specialist in 3D production) to every 3DTV programme.

The stereographer should oversee the 3D image space design in advance of the production and select the most appropriate equipment for the subject to provide a proper sense of depth.

The stereographer should establish the target screen size(s) for the programme during the early planning stages. This information will allow a reasonable depth budget to be set for target audience's viewing environment and help to minimize the risk of viewer discomfort.

When shooting a concert or a sports event, where several cameras are arranged and switched in real time, equipment suitable for camera angle and shooting distance needs to be selected.

Equipment capable of controlling the shifts and parallax between the right and left images in real time should be used with cameras used for wide panning shots and zooms. Where possible a "3D-puller" (a new job roll within a 3D vision team) should be assigned for each camera pair to control the depth so that a 3D image space will not be broken up.

Where such real time control is not practical, a range of shooting conditions for comfort should be verified in advance and the shifts and parallax between the left and right images should be adjusted post-production.

3.3 Verification

For a live 3DTV broadcast, the stereographer should work with the camera operators, 3D-pullers and other staff to ensure that 3D images can be viewed comfortably.

For non-real-time broadcasting of edited programmes, it is preferable that the stereographer used during the shooting supervises the post-production of the 3D images and is in attendance at any depth grade (where the various parameters controlling the 3D look are balanced and adjusted – this is analogous to a colour grading session). It is also preferable that when time permits the programme is previewed by several staff who have not been involved in the post-production process.

A subjective assessment test with non-expert observers may also be conducted as necessary. Where defects are found by during the preview or subjective testing, the shots or sequences affected should be adjusted or re-edited.

3.4 Broadcasting

When broadcasting 3D images, it is preferable to advise viewers on how to view 3DTV comfortably in terms of psychophysical effects and safety issues.

4 Conclusions

The importance of giving careful consideration to each stage of the production and broadcasting of 3DTV programmes to ensure the viewer does not experience discomfort cannot be underestimated.

Recommendation ITU-R BT. clearly states the key points to consider when evaluating 3DTV image quality and as such offers programme makers guidance on what to look out for during production if they wish to make the programme comfortable to watch. These points also offer guidance to those whose role it is to review the quality of the finished product.

4.1 Guidance to viewers of 3DTV services

As has been stated, the home viewing environment has become a critical factor that has to be taken into account when assessing how comfortable a stereoscopic 3D programme is to watch but there is very little advice available to viewers about how to get the best from the 3D services.

Below is an example of guidance that could form part of any information made available to viewers of 3DTV services:

Watching 3DTV programmes in your home

To get the best experience from watching 3D programmes at home it is important to make sure the viewing environment is set up properly. This will reduce any risk of eyestrain or feeling uncomfortable whilst viewing.

The following are some simple guidelines that will make sure you get the best viewing experience:

- 3D will look its best if it is viewed in a room with good ambient lighting.
- Many 3D televisions give a better 3D effect if you are seated directly in front of the screen (not to either side).
- Sit a reasonable distance from the screen – between three and six times the height of the screen usually gives the best experience.
- Make sure both lenses of the 3D glasses are clean and that "active" glasses have adequate charge in their batteries (see the manufactures instructions for your 3DTV).
- Stop watching and take off the 3D glasses if you feel any discomfort.
- Children should be supervised when watching 3D programmes and they should not watch 3DTV for long periods.

Some people have problems with depth perception and there are other medical conditions that can affect a person's ability comfortably watch 3DTV programmes. If you or a member of your family has a strong reaction while watching 3DTV, it would be advisable to consult an optician or other qualified practitioner as soon as practical.

Annex 1

Example notifications given to viewers in Japan

Background

The following notifications prepared by DPA[6], are presented to viewers before a stereoscopic 3DTV programme is broadcast either "on-screen' or by directing viewers to a website.

1 Notifications when 3D programmes are broadcast on same channel as 2D programmes

– This programme is 3DTV. (When a 3DTV programme starts.)

– The 3DTV programme is about to end, and will be followed by a 2DTV programme. (When a 3DTV programme ends.)

– Change the "3D/2D" mode as appropriate. (When the type of programme, i.e. 3D or 2D, changes.)

2 Notifications that should be broadcast with 3DTV programmes

– Watch TV in a well-lighted room and at an adequate viewing distance.

– Stop watching, take off your 3D glasses, and take a rest if feeling discomfort while watching 3DTV.

– Supervise infants' viewing of 3DTV.

– Check whether stereoscopic images can be correctly seen or not by using inserted clips before starting 3DTV programmes.

3 Notifications may inform viewers (even though some of these are basically in the product manual)

– Prepare appropriate products for 3DTV to use in programmes.

– Side-by-side images may be shown on the display when watching 3DTV programmes on 2D television.

– The on screen display (OSD) may disrupt 3D images.

– Refer to safety precautions in using 3D eyewear.

– Information on content of 3DTV programmes is available from the electronic programme guide (EPG) or homepage to help with programme choices.

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[6] DPA (The Association for the Promotion of Digital Broadcasting) is an organization of Japanese broadcasters and manufacturers associated with digital TV.

Annex 2

Examples of safety guidelines – Korea (Republic of)

A 3DTV Project Group (PG806) has been established in Korea with the aim of developing a 3DTV broadcasting specification and viewing safety guideline. Working group WG8062 is focusing on the development of a 3DTV viewing safety guideline for displays, content, viewing conditions, and viewer parameters.

The Telecommunications Technology Association of Korea (TTA) published "3DTV Broadcasting Safety Guideline" in December 2010. Its purpose is to give advice on how to reduce visual fatigue and the most suitable viewing conditions for the safe viewing of stereoscopic content. This advice is also intended to assist the 3D industries (programme makers and equipment manufacturers) reduce any potential risks from the viewing stereoscopic content.

The guideline will be updated as new information from clinical research into the viewing of 3DTV becomes available.

See also Annex 5 for details of the results of subjective visual comfort assessment for motion and disparity magnitude of 3D content carried out by the Republic of Korea.

1 The necessity for safety guidelines

1.1 Background

Unlike 2DTV, 3DTV might cause some viewers discomfort such as dizziness, headache or fatigue of the eyes. It is necessary therefore to prepare a 3DTV broadcasting safety guideline to minimize or remove the cause of such discomfort so safer and more comfortable viewing of 3D broadcasting services is ensured.

1.2 Typical discomforts

Fatigue of eyes

– Unclear vision (vision becoming dim)
– Eyes feeling heavy
– Double vision
– Eyes becoming dry.

Fatigue of body

– Headache or migraine
– Sickness and nausea
– Dizziness.

2 Viewing guidelines

2.1 Viewing time and rest time

Viewers are recommended to take a 5~15 min break every hour, which is also recommended for 2D video display [1].

2.2 Viewing distance

The recommend viewing distance is 3~6 times of the height of 3D video display. For example, 2~4 m is recommended for 55 inch TV. If there is not sufficient space for the above distance, viewers are recommended to view TV at the farthest distance possible.

– In case of 2D video display, viewing at too short distance deteriorates the perceivable spatial resolution, and viewing at too far distance reduces absorption. For 3D video display, another consideration is the size of binocular disparity. Viewing an image closer raises the size of binocular disparity entered into the viewer's eyes, causing optical discomfort [2].

2.3 Viewing position

Viewers are recommended to face the centre of the display.

– Viewing 3D video directly in front of the display minimizes distortion of scenes. Viewing the video at an oblique angle causes "shear distortion" which is a phenomenon where the 3D image is distorted as if it follows the viewer. It also distorts the shape and the size of image formed on the eyes. These distortions may cause optical discomfort.

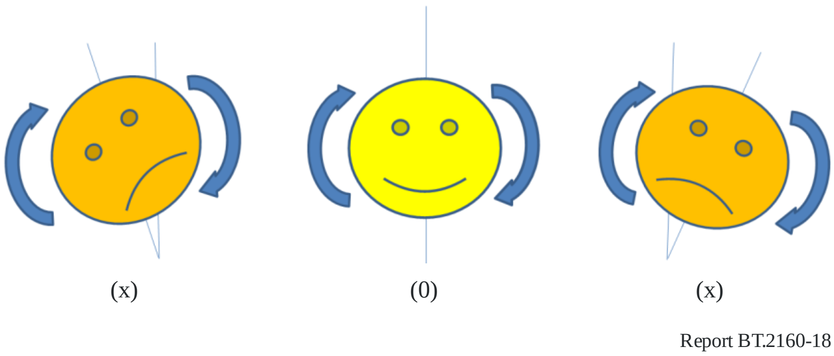
2.3.1 Horizontal viewing position

Viewers are recommended to keep their eyes level with respect to the display.

– If the head of a viewer is inclined considerably to either side (Fig. 1), the binocular disparity of the image is perceived as a vertical parallax into the viewer's stereopsis system. Therefore, the viewer has difficulty in perceiving the depth provided by the binocular disparity. Even if the viewer manages to perceive the depth, the vertical parallax increased by the inclined head makes it difficult for the viewer to fuse two images into a single 3D image.

FIGURE 1

Horizontal viewing position



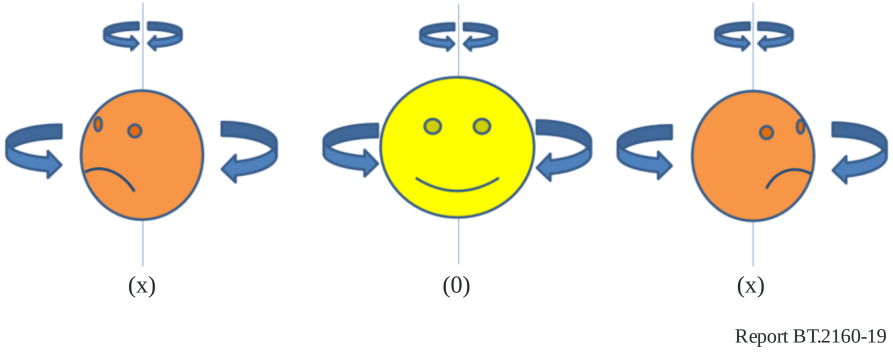
2.3.2 Right angle viewing position

Viewers should remain at right angles to the display (Fig. 2).

– Viewing a display with the head turned to either side creates a difference in size of image entering the eyes, causing difficulty fusing the two images into a single 3D image.

FIGURE 2

Right angle viewing position



2.4 Others criteria

Viewers are recommended to maintain comfortable viewing conditions by taking the following actions [1]:

– Adjust light, sound and air condition of the viewing space.

– Adjust brightness and colour of the display.

3 Viewer guidelines

3.1 Symptoms caused by 3D viewing on viewers

Viewers are recommended to stop viewing 3DTV if they have a headache, pain in eyes, dizziness, nausea, palpitation, unclear vision, unpleasant feeling, optical discomfort or double vision [1].

Fast movement of objects on the display or excessive accommodation-convergence mismatch/conflict may cause eye fatigue. If viewers experience any discomfort, they should stop watching and stare into a far distance to relax the eyes.

3.2 Stereo blindness and stereo abnormality

Viewers with stereo blindness or stereo abnormality may suffer optical discomfort with double vision. They are recommended to avoid watching 3D images.

– Not every person can perceive vivid stereoscopic depth from 3D images. About 1% of the population cannot perceive the stereoscopic depth at all. Up to 30% of the population perceive stereoscopic depth by detecting the stimulation for a specific depth only from the protruded (negative parallax) or retreated images (positive parallax) [3][4][5].

– Viewers having a strabismus or astigmatism may have a difficulty in perceiving the stereoscopic depth, and suffer more severe fatigue of eyes with double image than the viewers with normal vision.

– Amblyopia is accompanied by astigmatism in many children, and generally, these children cannot perceive the stereoscopic depth. Viewers with large difference between left and right eye may have a difficulty in deceiving the stereoscopic depth.

3.3 Chronic diseases

Viewers with any chronic disease (epilepsy, cardiac disorder, high/low blood pressure, etc.) are advised to pay special attention to any discomfort experienced when viewing 3D images.

3.4 Age

It is recommended that children under 10 are carefully supervised when viewing 3D images because they do not have fully developed optic systems and functions [1].

– Children have relatively shorter distance between eyes, and they perceive higher binocular disparity of 3D image than adults. Therefore, children perceive higher stereoscopic depth than adults from the same 3D image.

Ageing may deteriorate the stereopsis function.

– It is reported that ageing reduces the optical capability of deceiving the stereoscopic depth. Therefore, middle-aged/old viewers may have a difficulty in perceiving a vivid stereoscopic sense when compared to the younger age [6].

4 Content guideline

4.1 Setting stereo cameras

When producing stereoscopic image with stereo cameras, it is important that parameters are applied consistently to the left and right cameras. The following considerations are recommended:

– It is important to adjust the optic axes of the stereo cameras. The vertical adjustment error, rotation adjustment error and intersection error must be minimized.

– The basic camera parameters must be set so that there is no error of zoom, focus, iris and colour between right/left images. It is recommended to have left and right cameras synchronized.

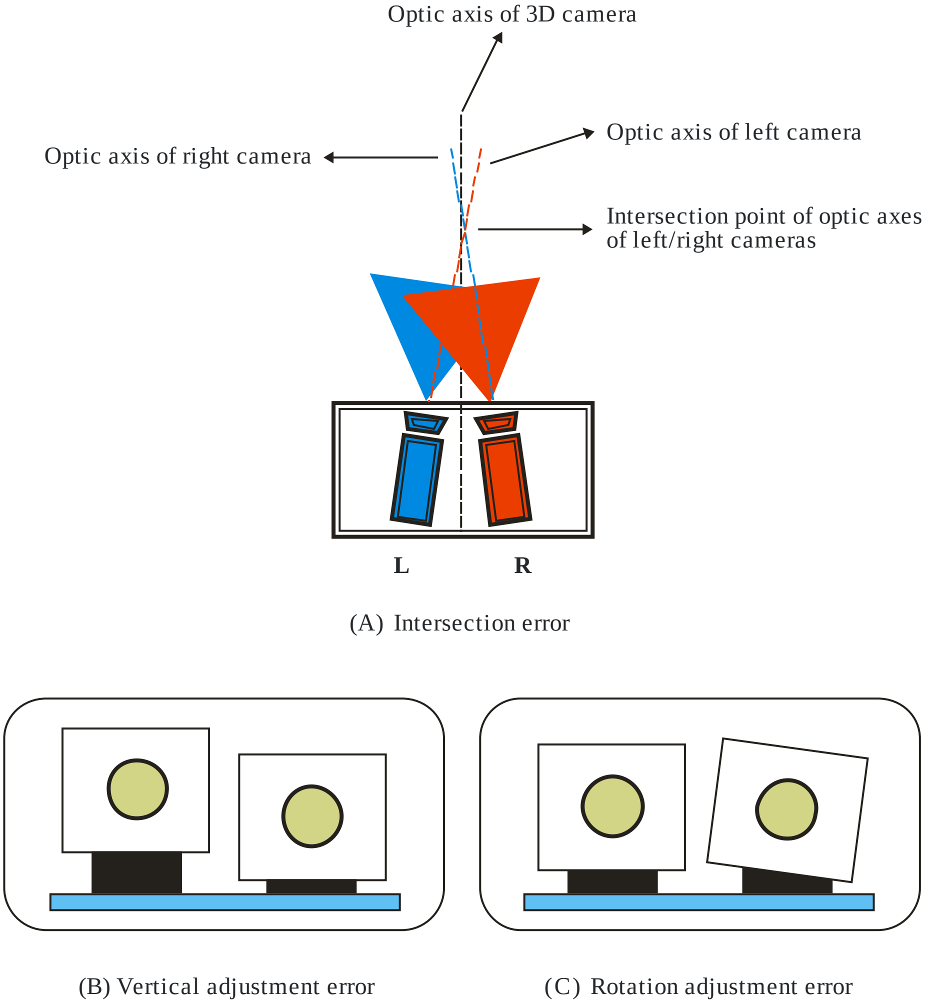
– Vertical inconsistency of images caused by inconsistency of optic axes is known to cause a fatigue of eyes.

– The state that the intersection point between optic axes of left and right cameras is not on the centre lines of the stereo cameras is called an intersection error. An intersection error may occur due to optic axes adjustment error even if the stereo cameras are set properly without any vertical adjustment error or rotation adjustment error. If the intersection error is excessive, the cameras cannot express the symmetric stereoscopic sense on the left/right symmetric stage, but express in appropriate stereoscopic sense.

– Excessive stereoscopic sense continued unnecessarily or sudden change of stereoscopic sense in the course of production of content may easily cause a fatigue of eyes.

FIGURE 3

Types of error of optic axis adjustment error



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4.2 Capturing stereoscopic images

Following considerations are recommended in capturing 3D stereoscopic images.

– Sudden changes in depth can cause eye fatigue. To minimize this, images should be produced so no sudden changes of disparity occur in a short period of time. Smooth camera operations when zooming or panning also reduces the risk of eye fatigue.

– It is also recommended that care should be taken during editing to prevent severe changes of disparity between shots or scenes.

– When taking close-up images with toed-in cameras (where the optical axes of the two cameras intersects), keystone distortion should be minimized and compensating work should be carried out on post-production if the images are not comfortable to watch.

– When using zoom lenses, the cardboard and puppet theatre effect should be minimized by adjusting the space between cameras.

– To avoid edge violations, any object near either side of the image should not be projected out of the screen (negative parallax) if at all possible.

– If the depth of an object perceived through binocular screen disparity is too small when compared to the known depth of the object, a cardboard effect may occur. In this case, this effect should be minimized with careful camera work [8].

– A puppet theatre effect is made when there is a gap between the stereoscopic image displayed and the size of the object perceived in the real world. Viewers are likely to perceive an object as too small compared to the background. This effect often occurs on smaller displays [8].

– A disparity between left and right images should be consistent if the image is produced properly. If a scene is taken with toed-in cameras, the image produces a keystone distortion in the echelon formation with inappropriate vertical parallax. The vertical parallax increases as the space between cross stereo cameras increases and the focal distance of the lens reduces [9].

– Toed-in cameras can create inappropriate horizontal parallax, which in turn, causes a distortion of stereoscopic depth. Viewers may perceive that an object is at a different distance when at the side of the display than when in the centre of the display [9].

4.3 Captions and Graphics

Captions must be displayed in front of objects to prevent violations that would make the caption appear to be inside an object. If an object has a high negative parallax (is projected a long way out of the screen), then placing captions in front of the object may make it uncomfortable to watch due to excessive disparity. In this case, it is recommended to change the position of the caption to prevent fatigue of eyes.

4.4 Screen disparity

– For uncrossed disparity, the screen disparity between left/right images should not exceed the average gap between eyes.

– For crossed disparity, excessive screen disparity between left/right images may cause a fatigue of eyes.

– Continued viewing of excessive binocular disparity causes a fatigue of eyes. Therefore, it is recommended not to present excessive crossed disparity for long periods of time.

5 Display guidelines

5.1 Crosstalk in the display

Image crosstalk caused by the display causes discomfort when viewing stereoscopic images. It is recommended to minimize crosstalk by consideration of the following:

– Crosstalk is a phenomenon that occurs due to inadequate separation of left and right images in the display. It varies depending on the display type and the left/right image separation method. In a polarized display (passive), for example, crosstalk is caused by the optical performance of the polarizing filter and the incomplete adjustment between the polarizing filter and the display pixel elements. In a shutter display (active), the pixel response speed becomes the main factor of the cause of crosstalk.

– Crosstalk in the display is an independent parameter to the content, and can be indicated in an objective value for each display. For example, the crosstalk for the left eye is induced from the brightness of the right image versus that of the left image seen by the left eye, and vice versa.

The crosstalk experienced subjectively by viewers may be caused by the content, as well as the display crosstalk. Therefore, it is recommended to consider the following when producing content:

– Subjective crosstalk experienced increases if there is a large contrast or binocular disparity between left and right images at the same position of the display [7].

5.2 Display refresh rate

In order to prevent flickering, the refresh rate of left and right images should be 60 Hz or higher. Therefore, the total refresh rate of a time-division 3D display should be 120 Hz or higher.

5.3 3D glasses

In addition to the display crosstalk, crosstalk may occur due to the glasses. Therefore, it is recommended to consider the following to minimize crosstalk:

– For polarized glasses, leakage of light caused by optical performance of the polarizing filter generates crosstalk.

– For active shutter glasses, crosstalk is generated by light penetration due to the optical performance of the glasses when the liquid crystal is closed.

– Active shutter glasses acquire information sent from the display for synchronization between left and right images. In order to minimize crosstalk and the signals and protocols for communication must be robust and immune from external interference, and interruption.

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Annex 3

Examples of safety guidelines Italian Health Ministry Circular Letters

The Italian Health Ministry issued a Circular Letter dated March 17, 2010, addressed to all the Regional Health Agencies, the Police, the associations of cinema operators and for information to the Ministry for Economy Development, which is responsible for telecommunications including broadcasting. The Italian Ministry action was prompted by a request of the Italian Consumer Protection Authority, and it was based on advice provided by the Ministry's High Advisory Council on Health. Some further clarifications were issued in a subsequent circular letter dated 6 August 2010.

The circulars are available (in Italian) on the website of the Ministry, and a translation is provided below.

The Ministry circular letter of March 17, 2010 states that:

– the scientific literature does not seem to provide firm proof that viewing stereoscopic programming would force human eyes and brain to perform unnatural processing of visual information; consequently there are no clinical indications at this moment against the use of 3D spectacles during cinema screenings, on condition that such screenings are limited in duration (the advice of the High Advisory Council on Health on this point was more detailed: it is suggested that viewing should be limited in time, and that it should contain intermissions proportionate to the total programme duration);

– some functional problems may arise in young viewers due to the use of 3D spectacles to view cinema presentations, because binocular vision may not yet be present or well established in young viewers, or because they may be cross-eyed or amblyopic, or because they may be going through a period of *visus* rehabilitation; however those problems should cause no irreversible damage or pathologies;

– consequently, the public that attends stereoscopic screenings should be informed that children under six years should not use 3D spectacles and that even adults should not use them for a duration that exceeds a single screening session.

A further circular letter of the Ministry, dated 6 August 2010, stated that in those cases when single-use glasses cannot be considered due to their technology or cost, 3D glasses must be properly disinfected and repackaged before they are provided to the next user since the risk of transmission of bacterial infections tends to increase with the successive use of the same spectacles by different viewers.

Annex 4

Psychophysical studies on three dimensional television systems

Summary

Before attempting to implement new broadcast schemes, we must gain a full understanding of the results of psychophysical studies in order to understand the effects to which the viewer is subjected and the performance that is required of the main equipment in these systems.

There are a number of issues to be studied before we can fully understand the effects of viewing three-dimensional images on human perception and visual functions. For the success of three-dimensional television broadcasting, all parties concerned, including broadcasters, producers, manufacturers, and regulators, should be well informed of the effects.

The psychophysical aspects of viewing stereoscopic images have been extensively studied. This Annex provides some key study items and the study results on the psychophysical aspects of stereoscopic television systems. It also describes the spatial distortion prediction system for 3DTV that calculates the spatial distortion of a reproduced stereoscopic image and predicts unnatural size distortion, excessive binocular parallax, and excessive parallax distribution on the basis of the shooting, display, and viewing conditions.

1 Key items for psychophysical studies

The following sections describe the key items for which further study is encouraged:

1.1 Naturalness and unnaturalness of images

1) Theoretical analysis of spatial reproduction characteristics of images taken by 3D cameras

   It is of fundamental importance to understand precisely how a real space is converted into a stereoscopic image space by a camera. In particular, the reproducibility of a stereoscopic image space should be analysed in terms of different settings of the lens axes of 3D cameras.

2) Size distortion

   The reproduction magnification ratio of an object at the shooting distance (the perceived size) varies with the imaging and display conditions. The resulting distortion in size may make an object be perceived as unnaturally small; this is called the “puppet theatre” effect.

3) Depth distortion

   The imaging and display conditions may reduce the reproduction magnification ratio of the depth direction and distort the perception of objects with visually imperceptible thicknesses. This is called the “cardboard” effect.

Section 2 describes the study results on the naturalness and unnaturalness of stereoscopic images.

1.2 Viewing comfort and discomfort

1) Differences in size, verticality, inclination and brightness, and cross-talk

   Viewers may not feel comfortable viewing left and right images that have size, verticality, inclination, and brightness differences. Cross talk between the left and right images may also have an impact on viewing comfort.

2) Psychological factors and the parallax distribution

The fundamental relationship between psychological effects brought about by 3D images and factors related to fatigue should be studied. In particular, “ease of viewing” and “sense of presence” may be key psychological factors. Attention should be paid to the distribution of parallaxes in the stereoscopic images. From the correlations between psychological factors and the parallax distribution, we can grasp the essential characteristics of stereoscopic images, e.g. the sense of presence they convey and their ease of viewing (visual discomfort).

3) Superimpositions within 3D images

With regard to superimpositions in a two-dimensional image, we only have to think about exactly where to display it on the screen. In the case of a stereoscopic image, however, we also need to pay attention to the depth of the superimposition. If we could find a preferred position for superimposition for stereoscopic images, we will be able to use it for actual programme production.

4) Change in parallax distribution during scene changes

The parallax distribution of stereoscopic images is discontinuous during scene-change frames, where the scene depth and perceived convergence distance change. We need to evaluate how these changes affect the visual discomfort experienced during viewing of stereoscopic images.

Section 3 describes the study results on the viewing comfort and discomfort of stereoscopic images.

1.3 Visual fatigue caused by parallax 3DTV viewing

Visual fatigue caused by viewing stereoscopic motion images is a particular safety concern. Viewer’s repeated adaptation to the discrepancy between eye convergence and accommodation causes a decline of their visual functions and results in visual fatigue.

Section 4 describes the study results on the visual fatigue caused by viewing stereoscopic images.

1.4 Individual differences in the stereopsis function

Visual functions vary greatly from person to person; so it is essential to understand that there are individual differences before 3D broadcasts begin. For instance, there are limits to the binocular parallax of left and right images that a person can fuse into one image; when the parallax exceeds these limits, a double image is perceived. In this situation, depth perception collapses and viewing becomes extremely uncomfortable. For this reason, it is necessary to know the range of binocular parallax over which two images can be fused into one. However, individual differences are vast and will necessitate a study of the stereopsis function of many people.

1.5 Effect on young people

We must bear in mind that young people’s sense of sight changes as they mature. Viewing of stereoscopic images possibly affects their visual functions in ways different from adults. It may be advisable that young children be cautioned about viewing stereoscopic images for extended periods of time.

2 Naturalness and unnaturalness of stereoscopic images − Geometrical analysis of spaces reproduced by stereoscopic images

2.1 Theoretical analysis of reproduced spaces

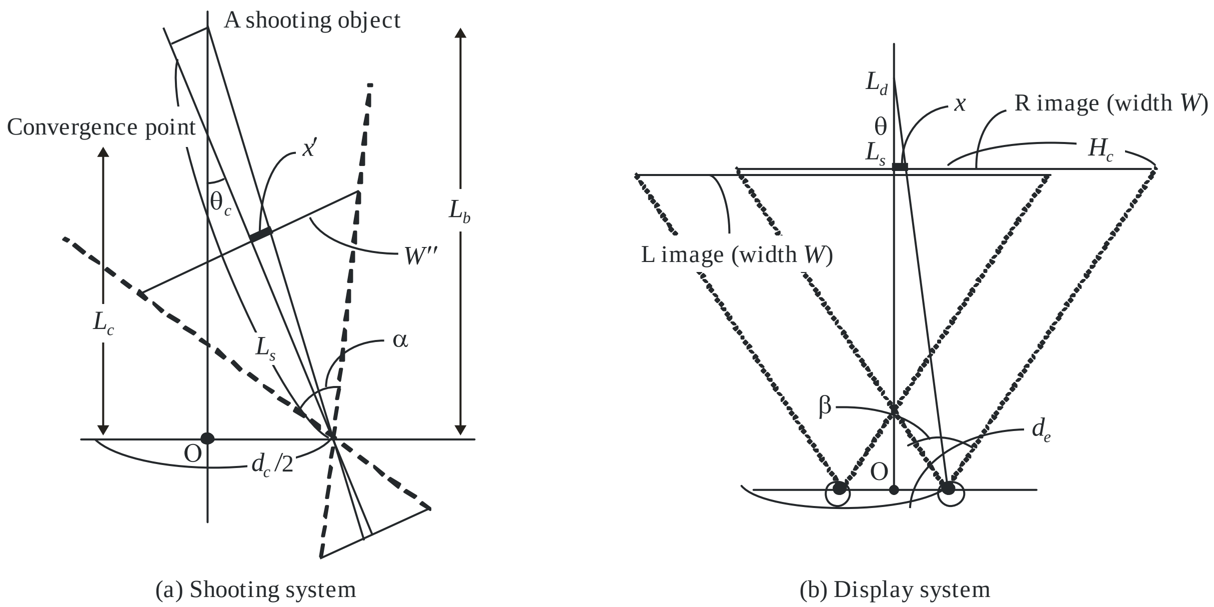
A basic requirement for the design of stereoscopic systems is an understanding of the transformation from real space (the space in which an actual object exists) to reproduced stereoscopic image space (the representation of this space in a stereoscopic image). In this section, we analyse the distortion of reproduced stereoscopic image space on the basis of image shooting and display system parameters [10].

2.1.1 Model of shooting/display systems

The configurations of the image shooting and display systems analysed here conform to the parameters shown in Fig. 4. The details of these parameters are shown in Table 1.

FIGURE 4

Shooting/display model



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Shooting and display systems can typically be configured in two different ways depending on how the optical axes are arranged.

Parallel configurations (where the two cameras of the stereo camera are aligned parallel to each other) are characterized such that objects at infinity are displayed at infinity by maintaining a constant horizontal separation of H_c between the left and right images when they are displayed (see Fig. 4). As a special case, when the separation d_c between the cameras and the horizontal offset H_c between the left and right images are equal to the separation d_e between the viewer's pupils, and the lens angle θ_b is equal to the angle of view of the display screen θ_d, the real space is in theory reflected without distortion in the reproduced stereoscopic image space [11]. However, it is not always possible to satisfy this condition in broadcasting where a wide variety of different subjects are liable to be viewed under widely varying conditions.

Another optical axis configuration is the so-called toed-in configuration wherein the optical axes of the two cameras intersect (see Fig. 5). This configuration is characterized such that an object situated at the intersection of the optical axes appears at the depth position of the screen on which its stereoscopic image is displayed. It is also relatively easy to present a sense of depth for objects in the space in front of and behind the object at the intersection of the optical axes. By virtue of these characteristics, this method appears to be used in most stereoscopic programmes.

TABLE 1

Parameters in shooting and display models

d_c	Camera separation
d_e	Eye separation
L_b	Shooting distance
L_c	Convergence distance
L_s	Viewing distance
L_d	Position of a stereoscopic object
α	Angles of view of lens
β	Viewing angle
θ_c	Camera convergence angle
θ	Convergence angle of eye
H_c	Horizontal gap between L and R images
W	Width of screen
W'	Width of virtual screen at the viewing distance in the shooting model
x'	Distance from the centre of the virtual screen at the viewing distance in the shooting model (see Fig. 4)

FIGURE 5

Parallel configuration

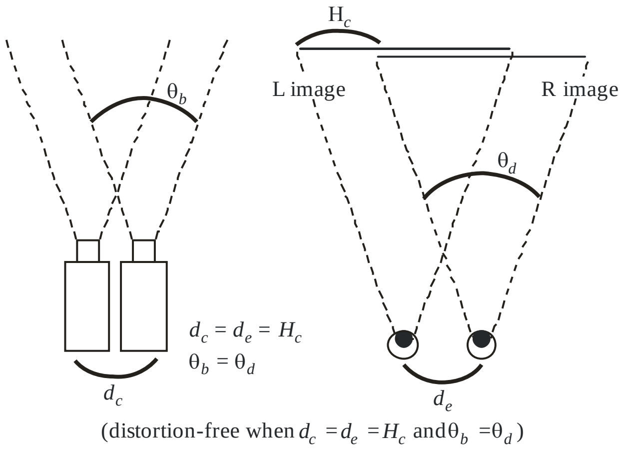

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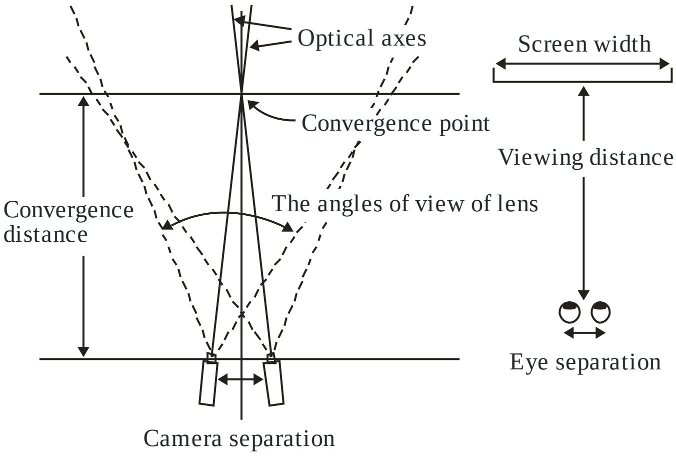
FIGURE 6

Toed-in configuration



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2.1.2 Depth distance in real space and stereoscopic image space

If an object's depth position in real space (the environment where images are shot) and stereoscopic image space (the reproduced environment) are L_b and L_d, respectively, then the relationship between these values obeys the following formula using the parameters of Table 1 and the geometrical relationship of the system configuration shown in Fig. 4.

$$L_d = \frac{1}{\frac{1}{L_s} - \frac{a_1 \cdot a_2}{L_c} + \frac{a_1 \cdot a_2}{L_b} - \frac{H_c}{L_s \cdot d_e}} \qquad (1)$$

In a parallel configuration, we can set $L_c \rightarrow \infty$ and $H_c = d_e$. In a toed-in configuration, we can set $H_c = 0$.

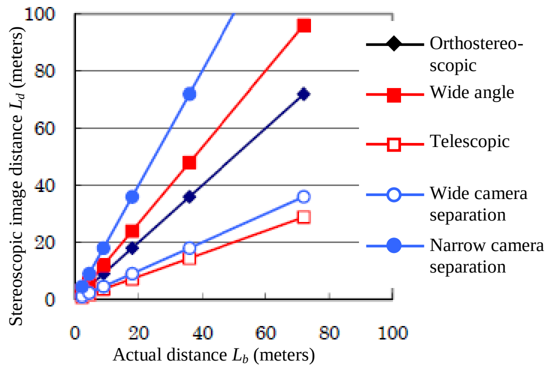
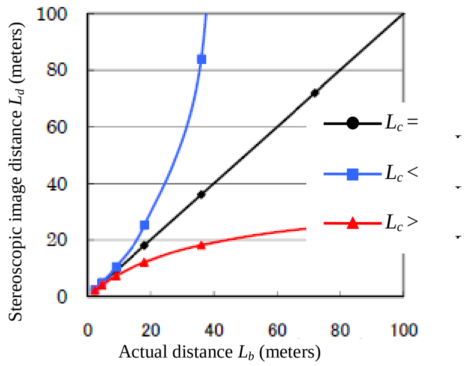
Table 2 shows the results of using equation (1) to investigate how the depth position L_d in the reproduced image and the actual depth position (the original camera-to-object distance) L_b are expressed in systems with parallel and toed-in configurations.

In Table 2, no consideration is given to the keystone distortion of the image shape that occurs in toed-in configurations. In other words, this Table shows the characteristics at the centre of the image where keystone distortion has little effect.

In the parallel configuration, L_b and L_d obey a proportional relationship regardless of the parameter settings. On the other hand, in the toed-in configuration, L_b and L_d are equal only for a certain specific combination of parameters ($L_c = a_1 \cdot a_2 \cdot L_s$), but otherwise have a non-linear relationship. The graph of Table 2 indicates that different characteristics are exhibited depending on the sizes of L_c and $a_1 \cdot a_2 \cdot L_s$.

TABLE 2

Distances in real space and in reproduced stereoscopic image space

Parallel camera configuration (Lens axes in parallel)	Toed-in camera configuration (Converging lens axes)
$L_d = \dfrac{L_b}{a_1 \times a_2}$ (See the note below for a_1 and a_2)	$L_d = \dfrac{1}{\dfrac{1}{L_s} - \dfrac{a_1 \cdot a_2}{L_c} + \dfrac{a_1 \cdot a_2}{L_b}}$
	
Orthostereoscopic condition: When $\alpha=\beta$ and $d_c=d_e=H_c$, actual space is copied into a stereoscopic image by the same, or 100% magnification.	Nonlinearity is apparent when L_c is not equal to $a_1 \cdot a_2 \cdot L_s$.
Note: $a_1 = \dfrac{d_c}{d_e}$、 $a_2 = \dfrac{W}{W'} = \dfrac{\tan\dfrac{\beta}{2}}{\tan\dfrac{\alpha}{2}}$	

2.2 Size distortion

The size of the reproduced image of an object shot by a camera at a certain distance (i.e. the size of recognized objects) varies with the image shooting conditions and display conditions, but is generally subject to size distortion. When size distortion causes objects to appear unnaturally small, it is often referred to as the "puppet theatre" effect [12].

2.2.1 Theoretical analysis

The puppet theatre effect has various interpretations. Here, we will not concern ourselves with the perceived absolute size of the reproduced image. Instead, we will concentrate on cases where the size of objects appears to be unnaturally deformed in comparison with the foreground and background.

If W_b is an object's size in the real space and W_r is its apparent size in the stereoscopic image space (i.e. its perceived size based on its depth position), then the relationship between these values is expressed by the formula below, where a_2 has the value shown in Table 2.

$$W_r = \frac{L_d}{L_b} \frac{\tan\frac{\beta}{2}}{\tan\frac{\alpha}{2}} W_b = \frac{L_d}{L_b} \cdot a_2 \cdot W_b \qquad (2)$$

Now let us introduce the magnification M_s of the reproduced image. As shown in equation (3), M_s expresses the apparent size change of objects, taking their depth position into consideration.

It corresponds to the ratio of the size W_r of the reproduced image to the size W_b of the object in real space.

$$M_S = \frac{W_r}{W_b} \tag{3}$$

Table 3 shows the results of applying M_s to the parameters of the parallel and toed-in camera configurations shown in Table 2. In the parallel configuration, M_s is constant regardless of the camera-to-object distance L_b, but in the toed-in configuration, M_s varies with L_b. In the toed-in configuration, the sizes of two objects at different depth distances (i.e. background and foreground objects) can be perceived very differently depending on the combination of parameters, and this is liable to cause puppet theatre effects in some cases.

TABLE 3

Analysis of magnitude distortion

Reproduction magnification ratio of an object (**Ms**)	
In the case of the parallel camera configuration: $Ms = \frac{1}{a_1}$	In the case of the toed-in camera configuration: $Ms = \frac{1}{\frac{1}{L_s} - \frac{a_1 \cdot a_2}{L_c} + \frac{a_1 \cdot a_2}{L_b}} \cdot \frac{a_2}{L_b}$
In the case of the parallel camera configuration, the reproduction magnification ratio is $1/a_1$.	In the case of the toed-in camera configuration, except where $L_c = a_1 \cdot a_2 \cdot L_s$, the reproduction magnification ratio of an object depends nonlinearly on the shooting distance and the background affects the perceived size of the object. Especially in the case of $L_c < a_1 \cdot a_2 \cdot L_s$, the Puppet Theater effect tends to be enhanced because the reproduced foreground is smaller than the background.

2.2.2 Subjective evaluation tests

In the discussion of the previous section, we showed that an object's reproduced magnification M_s changes with various different parameters. Thus, when two objects (e.g. foreground and background objects) are reproduced at different magnifications, it is expected that unnatural phenomena such as the puppet theatre effect will occur.

We tried to apply the geometrical discussion of the previous section to the results of subjective evaluation tests.

In the subjective evaluation tests, stereoscopic images were reproduced under a number of different imaging and display conditions, and the test subjects evaluated their subjective impressions of the object size [13].

For the evaluation images, we used images of a roughly life-sized mannequin (shown in Fig. 7) using three different configurations of shooting distances and camera lenses, each with three different distances separating the left and right cameras. This resulted in a total of nine different evaluation images. Table 4 lists the details of these imaging and display conditions. In these images, the foreground consists of the mannequin, and the background consists of a corridor doorway 4.5 m behind it. In each case, the depth position of the mannequin in the stereoscopic image was at the position of the screen, and the image was displayed life-size on a 120-inch screen.

The test subjects were asked to evaluate the subjective size of the reproduced stereoscopic image of the mannequin on the following five-grade scale:

5: Large
4: Somewhat large
3: Normal
2: Somewhat small
1: Small

FIGURE 7

Object used for subjective evaluation tests of puppet theatre effect

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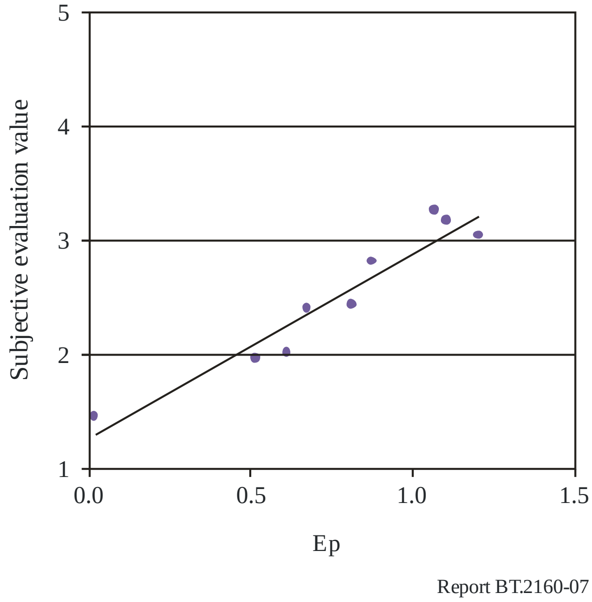
TABLE 4

Shooting and display conditions used in subjective evaluation tests of puppet theatre effect

conditions	1	2	3	4	5	6	7	8	9
contents	A			B			C		
the angles of view of lens α (degree)	51.3			27.0			18.2		
the distance to the foreground object (m)	3.0			6.0			9.0		
the distance to the background object (m)	7.5			10.5			13.5		
convergence distance Lc (m)	3.0			6.0			9.0		
camera separation dc (mm)	65	95	125	65	95	125	65	95	125
viewing angle β (degree)	33.4								
viewing distance Ls (m)	4.11								
a_1	1.00	1.46	1.92	1.00	1.46	1.92	1.00	1.46	1.92
a_2	0.63			1.25			1.88		
$Lc/(a_1*a_2*Ls)$	1.16	0.79	0.60	1.17	0.80	0.61	1.16	0.80	0.61
Ep	1.21	0.61	0.01	1.11	0.81	0.52	1.07	0.87	0.68

FIGURE 8

Correspondence with subjective evaluation scores



We used the ratio E_p of the foreground and background magnifications ($M_s^{(F)}$ and $M_s^{(B)}$) as a predicted value of the puppet theatre effect. Here, the depth position of the foreground and background are assumed to be given.

$$E_p = \frac{M_s^{(F)}}{M_s^{(B)}} \tag{4}$$

Figure 8 shows the correspondence between the predicted value E_p and the subjective evaluation scores. The evaluation scores and the reproduced image magnification ratio E_p show a strong correlation.

In practice, subjective size distortion phenomena such as the puppet theatre effect are thought to depend on the foreground and background and on the type of object depicted in the image, and it would be worth verifying these results with many more images. In this report, we have at least shown the geometrical criteria that cause this effect.

2.3 Depth distortion

Depending on the image shooting and display conditions, the relative size of the reproduced image in the depth direction may become smaller. In such cases, the apparent thickness of the reproduced object is distorted in the depth direction, causing a poor sense of depth. This phenomenon is sometimes called the cardboard effect [14] because it makes three-dimensional objects look like cardboard cut-outs.

2.3.1 Theoretical analysis

To quantitatively ascertain the thickness of a stereoscopic image based on the camera-to-object distance, we introduced the thickness term E_c expressed by the following formula:

$$E_c = \frac{\left({dL_d}/{dL_b} \right)}{M_s} \tag{5}$$

Here, M_s is the magnification of the reproduced image, and L_b and L_d are the depth distances of the object in real space (where the object image is actually shot) and stereoscopic image display space, respectively. E_c expresses the degree of local changes in the depth direction.

Table 5 shows the results calculated by applying this value to the parameters of parallel and toed-in configurations shown in Table 2.

TABLE 5

Analysis of depth distortion

Reproduction magnification ratio of depth $E_c = \dfrac{\left(dL_d / dL_b \right)}{M_s}$	
In the parallel camera configuration	In the toe-in camera configuration
$E_c = \dfrac{1}{a_2}$	$E_c = \dfrac{1}{\dfrac{1}{L_s} - \dfrac{a_1 \cdot a_2}{L_c} + \dfrac{a_1 \cdot a_2}{L_b}} \cdot \dfrac{a_1}{L_b}$ Especially in the case of L_b=L_c (when it is reproduced on the screen) $E_c = a_1 \dfrac{L_s}{L_c}$

In the parallel configuration, E_c depends on a_2, which is simply the ratio of the angles of view when the image is shot and when the image is displayed. The situation is more complex in the toed-in configuration, where several factors are involved. However, when considering an object close to the depth position of the display screen, it can be seen that it is related to the camera separation (a_1), the distance to the intersection of the optical axes when capturing the image (L_c), and the viewing distance (L_s). It is suggested that these parameters should be considered in order to avoid the cardboard effect.

2.3.2 Subjective evaluation tests

The cardboard effect is a phenomenon whereby individual objects in a scene are perceived as having no depth, although it is generally still possible to ascertain the positional relationships among groups of objects in the depth direction. Although an analysis of the occurrence of this phenomenon is inevitably complex, here, we attempt to predict its occurrence in cases where the analysis is restricted to binocular parallax.

In the discussion of the previous section, we showed that the thickness E_c of an object's image is affected by various parameters. When the thickness E_c is small, it is predicted that unnatural phenomena such as the cardboard effect can occur.

We tried to apply the geometrical discussion of the previous section to the results of subjective evaluation tests. In the subjective evaluation tests, stereoscopic images were reproduced under a number of different imaging and display conditions, and the test subjects evaluated the subjective thickness of the object [15].

For the evaluated images, we produced images of the object shown in Fig. 9 under the nine sets of conditions shown in Table 6.

The test subjects were asked to evaluate the subjective thickness of the reproduced stereoscopic image on the following five-grade scale:

5: Very thick
4: Thick
3: Somewhat thick
2: Not very thick
1: Not at all thick

FIGURE 9

Object used in the subjective evaluation tests of the cardboard effect

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TABLE 6

Shooting and display conditions used in subjective evaluation tests of the cardboard effect

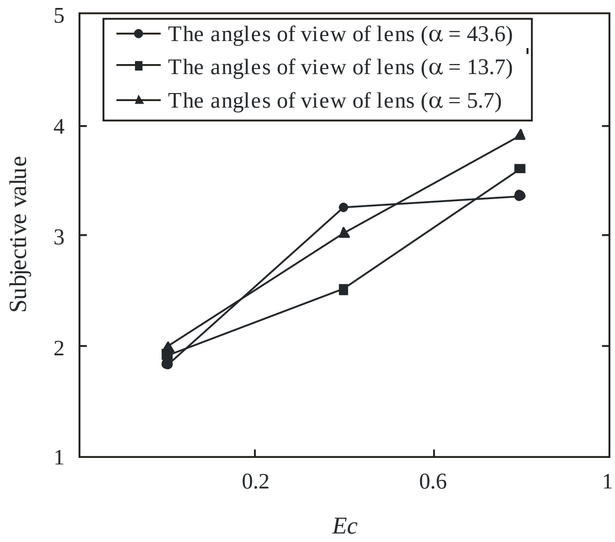
condition	1	2	3	4	5	6	7	8	9
camera configuration	toed -in								
the angles of view of lens α (degree)	43.6			13.7			5.7		
shooting distance Lb (m)	3.3			11.0			26.4		
convergence distance (m)	3.3			11.0			26.4		
camera separation dc (mm)	13	39	66	43	130	216	104	311	513
viewing angle β (degree)	43.6								
viewing distance Ls (m)	3.3								
a_1	0.20	0.60	1.02	0.66	2.00	3.32	1.60	4.78	7.89
Ec	0.20	0.60	1.02	0.20	0.60	1.00	0.20	0.60	0.99

Figure 10 shows the correspondence between the thickness E_c and the subjective evaluation scores. The vertical axis shows the results of normalizing the 5 evaluation categories in psychological space by using the method of successive categories. The calculation and subjective evaluations are clearly correlated.

The cardboard effect is a subjective effect that might be affected by other cues such as motion parallax and shading information. In this Report, we have at least shown the geometrical criteria that cause this effect.

FIGURE 10

Correspondence with subjective evaluation scores



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3 Viewing comfort and discomfort of stereoscopic images

3.1 Parallax distribution and visual comfort of stereoscopic images

3.1.1 Introduction

One of the issues that can arise when making stereoscopic images widely available to large numbers of viewers is the visual discomfort experienced by viewers of some scenes. This discomfort is thought to be caused by discrepancies and crosstalk between the characteristics of the images presented to the left and right eyes, such as differences in their geometrical characteristics or video properties, and is thought to be more of a problem in scenes where these characteristics are prominent. Another factor is parallax itself, which plays a key role in conveying the sense of depth.

It has often been noted that excessive parallax can cause visual fatigue. There are many productions where surprisingly large amounts of parallax are used intentionally for dramatic impact. If we can find out about the distribution of parallax within the same frame and how this distribution affects the viewer's visual discomfort, then this should provide us with very useful clues for the production of visually comfortable stereoscopic images in each scene. It can sometimes be difficult to analyse the parallax values included in a frame. In what follows, we describe such an analysis and apply it to a number of stereoscopic images. We then compare its results with those of subjective evaluation tests.

3.1.2 Parallax measurements

Here we summarize the parallax measurement method used in this study.

For many applications, we ideally need to be able to determine the depth (i.e. the amount of parallax) for each pixel of an image. However, algorithms for analysing parallax are generally prone to errors. Also, in practice there are cases where corresponding pixels do not exist in the images presented to the left and right eyes due to occlusion. In this study, we do not need to measure parallax on a strict per-pixel basis as long as we are able to extract the characteristics of a parallax distribution from the images. To achieve this aim, the method we propose combines phase correlation with a number of threshold processing methods. A detailed description of this algorithm can be found in the Reference below. The algorithm was used in the parallax analysis of stereoscopic images discussed below.

3.1.3 Subjective evaluation tests of parallax distributions and visual comfort

We performed subjective evaluation tests to investigate the relationship between visual comfort of stereoscopic images and their parallax distributions [16]. The subjective evaluation test conditions are shown in Table 7. The images used for the evaluation consisted of 48 different still images.

These images were presented as stereoscopic images with 2D images as a standard reference, and their relative visual comfort was evaluated on a seven-grade scale. The 2D images were produced by presenting the left-eye image to both eyes and were evaluated by test subjects wearing the same polarizing glasses used for the stereoscopic images. The parallax in the stereoscopic images was measured by using the phase correlation method discussed in § 2. Here, the amount of parallax was measured on a per-pixel basis with the screen corresponding to a value of zero, and positions behind and in front of the screen correspond to positive and negative parallax values respectively. In the viewing conditions shown in Table 7, the amount of parallax of a single pixel corresponds to a separation of approximately 1 mm between the left and right images on the screen.

Figure 11 shows the results of the visual comfort subjective evaluation tests and the results of measuring the amount of parallax in the images. In the graphs of this Figure, the numbers on the horizontal axis designate the images to be evaluated. The graph at the top shows the results of the subjective evaluation tests. The vertical axis shows the mean value of the evaluation scores from 24 evaluators, and the vertical bars represent the standard deviations of these scores. The lower graph shows the results of measuring the amount of parallax. The vertical axis shows the amount of parallax measured in pixel units, the plotted points show the average values of the parallax in the images, and the vertical bars show the range of the parallax distributions. The upper and lower ends of the vertical bars represent the maximum and minimum parallax values. A comparison of the two graphs shows that the images with an evaluation score of 3 or less have a very large parallax distribution range.

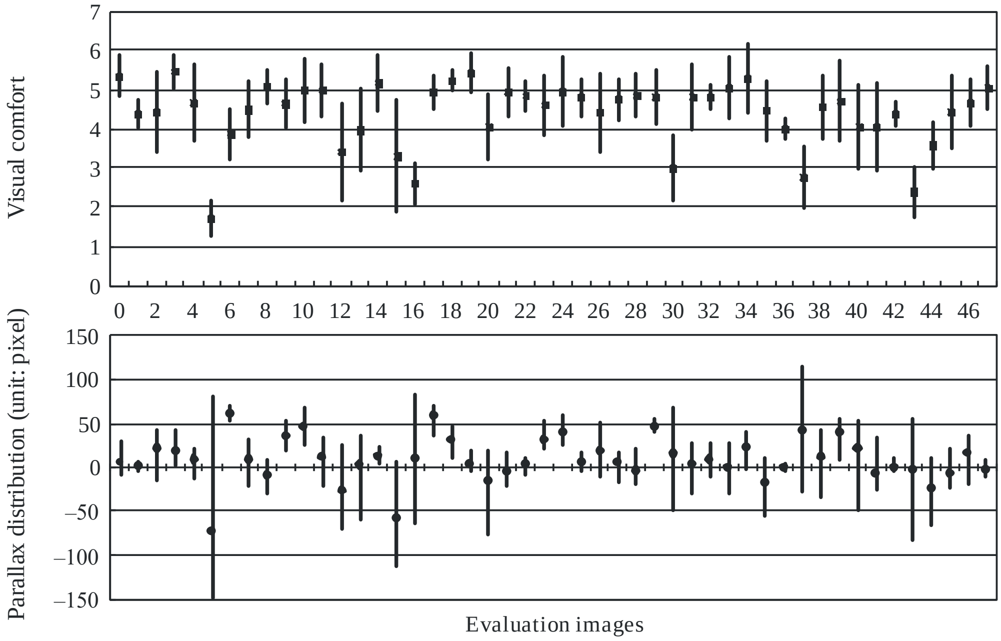
TABLE 7

Conditions of subjective evaluation tests of parallax distributions

Images used in test	48 still images (including a standard pattern)
Subject	24 adult males and females (not expert)
Repeat test	10 s viewing of 2D image (for reference), following by 10 s viewing of stereoscopic image (for evaluation)
Display system	Stereoscopic HDTV using polarizing glasses
Screen size	90 inches
Viewing distance	About 3H (3.33 m)
Peak brightness	15 cd/m^2
Method of evaluation	Relative evaluation on a scale of seven, based on 2D image

FIGURE 11

Evaluation test results and parallax measurement results



On analysing the correlation between the results of the subjective evaluation tests relating to visual comfort and the statistical quantities (mean, range, minimum, maximum, variance) of the parallax distributions, it can be seen that the parallax range exhibits a strong correlation with a correlation coefficient of −0.86 (99% confidence).

Figure 12 shows the relationship between the parallax distributions and visual comfort of the images used in the evaluation. The vertical axis shows the amount of parallax in pixel units with a value of zero corresponding to the position of the screen, and the horizontal axis shows the visual comfort derived by using the method of successive categories to combine the psychometric values. The plotted points represent the mean values of the parallax distributions in the images, and the vertical bars represent the range of the parallax distributions. From Fig. 12, we can see that in each image evaluated as being visually comfortable, the range of the parallax distribution is approximately 60 pixels or less. This translates to a value of 0.3 diopters. Images are evaluated as being comfortable when the parallax distributions are in the range from approximately 30 pixels in front of the screen to approximately 65 pixels behind it.

Next, we investigated the relationship between the average values of the parallax distributions and the visual comfort of the images. With seven of the images, we performed visual comfort evaluation tests in which the average value of the parallax distribution was shifted to different positions. These tests were performed with 20 test subjects. The other test conditions were the same as in Table 7. Figure 13 shows the experimental results. In this Figure, the points plotted with outlined symbols represent data obtained without horizontal shifting. As Fig. 13 shows, as the average value of the parallax distribution became closer to the screen position, the images were evaluated as being more visually comfortable.

FIGURE 12

Parallax distribution vs. visual comfort

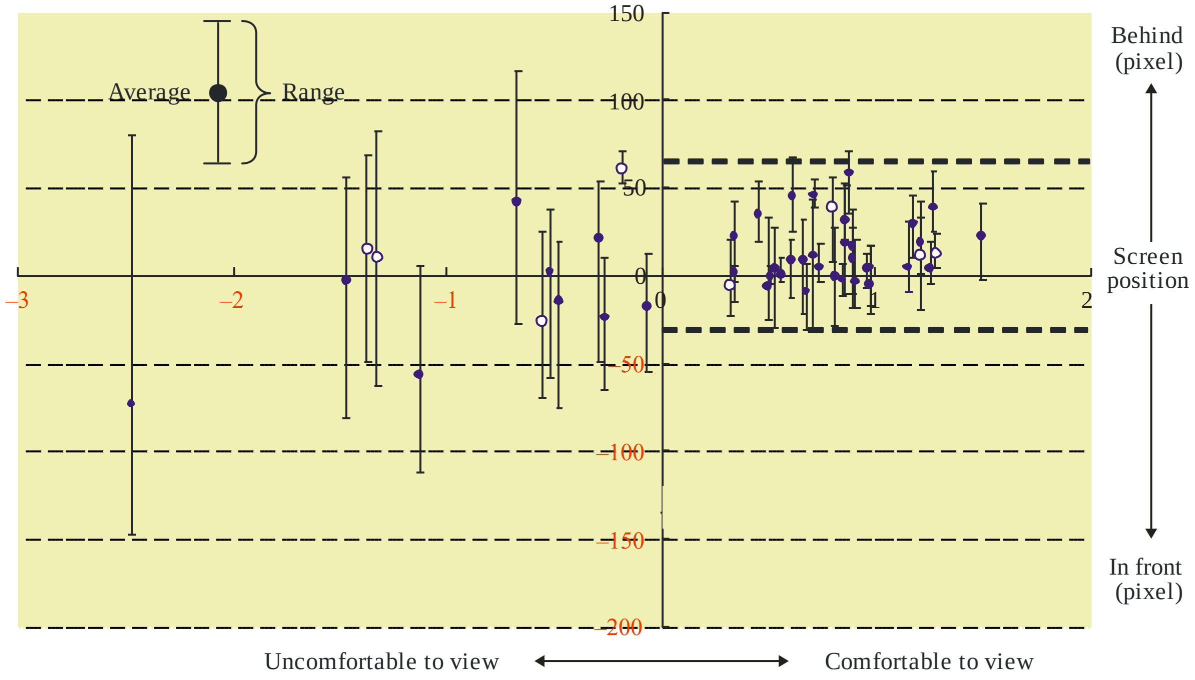


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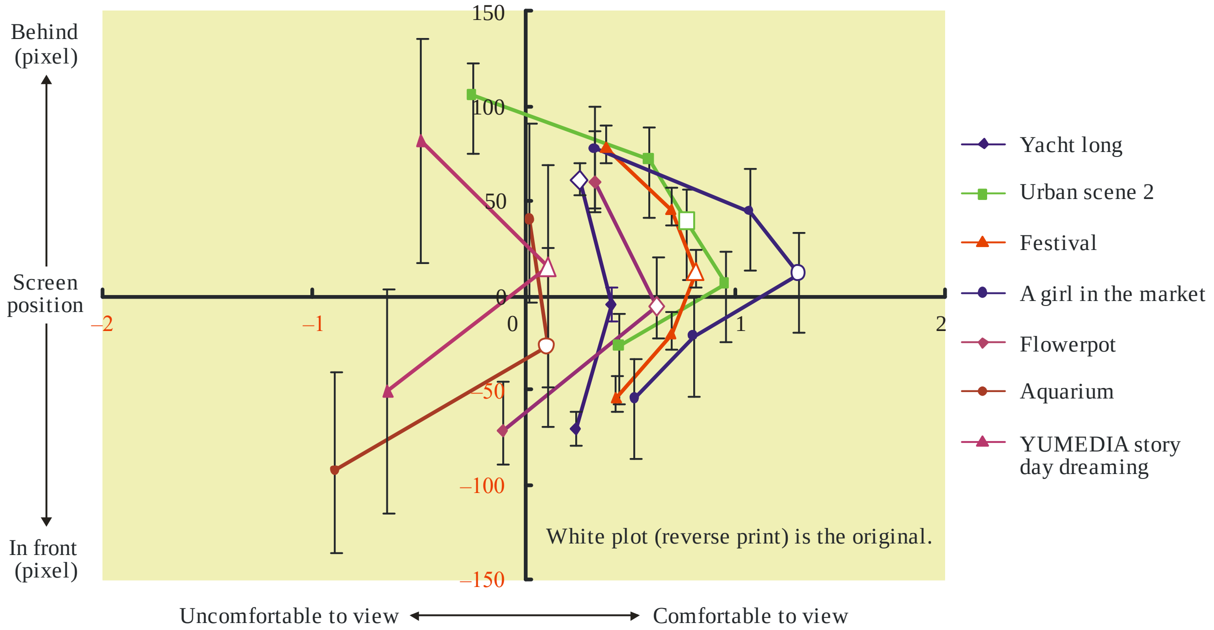
FIGURE 13

Average values of the parallax distributions vs. visual comfort



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3.1.4 Subjective evaluation of the sense of presence

When scenes are limited to small values of parallax there might be a reduction in the positive effects of the stereoscopic images, such as the sense of presence. In the tests reported in § 3, the images were evaluated in terms of their sense of presence as well as their visual comfort. Specifically, the stereoscopic images were presented with 2D images as a standard reference, and their sense of presence was evaluated on a seven-grade scale.

In the analysis of the test results, we found no significant correlation between the sense of presence scores and the statistical quantities of the parallax distributions. We extracted the images for which the stereoscopic image was evaluated as more visually comfortable than the 2D image (35 images in total), and as a result of analysing these images, we showed that there is a strong correlation between the range of the parallax distribution and the sense of presence (correlation coefficient 0.65).

On the other hand, we observed no factorial effect of the average value of the parallax distribution on the sense of presence evaluation scores.

3.2 Visual comfort and discomfort in viewing stereoscopic images

3.2.1 Discrepancies between left and right images

Here we present the results of evaluating visual comfort/discomfort in viewing stereoscopic images from the perspective of discrepancies between left and right images in the performance or characteristics of image capture and display equipment. A series of experiments was conducted on discrepancies in size, verticality, inclination, and brightness, as well as on cross-talk regarding discomfort. Natural images of HDTV were mainly used for the evaluation. The major findings of the studies are summarized in Table 8. The values represent the results of a subjective evaluation test on the five-grade impairment scale.

TABLE 8

Research on impairment caused by discrepancies and cross-talk between L/R stereo images

Factor	Image characteristic		Detection limit	Tolerance limit	Note	Reference
L/R image discrepancy	Geometric discrepancy	Size	1.2 %	2.9%	Taking size of one image as 100%	[1]
		Vertical displacement	0.7%	1.5%	Taking image height as 100%	
		Rotation	0.5 degrees	1.1 degrees	Angle of rotation about image centre	
	Brightness discrepancy	White clip level	70%	60%	Taking 100 IRE white level as 100%	[2]
		Black clip level	1%	2%	Taking 100 IRE white level as 100%	
Cross-talk	Contrast ratio of 100:1 in tests		1%-2%	5%-10%	Luminance ratio	[5]

TABLE 9

Research on parallax distribution, parallax range and parallax change over time

Factor	Evaluation item	Experimental results	Reference
Parallax distribution within image (frame)	Distribution pattern	Easily viewable if parallax is shaped far at top of image, near at bottom	[7]
	Range of parallax	Comfortable to view if parallax range is within 60 min.	[8]
	Subtitle position	Preferable if subtitle positions 10-15 min. in front of background image	[9]
Parallax change over time	Scene cuts	Uncomfortable to view if temporal change of parallax exceeds 60 min.	[9]

When shooting and displaying stereoscopic 3DTV programmes, there can be geometrical distortions, such as size inconsistency, vertical shift, and rotation error, between left and right images [1]. Results of experiments where three kinds of distortions occurred independently from each other are shown in Table 8.

As differences between left and right images in amplitude and offset can be corrected but clipped white or black levels cannot, the degree of interference when the white or black level of one of the left and right images is clipped was evaluated. The evaluation results on detection and tolerance limits were reported to depend on image content [2]. Some of the earlier studies on differences in brightness and contrast are given by References [3] and [4].

Stereoscopic image cross-talk, in which the left and right images "leak" and can be partially seen by the opposite eye, can also result in discomfort for the viewer, and experiments evaluating it have also been done. These values on detection and tolerance limits were reported to be highly dependent on image content and display contrast, and cross talk must be reduced further still on high contrast displays [5]. One of earlier studies on cross-talk is given by Reference [6].

3.2.2 Depth range, distribution and change in parallax

Cases of extreme parallax or sudden changes in parallax cause visual discomfort, so it is important to manage parallax with special care when producing programmes with stereoscopic images. Results of experiments subjectively evaluating the relationship between visual comfort and the distribution of parallax in images, and the change in parallax before and after scene cuts are shown in Table 9. The positioning of subtitles has also been evaluated. All tests were done under standard viewing conditions for HDTV. The range of parallax for visual comfort has already been reported in § 3.1 of Annex 4.

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4 Visual fatigue in viewing stereoscopic images

4.1 Experimental results on inconsistency between vergence and accommodation

It has been confirmed through subjective evaluation that viewing stereoscopic images can result in a great degree of visual fatigue compared to viewing 2D ones. On this issue, it has been shown that changes in visual performance can be observed before and after viewing stereoscopic images, and that the fusional amplitude (the parallax range over which viewers can fuse left and right images) in particular decreases. The experimental result suggested the possibility that a fusional amplitude can be one of indices for evaluating visual fatigue [1].

Here, conditions in which vergence and accommodation are not consistent were reproduced using specialized equipment, and an objective evaluation of visual fatigue was obtained by measuring fusional amplitude before and after using these glasses for one hour. Results of these trials are shown in Figs 14 and 15. In both experiments, a common one-hour HDTV programme was used. The figures indicate mean values of ratios of the relative range of convergence (a relative value using the fusional amplitude before viewing as the basis), with small values indicating a narrower fusional amplitude.

The results from viewing a flat image in 3D for one hour with a fixed amount of parallax (such that the image is displayed in front or behind the screen) are shown in Fig. 14. The results of changing the parallax over time with the vergence and accommodation being consistent in one case, and not consistent in the other are shown in Fig. 15. Parallax was changed 16 times over a period of two minutes, and this was repeated 29 times. In both experiments, the same one-hour HDTV programme was used.

A large change in ratio value was observed when viewing images with parallax than when viewing 2D ones, and even more fatigue was caused by the time-varying images with inconsistencies between vergence and accommodation. These results indicate that inconsistencies between vergence and accommodation as well as fluctuations in time due to parallax, can be factors causing visual fatigue [2].

4.2 Experimental results on parallax amount and lateral/depth motion

A series of experiments have also been done to examine the relationship between this issue of inconsistency between vergence and accommodation, and depth-of-focus of the eyes.

First, the accommodation responses were measured [3]. Subjects viewed image content for approximately one hour on a 120-inch screen at a viewing distance of 4.5 m. The 3D image contents were two motion video sequences, and parallax for the video displayed under the conditions of the experiment was within the depth of field in almost all cases, 2D video was also used for reference.

The result was assumed significant for visual fatigue when the change of amplitude of the accommodation response in the before and after viewing was bigger than 0.5 diopters. From this aspect the results of comparing accommodation response before and after viewing showed no significant difference for the 2D images, whereas for the 3D images, three of five subjects for the first image sequence and two of five subjects for the second sequence showed visual fatigue. On the basis of these results and the fact that the video used was within the depth of focus, it is presumed that causes of visual fatigue other than depth of focus must also be considered.

Next, experiments were done to compare images in different amount of parallax, as well as 3D images with and without motion [4]. In the experiments, Japanese text with added parallax was displayed on a field-sequential 3D HD monitor (28-inch diagonal). From a viewing distance of 3H, subjects read for approximately one hour while turning pages using a mouse. This was repeated several times, changing the amount of parallax. Experiments were also done with moving text. Two types of text motion were tested: forward and backward in the depth direction, and horizontal motion. Here, the amount of parallax was limited within the depth of focus. The timing of motion was generated from an existing 3D programme.

The degree of fatigue was estimated on the basis of subjective evaluation and accommodation response. The subjective evaluation results are presented in Fig. 16. The figure shows there was a significant difference at the parallax of −1.36 degrees whereas at +1.36 degrees there was not, i.e. there was a large variance. Fatigue was also inferred when there was motion in the depth direction. These results suggest that changes in the depth direction can cause visual fatigue even when the amount of parallax remains within the depth of focus.

FIGURE 14

Fusional amplitude after viewing image with large binocular parallax

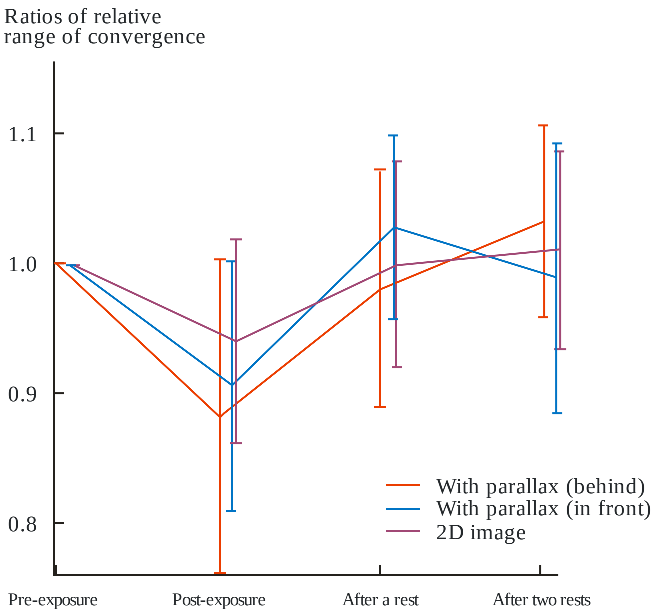

Figure shows mean value with standard deviation.

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FIGURE 15

Fusional amplitude after viewing image with time fluctuations in binocular parallax

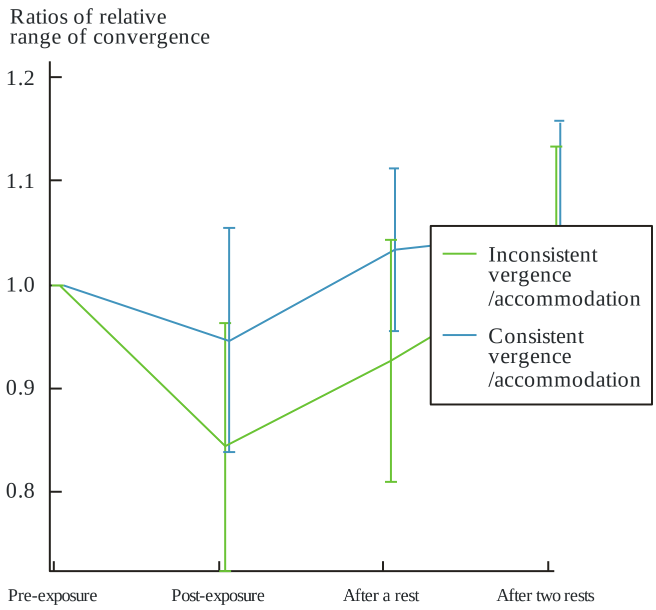

Figure shows mean value with standard deviation.

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FIGURE 16

Subjective evaluation of visual fatigue while changing amount of parallax and stationary vs. moving objects

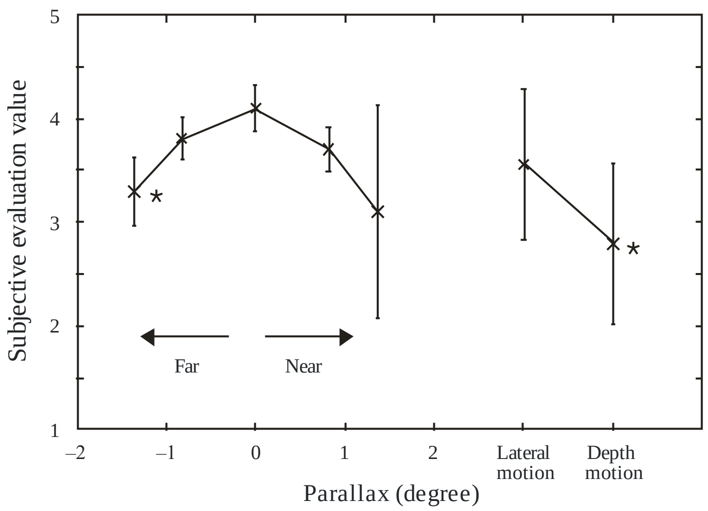

Figure shows mean values with standard deviation.
Asterisk indicates significant difference from still image on screen.

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4.3 Evaluation of fatigue caused by watching 3DTV

4.3.1 Experiment

Evaluation experiments consisting of 500 adult participants [5] and 131 minor participants [6] watching 3D content for approximately one hour on commercially available 46 to 50 inch 3DTVs that require the use of shutter glasses were conducted. The degree of fatigue after watching the 3DTV was evaluated under various viewing conditions.

The 3D content used in the experiment consisted of seven kinds of programmes (documentary, sports, music clip, animation, etc.) whose binocular disparities were mostly less than one degree. This content was recorded with a hard disk recorder (1 920 × 1080 60 i/10 bit/4:2:2) in the 3DTV format referred to as Side-by-Side, where the horizontal resolution of the HDTV image is reduced by a half.

Six types of viewing conditions were set, i.e. four viewing conditions in which participants watched 3D content with glasses in front of a 3DTV at three different distances (two, three and five times the screen's height H) and from an oblique position of 40 degrees, and two other control conditions in which participants watched 2D content with or without glasses in front of a 3DTV at a distance of three times the screens height. Table 10 shows the abbreviations for these conditions.

TABLE 10

Viewing conditions

Viewing Conditions	Contents	Glasses	Positions
2DNG	2D	No	3H
2DWG	2D	Yes	3H
3D2H	3D	Yes	2H
3D3H	3D	Yes	3H
3D40	3D	Yes	3H at 40° angle
3D5H	3D	Yes	5H

The experiment with 500 women and men between the ages of 20 and 69 was conducted from January to March 2011, and the experiment with 131 women and men between the ages of 12 and 19 was conducted from July to August 2012. Each participant watched 3DTV in one viewing condition only (Between-Group Design).

Visual acuity, Critical Flicker Frequency (CFF) [7], and the Advanced Trail Making Test (ATMT) [8] were used as objective indexes of fatigue, whereas the Simulator Sickness Questionnaire (SSQ) [9] and Visual Analogue Scale (VAS) [10] were used as subjective indexes. Fatigue caused by watching 3DTV was evaluated by the differences between those indexes evaluated before and after watching 3DTV. In addition, the participants answered a questionnaire about their physical conditions after watching TV programmes on the day when the experiment was conducted and the following day for all participants, and one week later for minor participants.

4.3.2 Results

The average value of each index before and after watching 3DTV was obtained for each viewing condition. A statistical analysis was then conducted to test whether these values show significant differences between different viewing conditions.

The results of the objective indexes indicated that there was no difference between watching 3DTV and traditional TV (i.e. watching 2D content without glasses) in degree of decline of visual and cognitive functions due to fatigue.

On the other hand, the results of subjective indexes indicated that there were some differences between watching 3DTV and traditional TV in the sensation of fatigue. The statistical analysis of the adult data demonstrated that there were significant differences between 2DNG and 2DWG, 3D3H, 3D40, and 3D5H for the Oculomotor of SSQ change and significant differences between 2DNG and 2DWG, and 3D3H for cumulative VAS change, as shown in Fig. 17. Because there was no significant difference between watching 2D and 3D contents with 3D glasses (i.e. between 2DWG and the other 3D conditions), the sensation of fatigue may not be attributed to watching 3D content, but to wearing the 3D shutter glasses.

Nevertheless, the results of the minor data with the subjective indexes indicate that there was no significant difference between any pair of the viewing conditions, as shown in Fig. 17. The comparison of the Oculomotor of SSQ scores of different age groups indicate significant differences between the 12-19 age group and the 46-59 and 60-69 age groups in the 2DNG condition, and there were marginal differences between the 12-19 age group and the 60-69 age group in the 3D viewing conditions, as shown in Fig. 18. The results suggest that minors tend to feel a sense of fatigue in both 2D and 3D viewing conditions and elderly adults tend to feel less fatigued in 3D viewing conditions.

Although there was no difference in the sensation of fatigue between the different conditions when evaluated immediately after watching 3DTV, the results suggest that the sensation of fatigue may be persistent if 3DTV is watched at a distance closer than the standard viewing position (i.e. three times the screen’s height).

It should be noted that the results of the present study were obtained under conditions close to typical viewing situations at home, where the subjects simply watched 3D programmes whose binocular disparities were relatively small on commercially available 46 to 50-inch 3DTVs, and therefore these findings may not be applied to other viewing conditions and 3D content. Yano et al. [4], for instance, evaluated visual fatigue when subjects read the text of Japanese literature on a 28 inch CRT and reported that changes in depth direction can cause visual fatigue even when the amount of parallax remains within the depth of focus. Emoto et al. [2] evaluated visual fatigue when subjects counted the number of characters of Japanese translations superimposed on German opera and reported that there were differences in the P100 latency [11] of the visual evoked cortical potentials (VECP) between viewing 2D and 3D content, while the subjective evaluation revealed no difference.

FIGURE 17

Mean values of differences between subjective indexes before and after watching 3DTV for each viewing condition

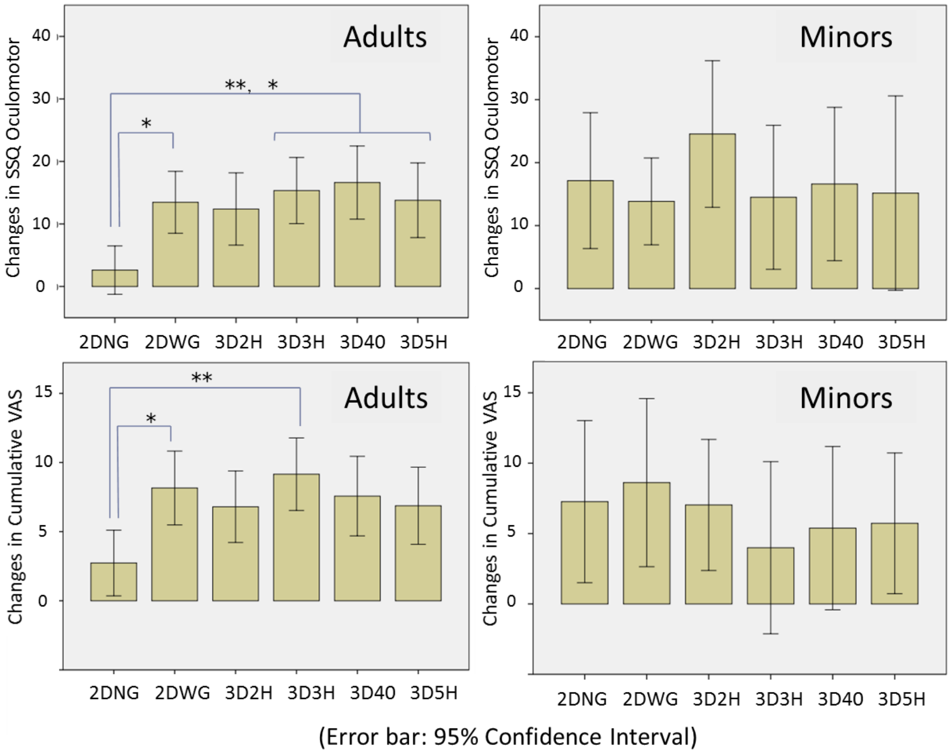
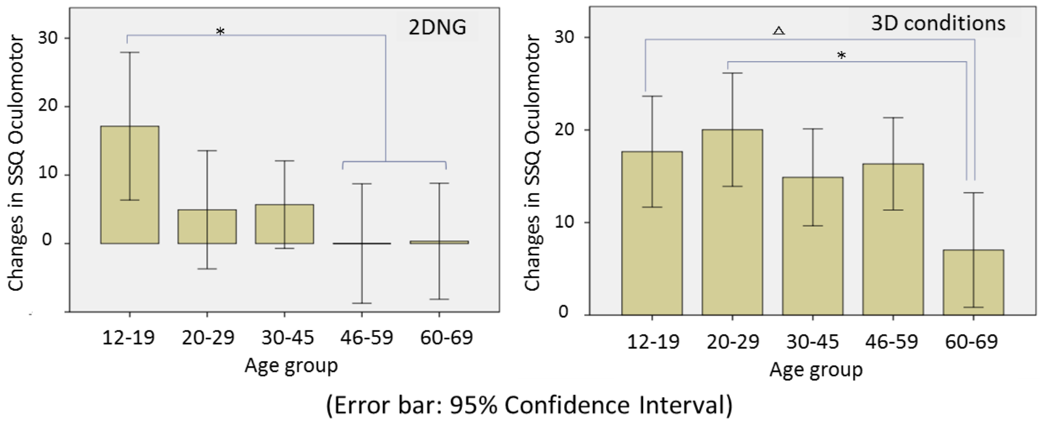


FIGURE 18

Mean values of differences between subjective indexes before and after watching 3DTV for each age group



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5 Spatial distortion prediction system for 3DTV

5.1 Introduction

Spatial distortion of reproduced stereoscopic images is determined by a combination of factors including programme production techniques, display devices, 3D glasses, viewing conditions, and viewer characteristics. It is highly desirable to predict beforehand the degree and type of spatial distortion of the reproduced stereoscopic images so that more natural and more comfortable stereoscopic images can be presented to viewers.

This document describes a spatial distortion prediction system for a 3DTV (see Ref. [1]). This system calculates the spatial distortion of a reproduced stereoscopic image and predicts the extent of the puppet-theatre and cardboard effects, excessive binocular parallax, and excessive parallax distribution on the basis of the shooting, display, and viewing conditions.

5.2 Spatial distortion in 3DTV

Conditions under which images are captured, displayed, and viewed can contribute to the introduction of spatial distortions, that is, the differences between the real and the reproduced 3D spaces. Some spatial distortions might cause unnatural effects, such as the puppet-theatre effect and the cardboard effect. The puppet-theatre effect is an undesirable miniaturization effect that makes people look like animated puppets; the cardboard effect is a stereoscopic distortion causing an unnatural depth perception, where objects appear flat as if the scene is divided into discrete depth planes. When some objects are close to the camera, the entire stereoscopic image might appear to pop out from the screen and excessive binocular parallax and excessive parallax distribution may occur. Excessive parallax might also arise for background objects, which is known to cause visual discomfort or to prevent binocular fusion.

5.3 Spatial distortion prediction system for 3DTV

5.3.1 Use cases

A system capable of predicting spatial distortion and excessive parallax would be of great benefit to the industry, helping to provide more natural and more comfortable stereoscopic images.

Because a stereoscopic image can only be viewed properly under particular viewing conditions (for most stereoscopic displays), the system can be used to select appropriate shooting parameters for a particular "standard" display/viewing environment. For a programme directed at children, the system might also be used to tailor the shooting parameters to their small interpupillary distance.

When a director intends to emphasize the reproduced depth to make objects jump out from the screen to have an impact on the viewers, the director must manage the shooting conditions to avoid spatial distortion that causes the puppet-theatre effect and excessive parallax distribution. It is particularly difficult to produce the intended stereoscopic images for large displays when shooting on location. This is because a small stereoscopic display or even a 2D display is often used to monitor the stereoscopicity at a close distance or to merely measure the horizontal disparities, resulting in the director choosing the shooting conditions more by trial and error than careful selection. The system would make it possible for the director to control the stereoscopicity accurately and easily.

In a 3DTV broadcast, a broadcaster might have control of the shooting conditions but has little control over the display and viewing conditions. On the other hand, the opposite is true for the viewer. Even so, the system might help identify suitable viewing conditions to recommend to viewers.

5.3.2 System outline

The system calculates the spatial distortion of a reproduced stereoscopic image and predicts the extent of the puppet-theatre and cardboard effects, excessive binocular parallax, and excessive parallax distribution on the basis of the shooting, display, and viewing conditions listed in Table 11. The relationship between the space to be shot (real space) and the space of the reproduced stereoscopic image (reproduced space) is calculated geometrically in terms of their depth and size. The shooting conditions and the right and left images can be obtained from a stereoscopic camera system.

TABLE 11

Parameters for shooting, display, and viewing conditions

Shooting parameters	Display parameters	Viewing parameters
Camera field of view Camera convergence distance Camera separation	Screen width Horizontal offset	Viewing distance Interpupillary distance

Figure 19 shows a ground plan of real and reproduced space grids without spatial distortion; the real space grid (shown by red dots) and the reproduced space grid (shown by blue dots and texture) coincide.

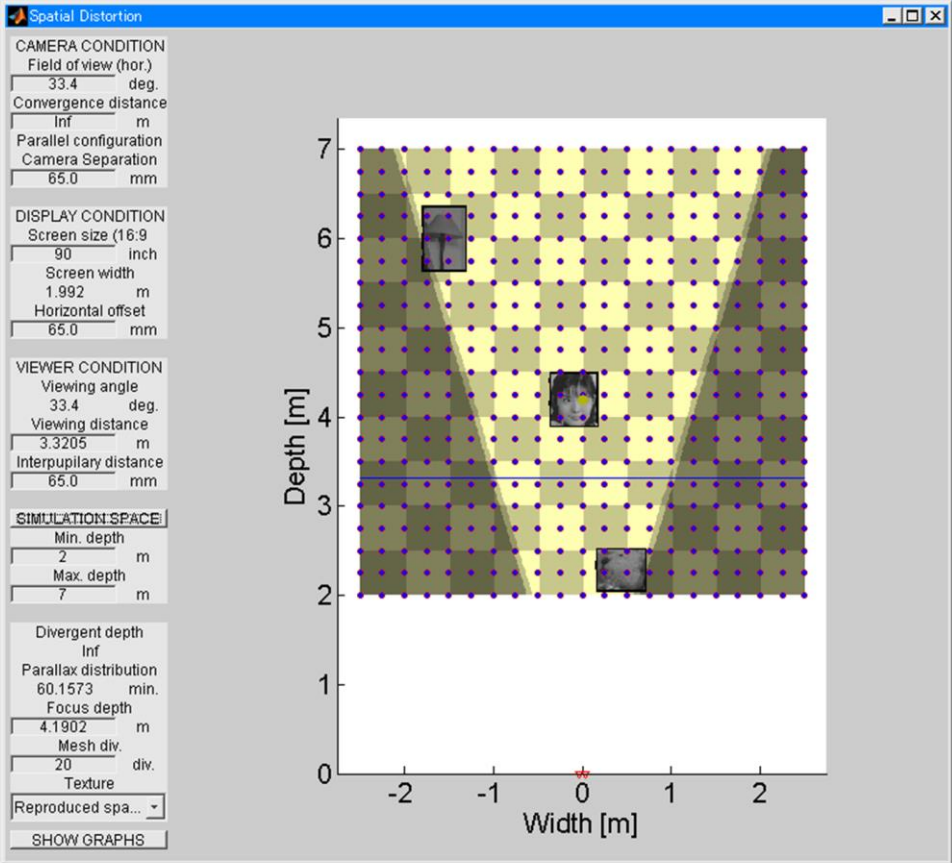
It should be noted that the real space grid is always displayed as a square. The shooting, display, and viewing conditions are shown in the left pane of the window. The camera field of view and the display-viewing angle are equalized, as are the camera separation, interpupillary distance, and horizontal offset.

The system can measure the parallaxes of up to three objects, namely the object of interest, background, and foreground. Each object's depth in real space is calculated on the basis of the measured parallax and the shooting conditions. In order to determine the depth range of the space grid for calculating the spatial distortion, the user selects two portions, one at the maximum depth (a desk lamp in this example) and another at the minimum depth (a stuffed animal).

A portion including the object of interest (a woman) should be selected to calculate the extent of the perceived puppet-theatre effect. The depth of the object of interest may be determined as the focus plane.

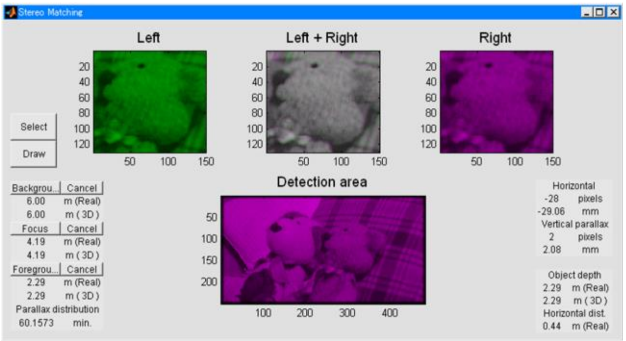
FIGURE 19

Screen shots of the spatial distortion prediction system



(a) Spatial distortion prediction window (under orthostereoscopic conditions)

(b) Captured image



(c) Object selection window

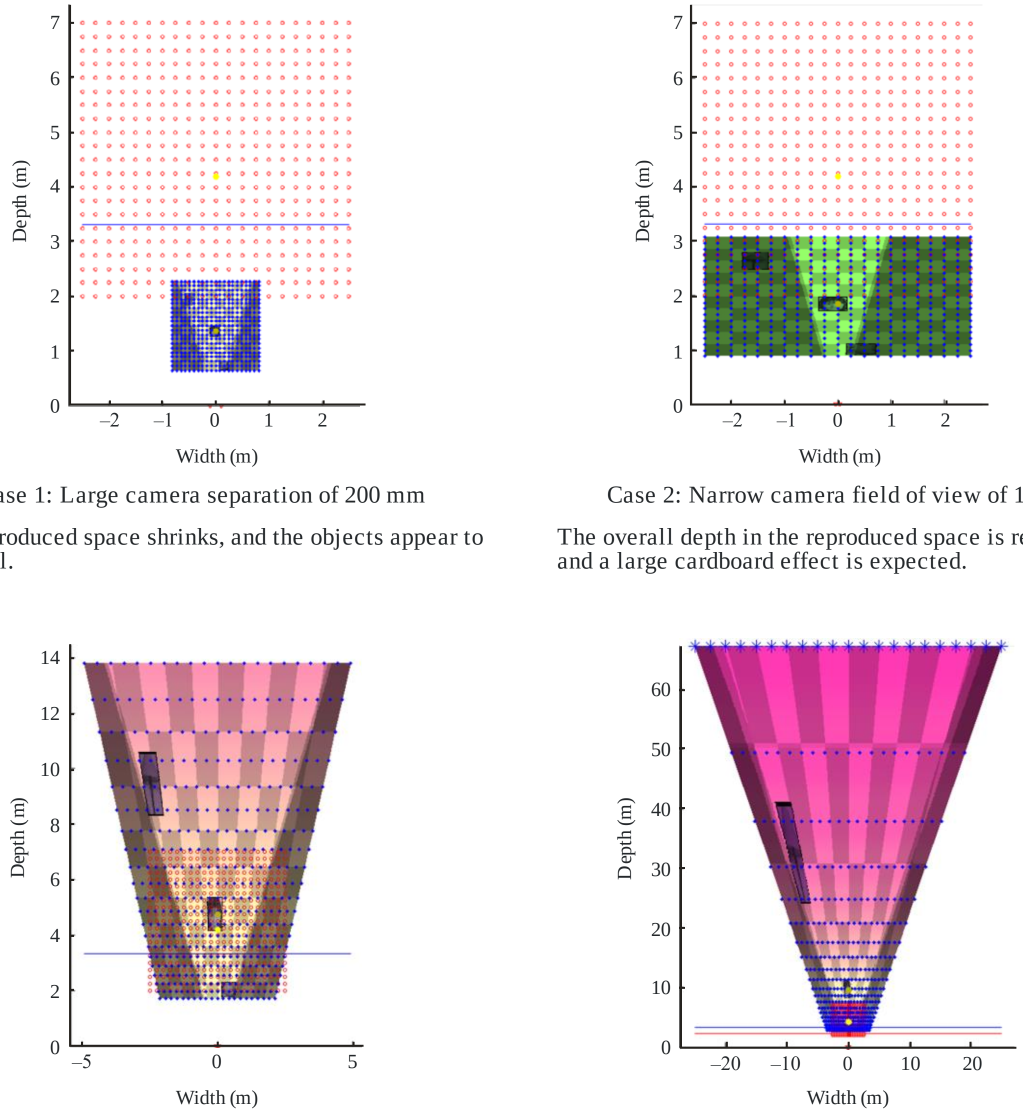
Report BT.2160-16

5.3.3 Examples of conditions and simulations

Figure 20 shows the simulation results obtained under four conditions for which some parameters were changed while other parameters remained the same as in Fig. 19. The extent of the perceived puppet-theatre and cardboard effects is expressed by changing the hue of the texture: magenta is increased in proportion to the extent of the perceived puppet-theatre effect and green is increased in proportion to the extent of the perceived cardboard effect. This system also produces an alert when excessive binocular parallax or parallax distribution is predicted.

FIGURE 20

Simulation results



Case 1: Large camera separation of 200 mm

The reproduced space shrinks, and the objects appear to be small.

Case 2: Narrow camera field of view of 15º

The overall depth in the reproduced space is reduced, and a large cardboard effect is expected.

Case 3: Short interpupillary distance of 45 mm

A slight puppet-theatre effect is expected, and the object of interest (woman) appears small.

Case 4: Short convergence distance of 2.3 m

The puppet-theatre effect is expected. Objects at a depth of approximately 7.5 m are reproduced at infinity.

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NOTE – Magenta colour is increased in proportion to the extent of the perceived puppet-theatre effect. Green colour is increased in proportion to the extent of the perceived cardboard effect.

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Annex 5

Results of subjective visual comfort assessment for motion and disparity magnitude of 3D content – Korea (Republic of)

1 Summary and proposals

This annex presents the results of visual discomfort induced by motion characteristics and depth magnitude in stereoscopic 3D content. Based on subjective measurements, the following aspects have been observed:

– fast spatial and temporal changes of disparity in stereoscopic 3D content should be avoided. The fast change of binocular disparity may induce visual discomfort accompanied by symptoms such as focusing difficulty and eyestrain;

– to prevent visual discomfort, excessive disparity of stereoscopic 3D content should be avoided. Excessive binocular disparity may induce visual discomfort accompanied by symptoms such as focusing difficulty and eye strain.

These observations should be referred when developing viewing safety guidelines of stereoscopic 3D systems.

2 Experimental environments

The apparatus used for the experiments was a half mirror type stereoscopic 3D monitor (Redrover SDM-400®, linear polarized 3D display). It consisted of two 40-inch LCD displays with a refresh rate of 60 Hz and a half mirror. The spatial resolution of the monitor was set to 1 920 × 1 080 pixels. The crosstalk levels of the stereoscopic 3D monitor were 0.75% and 0.27% for the left and right eye, respectively, which were lower values than the visibility threshold [1], [2]. The viewing distance between the subject and the 3D display was fixed to three times the picture height (i.e. 1.5 metres). All experimental environments followed Recommendations ITU-R BT.500-11 [3] and ITU-R BT.1438 [4].

Table 12 is a summary of the experimental environment.

FIGURE 21

Stereoscopic 3D monitor used in our subjective assessments

TABLE 12

Experimental conditions

Room illumination	3.45 lux
Ratio of luminance of inactive screen to peak luminance	0.003
Brightness	500 cd/m^2 (112 lux)
Height of display (H)	498 mm
Viewing distance	1 500 mm

3 Subjective measurement of visual discomfort induced by motion characteristics

This section presents subjective assessment results for the amount of visual discomfort induced by planar motion and in-depth motion characteristics [5]:

1) velocity of horizontal motion: the average change in the horizontal visual angle and apparent depth for the planar motion;

2) velocity of vertical motion: the average change in the vertical visual angle and apparent depth for the planar motion; and

3) velocity of in-depth motion: the average change in the angular disparity.

3.1 Visual stimulus

A set of visual stimuli was generated with various velocities and directions of object motion using a computer graphics tool.

As shown in Fig. 22, these visual stimuli consisted of a grey meteor object (chromaticity: D65, illumination: 25 cd/m^2), a background region (chromaticity: D65, illumination: 50 cd/m^2), and a guide for a zero parallax position [6], [7].

As shown in Table 13, a total of 49 visual stimuli were generated (21 stimuli for horizontal motion, 21 stimuli for vertical motion, and 7 stimuli for depth motion). 42 visual stimuli had horizontal and vertical motions at seven different velocities, moving at 1°crossed disparity, zero disparity, and 1°uncrossed disparity, respectively. 7 visual stimuli had depth motion at seven different velocities.

The meteor object with in-depth motion periodically moved back and forth between 1° crossed disparity and 1° uncrossed disparity (the starting point of movement for the meteor object was 1° uncrossed disparity). The size of the meteor object was 2° except for the case of depth motion [7], when the size of the object changed continuously while the object moved back-and-forth in the depth direction. The size of the object was set to 2° when the object arrived at the screen position. Figure 22 shows some examples of the visual stimulus.

The visual stimulus with horizontal and vertical motions contained a pair of high contrast coloured bars and the visual stimulus with depth motion contained a high contrast coloured ring. The bars and ring were at the zero disparity so as to provide a depth plane of reference for viewers.

TABLE 13

Attributes of visual stimulus used in the experiments

Motion direction	**Depth position**	**Motion velocity in degree/s+**
Horizontal motion	1°crossed disparity	2 (=37 mm/s), 4 (=75 mm/s), 6 (=112 mm/s), 8 (=150 mm/s), 12 (=225 mm/s), 16 (=300 mm/s), 32 (=613 mm/s)
	zero disparity	2 (=52 mm/s), 4 (=105 mm/s), 6 (=157 mm/s), 8 (=210 mm/s), 12 (=315 mm/s), 16 (=422 mm/s), 32 (=860 mm/s)
	1°uncrossed disparity	2 (=88 mm/s), 4 (=175 mm/s), 6 (=263 mm/s), 8 (=351 mm/s), 12 (=528 mm/s), 16 (=706 mm/s), 32 (=1 441 mm/s)
Vertical motion	1°crossed disparity	1 (=17 mm/s), 2 (=37 mm/s), 4 (=75 mm/s), 6 (=112 mm/s), 8 (=150 mm/s), 12 (=225 mm/s), 16 (=300 mm/s)
	zero disparity	1 (=26 mm/s), 2 (=52 mm/s), 4 (=105 mm/s), 6 (=157 mm/s), 8 (=210 mm/s), 12 (=315 mm/s), 16 (=422 mm/s)
	1°uncrossed disparity	1 (=44 mm/s), 2 (=88 mm/s), 4 (=175 mm/s), 6 (=263 mm/s), 8 (=351 mm/s), 12 (=528 mm/s), 16 (=706 mm/s)
Depth motion	Between 1° crossed disparity and 1° uncrossed disparity	0.42 (=320 mm/s), 0.85 (=640 mm/s), 1.29 (=960 mm/s), 1.75 (=1 280 mm/s), 2.8 (=1 920 mm/s), 3.53 (=2 560 mm/s), 7.17 (=5 120 mm/s)

FIGURE 22

Examples of visual stimulus

(a) (b) (c)

(a) Horizontal motion at 1° crossed disparity

(b) Vertical motion at 1° crossed disparity and

(c) Depth motion. For depth motion, the meteor object periodically moves back and forth between 1° crossed disparity and 1° uncrossed disparity.

3.2 Subjective assessment method of visual comfort

A total number of 49 visual stimuli were randomly presented to each subject. The display duration of each visual stimulus was 10 seconds and the resting time followed for 15 seconds using a mid-grey image. During the resting time, subjects assessed the overall level of visual comfort for each visual stimulus.

A total of 40 subjects, aged between 20 and 37, participated in the subjective assessment. The subjects were recruited under approval of the KAIST IRB (Institutional Review Board). All subjects had normal or corrected vision and a minimum stereopsis of 60 arcsec (as measured in a stereo fly test).

In order to grade the degree of visual comfort, the adjectival categorical judgment method of single stimulus (SS) was used with five-grade scale as shown in Fig. 23(a)

5: very comfortable,

4: comfortable,

3: mildly uncomfortable,

2: uncomfortable,

1: extremely uncomfortable [3]0.

The subjective assessment methods were not standardized when assessing the visual discomfort of the stereoscopic content. As mentioned in Recommendation ITU-R BT.1438 [4], evaluation methods for the assessment of particular factors of stereoscopic television systems require further study. In many studies, meanwhile, the subjective test methods described in Recommendation ITU-R BT.500 have been applied with slight modifications [7]-[13].

When a reference image is available, the double-stimulus impairment scale (DSIS) or double-stimulus continuous quality-scale (DSCQS) methods can be used. When no reference is available, single-stimulus (SS) methods or the single stimulus continuous quality evaluation (SSCQE) method can be used. These methods were also mentioned in Recommendation ITU-R BT.1438, which specifically mentions the evaluation of stereoscopic content [4].

In this experiment, a modified version of the SS methods using a five-point category rating scale was used. In the SS methods, a sequence of images is presented and the assessor provides an index of the entire presentation [3]. Hence, in some studies, SS methods have been used for assessing the visual discomfort of individual short video sequences (e.g. 10 seconds) without any reference sequence [7] and even of long video sequences (e.g. 15 minutes) [14]. This was the case for our experiment.

In general, three types of SS methods have been used in television assessments: the adjectival categorical judgment method, the numerical categorical judgment method, and the non-categorical judgment method [3]0. As mentioned in Recommendation ITU-R BT.500-11 [3], categorical scales have most often used the ITU-R five-grade scales.

5: Imperceptible

4: Perceptible, but not annoying

3: Slightly annoying

2: Annoying

1: Very annoying.

Because the categories may reflect whether or not an attribute is detected (e.g. to establish the impairment threshold).

For this reason, the categorical scales in the SS methods adapted from the ITU-R impairment scale [3] were applied. The semantic terms of categories (i.e. very comfortable, comfortable, mildly comfortable, uncomfortable, and extremely uncomfortable) were the same as in [7].

The term of "very comfortable" indicates that visual discomfort is imperceptible. The term of "comfortable" indicates that visual discomfort is perceptible but not annoying. On top of this method, an additional questionnaire was used in order to investigate physical symptoms accompanied by the perceived visual discomfort. The two score sheets used in our assessment are illustrated in Fig. 23.

The questionnaire consisted of five terms: eye strain, general discomfort, nausea, focusing difficulty, and headache [15]. A description of each term is as follows:

– eye strain: bleary, dry eyed, eyestrain, gritty, eye ache, sting, eyes heavy, hazy, warm eyes, flickering and watery eyes;

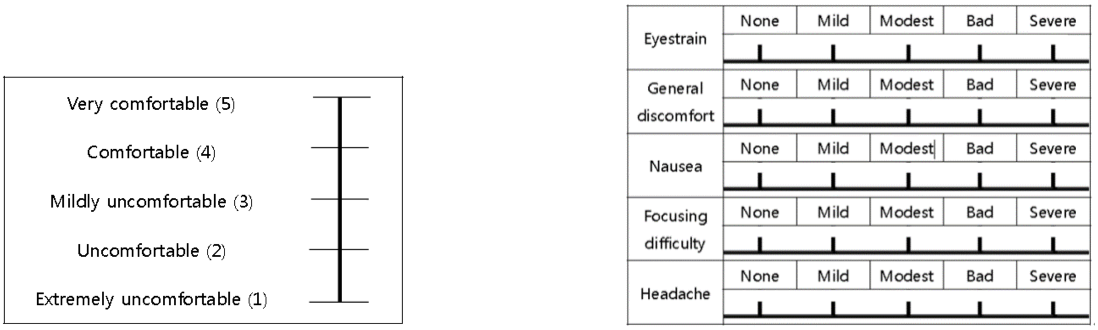
– general discomfort: feeling heavy in the head, difficulty in concentration, dizzy, stiff shoulder and stiff neck;

– nausea: vomiting, vertigo and nausea;

– focusing difficulty: difficulty in focusing, double vision, near vision difficulty and far vision difficulty;
– headache: pain in the temple and pain in the middle of the forehead.

FIGURE 23

The two score sheets used for subjective visual comfort assessment



(a) (b)

(a) Categorical scales that assess the overall level of visual discomfort.
(b) Questionnaire that assesses the symptoms of visual discomfort.

3.3 Experimental results and discussion

This section presents the results of the subjective visual comfort assessment for horizontal, vertical, and depth motions, respectively. For the analysis of the experimental results, the comfort score of 4 was assumed as a threshold of visual discomfort. It implies that one is likely to feel a visual comfort below the threshold. Figures 24, 26 and 28 show the results of the subjective assessment for horizontal, vertical, and depth motions, respectively and Figs 25, 27 and 29 show the results of the accompanying questionnaires.

The psychometric functions shown in Figs 24, 26 and 28 were obtained using the mean of the median rating scores to remove the outliers [16]. Namely, 50% of the median rating scores were used for the psychometric functions. 25% of the upper rating scores and 25% of the lower rating scores were removed as outliers [16]. As shown in the Figures, the visual comfort score decreased as the movement velocity increased.

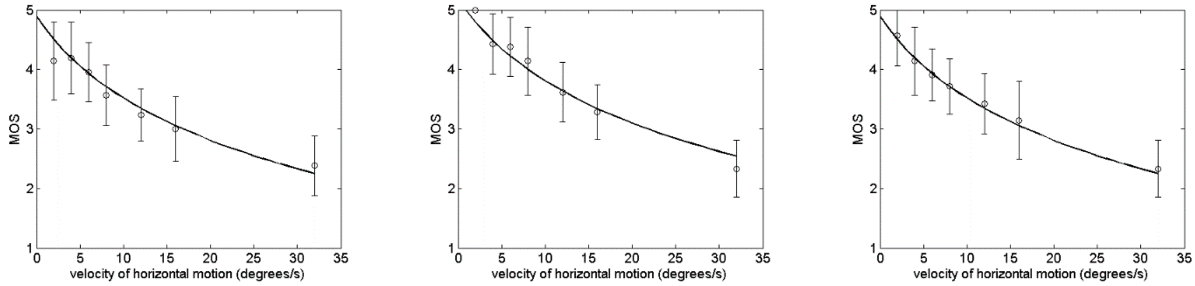
From these observations, we constructed visual comfort models by fitting the appropriate psychometric functions. Consequently, we obtained the fits to three log models in terms of movement velocity for each directional motion. The log models were derived in agreement with Fechner’s log law [17], [18].

Figure 24 shows the experimental results of horizontal motion. In the Figure, the y-axis represents the mean opinion score (MOS) of the perceived visual comfort and the x-axis denotes the velocity of the horizontal motion. The results show that an increase in the velocity of horizontal motion induced more visual discomfort. Figure 25 represents the results of the questionnaire. In the Figure, they-axis represents the severity of the symptoms of visual discomfort (5: none, 1: severe).

The x-axis of Fig. 25 represents the velocity of depth motion. The questionnaire reveals that the subjects experienced focusing difficulties. This phenomenon was caused by motion blur and motion judder.

FIGURE 24

Visual comfort models for horizontal motion, which represent the relationship between visual comfort and motion velocity. The models were obtained by fitting the results of subjective assessment



(a) (b) (c)

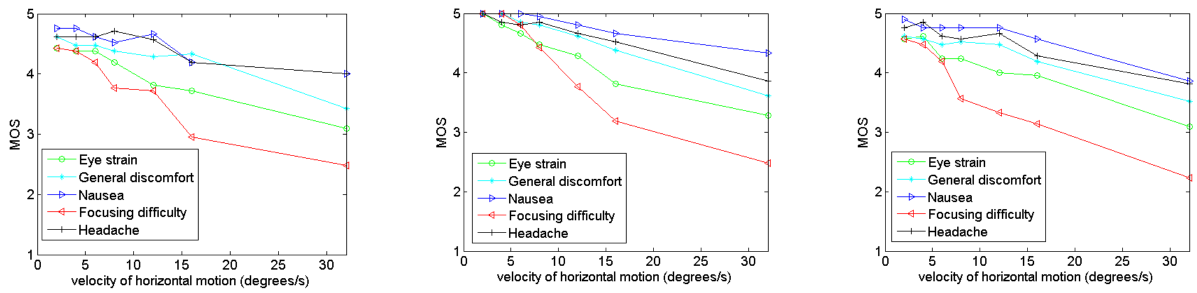
(a) 1° crossed disparity

(b) Zero disparity and

(c) 1° uncrossed disparity. Error bars represent standard deviations of median rating scores.

FIGURE 25

The degree of the symptoms of visual discomfort for horizontal motion



(a) (b) (c)

(a) 1° crossed disparity

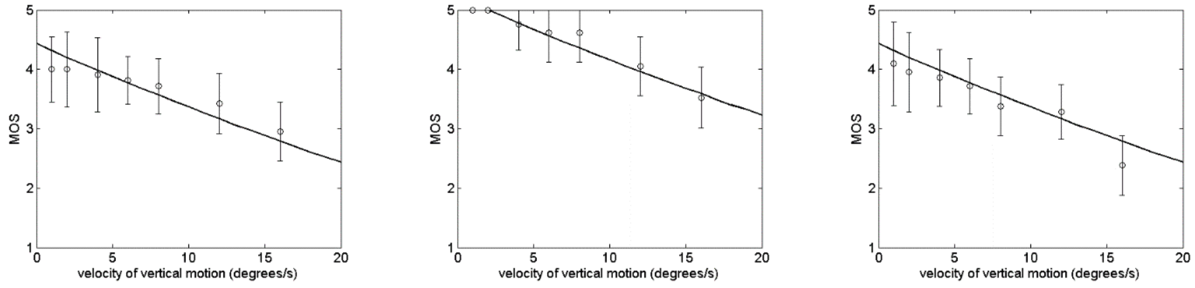
(b) Zero disparity and

(c) 1° uncrossed disparity.

Figure 26 shows the experimental results of vertical motion. As in horizontal motion, more visual discomfort was induced as the velocity of vertical motion increased. Figure 27 represents the results of the questionnaire, which show that the subjects experienced focusing difficulties. This phenomenon was caused by motion blur and motion judder.

FIGURE 26

Visual comfort models for vertical motion, which represent the relationship between visual comfort and motion velocity. The models were obtained by fitting the results of subjective assessment

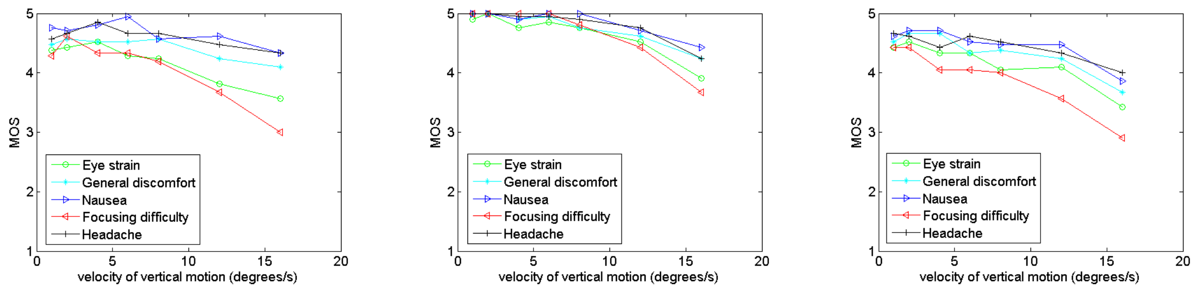


(a) (b) (c)

(a) 1° crossed disparity;
(b) zero disparity; and
(c) 1° uncrossed disparity.

FIGURE 27

The degree of the symptoms of visual discomfort for vertical motion



(a) (b) (c)

(a) 1° crossed disparity;
(b) zero disparity; and
(c) 1° uncrossed disparity.

FIGURE 28

Visual comfort model for depth motion, which represents the relationship between visual comfort and motion velocity. The model was obtained by subjective assessment

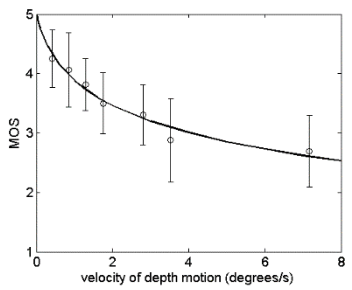
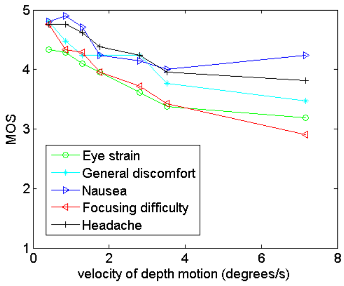


Figure 28 shows the experimental results of in-depth motion. Similar to the previous results, an increase in the velocity of in-depth motion induced more visual discomfort. Furthermore, the results of the questionnaire presented in Fig. 29 reveal that the levels of eyestrain and focusing difficulty also decreased as the velocity of in-depth motion increased.

This experimental result can be interpreted as follows: The faster the velocity of depth motion, the faster the amount of conflict between accommodation and convergence was induced. Thus, the load of the oculomotor system increased to control this fast change. Hence, as previously mentioned in [8], an increasing load of the oculomotor system may decrease the level of visual comfort.

FIGURE 29

The degree of the symptoms of visual discomfort for depth motion



4 Subjective measurement of visual discomfort induced by depth characteristics

This experiment assesses the visual discomfort induced by depth magnitude [19]. Psychophysical experiments have been conducted to investigate the relationship between subjective visual comfort and the amount of binocular disparity.

4.1 Visual stimulus

Figure 30 shows an example of the visual stimulus used in this experiment. The visual stimulus consists of two overlapping squares, *i.e.* foreground and surrounding squares, and background.

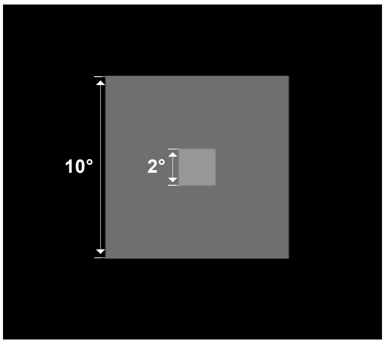
The luminance values of the foreground square and the surrounding square were respectively set to 50 cd/m^2 and 25 cd/m^2 (CIE daylight D65) with afield size of 2º and 10º visual angles.

To avoid the visual effect of the background, the luminance value of the background region was set to 0 cd/m^2. The size of the visual field for the foreground square and the surrounding square were determined to cover the size of the fovea and the parafovea respectively. Binocular disparity was only given to the foreground square in the range of +3.7º to –3.7º with a step size of 0.6º, where positive polarity refers to crossed disparity while negative polarity refers to uncrossed disparity.

The range of binocular disparity has been determined in order for a visual comfort model to cover the entire possible range of binocular fusion in real stereoscopic images. The other regions were at zero disparity. Hence, a total number of 13 visual stimuli were randomly presented to human observers.

FIGURE 30

Visual stimulus used for subjective assessment of the visual discomfort induced by depth characteristics



4.2 Subjective visual comfort assessment method

A total number of 13 visual stimuli were randomly presented to each subject. The display duration of each visual stimulus was 10 seconds and the resting time followed for 10 seconds using a mid-grey image. During the resting time, subjects assessed the overall level of visual comfort for each visual stimulus. A total of 18 subjects, aged between 20 and 37, participated in this subjective assessment. The subjects were recruited under approval of the KAIST IRB. All subjects had normal or corrected vision and a minimum stereopsis of 60 arcsec (as measured in a stereo fly test).

In order to grade visual comfort, the adjectival categorical judgment method of single stimulus (SS) was used with five-grade scale

5: Very comfortable

4: Comfortable

3: Mildly uncomfortable

2: Uncomfortable

1: Extremely uncomfortable [3].

Further, an additional questionnaire was given to participants, consisting of five representative terms that describe physiological symptoms of visual discomfort: eye strain, general discomfort, nausea, focusing difficulty, and headache [15].

Five-grade scale was used for each questionnaire (5: none, 4: mild, 3: modest, 2: bad, 1: severe). For more details of the subjective assessment methods, refer to § 2.2.

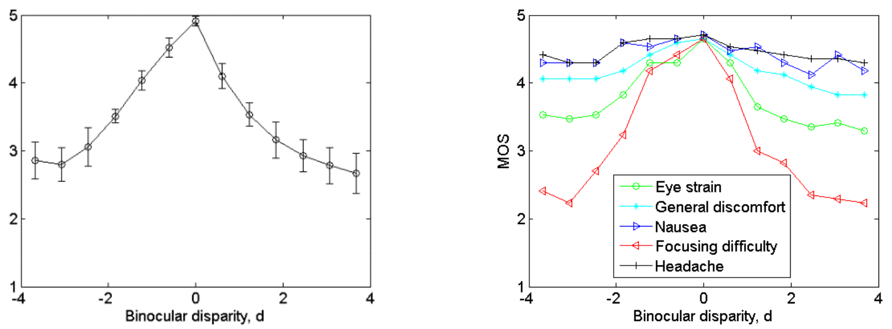
4.3 Experimental results and discussion

Figure 31(a) shows the degree of visual comfort with diverse amount of binocular disparities. In Fig. 31, the x-axis indicates binocular disparity while the y-axis indicates a MOS. As shown in the Figure, human observers reported a higher degree of visual discomfort as the binocular disparity increased. An increase in binocular disparity imposes a higher operating load for the human oculomotor system, which may induce physiological symptoms of visual discomfort [8].

Figure 31(b) represents the degree to which each symptom was obtained from the questionnaire according to the amount of binocular disparity. From these results, it can be observed that as binocular disparity increases, the overall symptoms of visual discomfort (such as focusing difficulty and eye strain) become more severe.

FIGURE 31

Visual discomfort induced by binocular disparities



(a) (b)

(a) MOS of visual comfort

(b) The degree of each symptom of visual discomfort.

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Annex 6

The influence of stereopsis and abnormal binocular vision on ocular and systemic discomfort while watching 3D television – Korea (Republic of)

1 Summary and proposals

In preliminary experiments, it was observed:

– Subjects with abnormal binocular vision such as strabismus, amblyopia, and anisometropia showed decreased 3D perception.

– Ocular and systemic discomforts (3D fatigue) were more related to a higher degree of stereopsis.

– Those with abnormal binocular vision are more susceptible to 3D fatigue if they have a normal degree of stereopsis.

– If a person cannot perceive 3D, or feels severe 3D fatigue while watching 3D content, he or she should consult ophthalmologic specialists for evaluation of abnormal binocular vision.

These observations should be referred to when developing viewing safety guidelines of stereoscopic 3D systems.

2 Abstract

Perception of a three-dimensional (3D) image involves a fusional mechanism. With normal binocular vision, one can perceive 3D images with motor and sensory fusion. People with abnormal binocular vision, including strabismus, amblyopia, and anisometropia, may have a variable range of fusional ability. Some people cannot use a fusional mechanism at all, and others can only use a fusional mechanism to a normal degree with an additive effort to obtain it.

This kind of additive effort can increase fatigue while watching 3D images (which is known as 3D fatigue). In addition, the degree of abnormal binocular vision, which can be measured with a

stereopsis test, can affect the degree of 3D perception. Yet, the degrees of 3D perception and 3D fatigue in abnormal binocularity have not been evaluated in comparison with normal binocularity.

The purpose of this study is to evaluate the degree of 3D perception and ocular and systemic discomfort in people with abnormal binocular vision, including strabismus, amblyopia, and anisometropia, and their relationship to stereoacuity while watching a 3D television.

3 Participants and methods

Children 9 years of age or older, who had at least one abnormal binocular condition, including strabismus, anisometropia, and amblyopia, were recruited for the abnormal binocular vision (ABV) group.

Subjects without those abnormal conditions were included in the control group. Anisometropia was defined as when the difference of the spherical equivalent (SEQ) in refractive errors between both eyes was more than 2 diopters. Amblyopia was diagnosed as when the best-corrected visual acuity was less than 0.8, or when the difference between both eyes was more than two lines of Snellen acuity. The ABV group was divided into three subgroups according to the etiology of their ABV. When a person was strabismic or had anisometropic amblyopia, he or she was included in the amblyopia subgroup for analysis. Informed consent was obtained from all of the volunteers. Volunteers with a history of other ophthalmologic diseases, including glaucoma and retinal disease, and with systemic diseases, such as cerebral palsy and delayed maturation, were excluded.

The best-corrected visual acuity and refractive errors were measured. The angle of ocular deviation was obtained with the alternate prism-cover test. Stereoacuity was examined with the Stereo Fly test (Stereo Optical Co., Chicago, IL, USA) for near stereopsis and with the Frisby-Davis distance stereotest (FD2; Stereotest, Sheffield, UK) for distant stereopsis. The fundus was also checked with a fundus camera.

The 3D video, which was produced by the national broadcasting system of South Korea, was shown for 20 minutes on a 55-inch 3D high-definition television. The room was illuminated to 5 lux. The viewing distance was 2.8 metres. The volunteers watched 3DTV with shutter glasses or Polaroid glasses according to the type of 3DTV.

After watching 3DTV, a survey was performed to evaluate the degree of 3D perception and the subjective symptoms of ocular and systemic discomfort (Table 14). The questionnaire was comprised of 13 items, which included the degree of 3D perception and frequently reported ocular and non-ocular symptoms after watching 3DTV. Each item was answered according to a six-category scale (0-5). A value of 0 corresponded to no impact and a value of 5 corresponded to an impact too severe to watch 3DTV. The degree of 3D perception and subjective ocular and systemic discomforts were compared between the two groups.

The stereoacuity results were grouped as either "normal" (≤ 60 arcsec), "moderate" (> 60 and ≤ 800 arcsec), or "poor" (> 800 arcsec to nil) stereopsis according to the amount of stereoacuity. The degree of 3D perception and the number of ocular and systemic symptoms were compared among the stereoacuity groups. Those things were also compared between the subjects who showed normal stereopsis in the ABV group and in the control group.

For statistical analysis, Kruskal-Wallis and Mann-Whitney U tests were used with SPSS 12.0K for Windows. For multiple testing problems, P values were adjusted with Bonferroni correction. To compare the distribution of the subjects in the near stereoacuity case, a chi-square test was used.

4 Results

One hundred and thirty subjects were enrolled in this study, with 98 in the ABV group and 32 in the control group. The mean age of the subjects was 13.0 ± 4.87 years. Seventy-five (57.7%) subjects were female. The ABV group included 49 people with strabismus, 22 with amblyopia, and 27 with anisometropia. In strabismic people, 34 had exodeviation, 11 had esodeviation, and 4 had hyperdeviation. The mean deviation angles (prism diopters) among those people were 11.6 ± 6.74, 7.7 ± 14.72, and 5.5 ± 5.74, respectively. In amblyopic people, the mean visual acuity of the worse eye was 0.58 ± 0.27. In anisometropic people, the mean difference of the SEQ between the two eyes was 2.71 ± 1.58.

The mean stereoacuity at a distance was 14.06 ± 9.79 arcsec in the control group and 34.85 ± 16.32 arcsec in the ABV group ($P < 0.001$). There were no subjects with poor distant stereopsis measured with FD2. For near stereoacuity, all subjects in the control group showed normal stereopsis, and 53 people of the ABV group had normal, 33 had moderate, and the other 12 had poor near stereopsis. Thus, there was a significant difference in the distribution of near stereoacuity between the two groups ($P < 0.001$). In the ABV group, the mean distant stereopsis was 31.02 ± 16.99 in the strabismus subgroup, 45.00 ± 11.95 in the amblyopia subgroup, and 33.52 ± 15.12 in the anisometropia subgroup ($P < 0.001$).

The distant stereoacuity of the amblyopia subgroup was poorer than that in the strabismus ($P = 0.006$) and anisometropia subgroups ($P = 0.012$). There was no difference between the strabismus and anisometropia subgroups ($P = 0.556$). The distribution of near stereoacuity was not significantly different among the subgroups of the ABV group ($P = 0.126$). In the strabismus subgroup, the exotropic group showed better stereoacuity at near and distant fixation than the esotropic group ($P < 0.001$).

The results of the survey showed that the ocular and systemic discomforts were not different between the ABV and control group. The ABV group showed decreased 3D perception ($P = 0.007$).

Subgroup analysis revealed that there was no difference among subjects with strabismus or anisometropia and the control group. Subjects with amblyopia showed more decreased 3D perception than the others ($P < 0.05$). Among the subjects with strabismus, exotropic people reported more discomfort than esotropic people ($P < 0.05$).

The ocular and systemic discomforts were compared according to the amount of stereoacuity. The subjects with good stereopsis (as measured with a Titmus stereofly test) reported more dizziness, headaches, eye fatigue, and pain ($P < 0.05$) than the other subjects with decreased stereopsis (> 60 arcsec). The subjects with decreased stereopsis showed more difficulty in 3D perception ($P < 0.001$).

There was no difference in the amount of ocular and systemic discomfort between the subjects with moderate stereopsis and with poor stereopsis. Subjects with poor stereoacuity showed more difficulty in 3D perception than those with moderate stereoacuity.

Among subjects with good stereopsis, those in the ABV group felt more eye fatigue than those in the control group ($P = 0.031$); those subjects also experienced more headaches than those in the control group to a marginally significant degree ($P = 0.076$).

5 Discussion

Generally, a subject with ABV may have difficulty perceiving 3D images. For sensory fusion to occur, the images located on the corresponding retina must be similar in size, colour, and sharpness. Unequal observed images are a severe sensory obstacle to fusion.

If a person has anisometropia or amblyopia, the quality of observed images can be unequal, and this might disturb sensory fusion. A person with strabismus can have problems in both sensory and motor fusion. Those problems decrease stereopsis, which can be measured with a stereoacuity test. The decrease of stereoacuity can vary according to the degree of binocular abnormality and fusional ability. A person with binocular abnormality can show normal stereoacuity if his or her fusional amplitude is large enough to overcome the abnormality. However, it is possible that maintaining fusion can induce more fatigue and discomfort despite the presence of ABV.

In this study, there was no difference in the amount of ocular and systemic discomfort between the ABV and control groups. The presence of abnormality in binocular vision itself did not play an important role in symptoms after watching 3DTV. However, the ABV group showed variable degrees of stereopsis. 45 subjects of the ABV group showed moderate to poor near stereoacuity, but the other 53 in the ABV group showed normal near stereoacuity. When ocular and systemic discomfort according to the amount of stereoacuity was evaluated, subjects with normal stereopsis experienced more discomfort than those with moderate to poor stereopsis, although they perceived stereoscopic images better. We believe that the subjects with moderate to poor stereopsis had difficulty in fusion while watching 3DTV. That might have made the 3D images indistinguishable from the 2D images for them, and they did not experience more ocular and systemic symptoms.

Among the subjects with normal stereopsis in both groups, the subjects of the ABV group experienced more ocular fatigue than those of the control group. They had more headaches with marginal significance. We think that those subjects should make additional efforts, such as fusional vergence and accommodation, to maintain fusion while watching 3DTV.

Fusional vergence is needed to perceive two images with horizontal disparity as one stereoscopic image when watching a 3DTV. Accommodation is accompanied by vergence of eye movement, which is unnecessary, because the distance between the eyes and the 3D display screen does not change. This vergence-accommodation conflict was reported as an important factor in so-called 3D fatigue.

If a subject used more vergence while watching 3D images, they experienced more fatigue than the others. Emoto *et al.* reported that fusional amplitude showed a greater decrease in stereoscopic viewing than in viewing conventional TV. Although some with strabismus, anisometropia, or amblyopia showed normal stereoacuity, we believe they might have experienced more ocular and systemic discomfort while watching 3DTV.

In conclusion, ocular and systemic discomforts were more related to better stereopsis, although subjects with ABV showed decreased 3D perception. Subjects with binocular visual abnormalities such as strabismus, amblyopia, and anisometropia, are more susceptible to ocular and systemic discomfort if they have good stereopsis. Therefore, we recommend that if people have asthenopic symptoms or do not experience depth perception while watching 3DTV, they need to get their eyes aligned and checked for stereopsis.

TABLE 14

Questionnaire

	0	1	2	3	4	5
Dizzy						
Headache						
Nausea						
Eye fatigue						
Eye pain						
Tearing						
Eye dryness						
Blurred vision						
Difficulty in focusing						
Double vision						
Transient visual dimness after watching TV						
Couldn't feel stereoscopic vision						
Difficulty in eye tracking the motion on TV						

0: never experienced 3: severe impact
1: mild impact 4: very severe impact
2: moderate impact 5: too severe of an impact to watch 3DTV

Annex 7

The influences of Parkinson’s diseases on dynamic 3D perception and fatigue while watching 3D television – Korea (Republic of)

1 Introduction and study results

Stereopsis is an awareness of the distances of objects from an observer. Binocular vision is necessary to perceive stereopsis. Therefore, stereopsis is often used to refer to binocular depth perception. For this to occur, many components of stereopsis such as retina disparity, eye movement, primary perception of brain and functions of image processing are necessary.

People with Parkinson’s disease (PD) often experience the degeneration of dopamine-generating cells in the brain, have retina problems, eyeball movement problems and visual perception problems. Dopamine is a chemical messenger for light adaptation, and it controls the flow of information through cone circuits and rod circuits in the retina. A loss of dopaminergic neuronal cells, as found in the inner nuclear and inner plexiform layers of the human retina, has been found in those with PD. In terms of eye movement, convergence amplitudes are significantly poorer in PD group than in control subjects. In the brain, the amount of visual attention, as well as the type of visual and spatial perception, decreases in those with PD.

These impairments can lead to poorer cognitive functioning. For these reasons, we assumed that retinal problems, eye movement, and the brain cognitive functions of people with PD can affect the level of stereopsis. As such, we have developed a method to easily evaluate the degree of stereopsis (especially dynamic stereopsis) that can be observed when people with DP are watching 3-dimensional television (3D V).

PD patients are known to perceive visual stimuli poorly and some researchers have reported that they experience a lower stereopsis function than normal control subjects when taking the Titmus fly test. Because of these problems, we analysed stereopsis and fatigue of people with PD, who have intact stereoacuity, while they were watching 3DTV. Forty-eight subjects with PD and thirty-two age-matched controls were enrolled. Before watching 3DTV, we examined visual acuity, the angle of strabismus, and refractive errors, and we performed the static stereopsis test (Titmus fly test) and the cognitive function test. We used a 17-minute 3D movie, and conducted a questionnaire to measure subjective dynamic 3D perception and 3D fatigue while watching 3DTV.

In this study, subjective dynamic 3D perception was not considered distinct from the PD patients to the control subjects, generally. However, in a subgroup analysis of those with PD, the severity of the disease correlated to subjective dynamic stereopsis in the PD patients. In terms of safety, 3D fatigue is not distinct from the control subjects to the PD patients. Therefore, most people with PD can experience 3D effects without experiencing 3D fatigue. However, the severity of PD can affect dynamic 3D perception even though viewers may have intact stereoacuity. For more information about these experiments, please see Attachment to Annex 7.

2 Summary and proposals

In preliminary experiments, it was observed:

- Those with Parkinson's disease (PD) can sufficiently experience 3D effects.
- However, the severity of PD can affect dynamic 3D perception.
- In terms of safety, watching 3DTV is not harmful for people with PD if they comply with the "3D video safety guidelines".

These observations should be considered when developing viewing safety guidelines for stereoscopic 3D systems.

Attachment

Subjects and methods

Subjects were recruited with Parkinson's disease (PD) and also as age-matched normal control subjects. All subjects showed stereoacuity levels of under 800 arcsec. Informed consent was obtained from all of the patients and control subjects.

The levels of visual acuity and number of refractive errors were measured. The angle of ocular deviation was obtained by using the alternate prism-cover test. Stereoacuity was examined with the Stereo Fly test (Stereo Optical Co., Chicago, IL, USA) for near stereopsis.

The 3D video, which was produced by the national broadcasting system of South Korea, was shown for 17 minutes on a 55-inch 3D high-definition television. The viewing distance was 2.7 metres. After watching 3DTV, a survey was performed to evaluate the degree of subjective 3D perception.

The questionnaire was comprised of six items, which included the degree of 3D perception and also some frequently reported symptoms after watching 3DTV (Table 15). Each item was answered according to a five-category scale (1-5). A value of 1 corresponded to no impact and a value of 5 corresponded to an impact too severe to watch 3DTV. The degree of subjective 3D perception and level of discomfort were compared between the three groups.

For statistical analysis, the Independent-Samples Kruskal-Wallis Test and Kendall's Tau correlation were used with SPSS 20.0K for Windows.

Experimental results and discussion

Eighty subjects were enrolled in this study. There were 48 people with PD and 32 age-matched normal subjects. The mean age between the two groups was 67.3 ± 9.76 and 65.6 ± 9.71 years, respectively. The mean cognitive function test (MoCA) between the two groups was 21.9 ± 5.17 and 24.4 ± 3.00, respectively. Cognitive function tests were significant between the PD group and the control subjects ($P = 0.018$).

The mean subjective dynamic 3D perception score of the PD group was similar to that of the control subjects (4.06 ± 1.19 vs. 3.90 ± 1.34, respectively). These scores show that people with PD can perceive dynamic 3D content as well as normal control subjects. However, this finding correlated with the H-Y stage ($r = -0.253$, $P = 0.048$). The more severe the condition, the lower their subjective 3D perception scores were. From the results, it can be inferred that those with severe PD might experience a small 3D effect even if they do not have any problems in their eyes.

There was no difference in the amount of 3D fatigue between the two groups except significantly in terms of eye fatigue. Although those with PD felt more eye fatigue than the control group, the mean score reflected a mild impact (2.21 ± 1.05). Therefore, in terms of safety, 3DTV can be considered not bad for PD patients.

TABLE 15

Questionnaire

Item	1	2	3	4	5
Dizzy					
Headache					
Nausea					
Eye fatigue					
Cold sweat					
Feel stereoscopic vision					

*1: never experienced, 2: mild impact, 3: moderate impact, 4, severe impact, 5: very severe impact

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Annex 8

Visual discomfort induced by the binocular disparity of stereoscopic video – Korea (Republic of)

1 Introduction and study results

One of the biggest reasons that people lost their interest in stereoscopic images was the visual discomfort they experienced while watching 3D content. Therefore, 3D watching safety guidelines should be considered to commercialize 3D broadcasting content if producers expect to achieve long hours of repeated watching.

Positive disparity, negative disparity, depth budget, and depth motion cause inconsistency of accommodation and vergence in the creation of stereoscopic 3D content, and they also differ in terms of binocular disparity, which is the positional difference of two images delivered to human eyes, and therefore the visual fatigue caused by binocular disparity while watching 3D images requires a study in terms of content. Therefore, to assess the visual comfort level depending on the level of binocular disparity, the main properties of binocular disparity were designed to have five different levels and 3D content was created for each level. An experiment with 100 participants was performed with the subjective quality assessment method recommended by Recommendations ITU-R BT.500-11 and ITU-R BT.1438.

The experimental results showed some differences in visual discomfort depending on the positive disparity, negative disparity, maximum relative disparity, and change rate of binocular disparity. Binocular disparity was the fundamental element present in the stereoscopic images, but the excessive amount was the main cause of visual discomfort in the perception of those images. Additionally, the changing rate of binocular disparity affected the visual discomfort level.

2 Summary and proposals

This annex describes the allowable range of visual discomfort with respect to positive disparity, negative disparity, depth budget, and the motion change by disparity. Based on subjective assessment, the following aspects have been considered for the production guidelines of stereoscopic 3D video.

– Excessive positive disparity, excessive negative disparity, and excessive depth budget cause excessive screen disparity in 3DTV applications, and hence the content may not be perceived as 3D and can cause visual discomfort. Therefore, care while 3D watching is recommended.
– The high level of the change rate of binocular disparity in videos with depth motion may cause visual discomfort. Therefore, care while 3D watching is recommended.

These observations should be considered when developing viewing safety guidelines for stereoscopic 3D systems.

Attachment

Results of subjective visual comfort assessment for disparity and motion depth magnitude of 3D content

1 Experimental environments

A 55-inch circular polarized 3DTV (LG Electronics, Korea) was used to present 3D images to participants. The resolution was set to 1 920 × 1 080 pixels, and the viewing distance was maintained at 2.7 m, which is three times the screen height of the TV. Figure 32 shows the viewing environment of the subjective measurement test. All experimental environments followed Recommendations ITU-R BT.500-11 [2] and ITU-R BT.1438 [3]. Table 16 is a summary of the experimental environment. This study was arranged to simulate the viewing environment of a typical household because the objective of the study was to measure the effect of 3DTV viewing at home.

FIGURE 32

Stereoscopic 3D monitor used in our subjective assessments

TABLE 16

Experimental environment home table

	Recommendation ITU-R BT.500-11	Ours
Environmental illumination	200 lux	210 lux
Maximum observation angle	Maximum 30	Maximum 21.8
Peak luminance	≥ 200 cd/m^2 (45 lux)	
Height of display (H)		726 mm
Viewing distance		3H (2.7 m)

2 Subjective measurement of visual discomfort induced by disparity characteristics

2.1 Visual stimulus

In order to determine the limit and the range of the allowable binocular disparity to guarantee the safety of 3DTV watching, the visual discomfort level should be assessed while changing the level of binocular disparity with a standard stimulus. For this study, video content with five different levels of standard stimuli were designed. As shown in Table 17, a total of 45 visual stimuli were generated (15 stimuli for disparity and30 stimuli for depth motion).

Video clips with different disparity levels were created by controlling the disparity precisely in a production studio. Positive disparity was set to the maximum 4.5% (86 pixels) in the positive direction, negative disparity was set to the maximum 4.0% (72 pixels) in the negative direction, and the depth budget was set to the maximum 4.5% (86 pixels) by assigning the positive and negative portions equally. Two types of depth motion, when the motion appeared just once or repeatedly, were implemented. Additionally, the change of disparity was set to 2%, 4%, and 6% all starting from 0%, and they were presented in terms of 5-level stimuli depending on the depth motion of the object.

TABLE 17

Attributes of visual stimulus used in the experiments

<table>
<tr><th></th><th>Depth position</th><th colspan="2">Visual stimulus (disparity range)</th></tr>
<tr><td rowspan="3">Disparity</td><td>Positive</td><td colspan="2">0.5%, 1.5%, 2.5%, 3.5%, 4.5%</td></tr>
<tr><td>Negative</td><td colspan="2">0.5%, 1.2%, 2.0%, 3.0%, 4.0%</td></tr>
<tr><td>Depth budget</td><td colspan="2">1.0%, 2.0%, 4.0%, 6.0%, 8.0%</td></tr>
<tr><td rowspan="3">Depth motion</td><td rowspan="3">Loop (negative)</td><td>Depth motion level</td><td>0%~2%, 0%~4%, 0%~6%</td></tr>
<tr><td>Standard stimulus duration</td><td>0.5 s, 1 s, 2 s, 4 s, 6 s</td></tr>
<tr><td>Stimulus presentation duration</td><td>15 s, 15 s, 15 s, 15 s, 15 s</td></tr>
</table>

TABLE 17 (*end*)

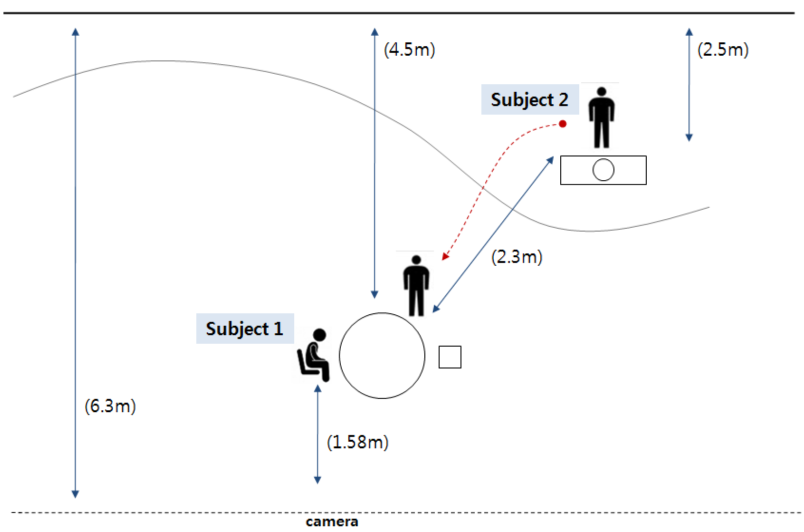
Attributes of visual stimulus used in the experiments

<table>
<tr><td rowspan="3">Depth motion</td><td rowspan="3">Once (negative)</td><td>Depth motion level</td><td>0%~2%, 0%~4%, 0%~6%</td></tr>
<tr><td>Standard stimulus duration</td><td>0.5 s, 1 s, 2 s, 4 s, 6 s</td></tr>
<tr><td>Stimulus presentation duration</td><td>3.5 s, 4 s, 5 s, 7 s, 9 s</td></tr>
</table>

FIGURE 33

Disparity images used in the experiments

Stimulus	Positive
Camera	Sony HDR-1500R
Camera movement	No
Rig	TS-2 (3Ality)
Characteristics	Fixed at negative 0%
Subject movement	Yes
Image	

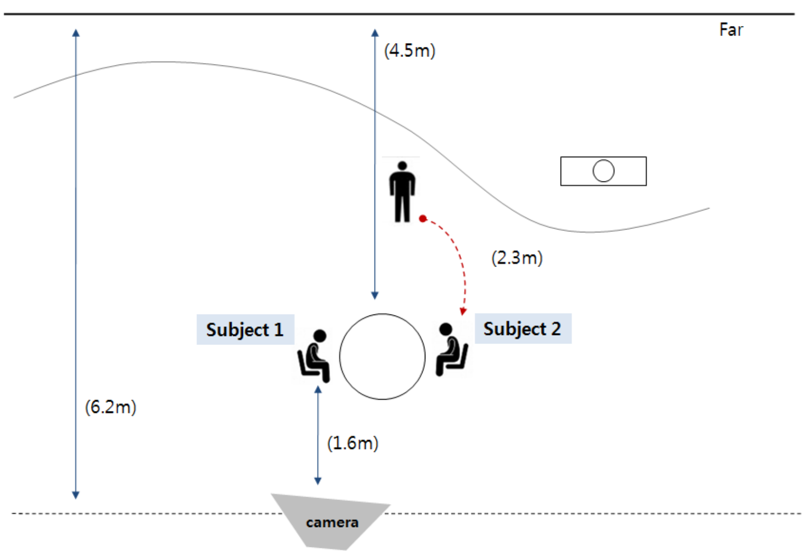


Near distance (m)	Far distance (m)	Focal length (mm)
1.58 m	6.3 m	7.80 mm
IOD (%)	**Convergence Point (‘fit “inch)**	**Focus Point (‘fit “inch)**
0.0%	6’ 24“ (Shoulder of the female subject)	6’ 43“ (Face of the female subject)

(a) Positive disparity images

A woman is sitting down at a coffee shop. A waiter comes with a cup of coffee, places it on the table, and goes back

Stimulus	Negative
Camera	Sony HDR-1500R
Camera movement	No
Rig	TS-2 (3Ality)
Characteristics	Fixed at positive 0%
Subject movement	Yes
Image	

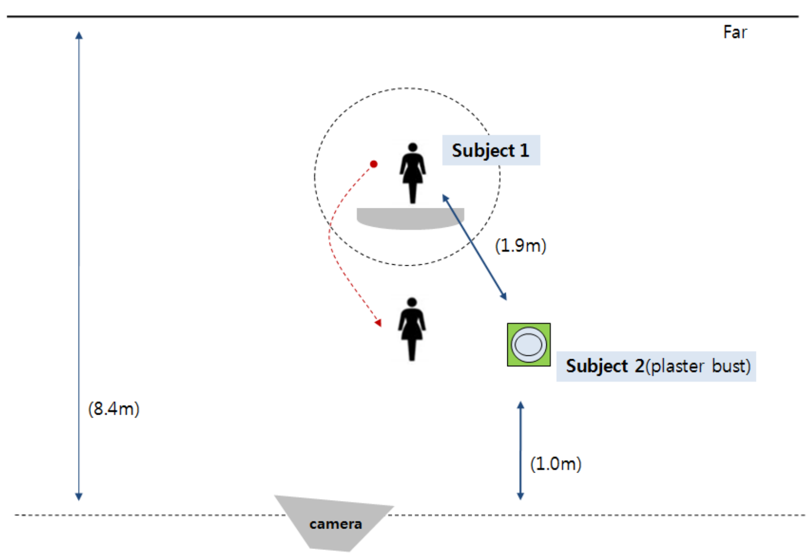


Near distance (m)	**Far distance (m)**	**Focal length (mm)**
1.6	6.2	7.80
IOD (%)	Convergence point (‘fit “inch)	Focus point (‘fit “inch)
0.0%	22’ 28“(Back wall)	6’ 26“ (Face of the female subject)

(b) Negative disparity images

A woman is sitting down at a coffee shop. A man sits down in front of her, and starts friendly conversation

Stimulus	Depth Budget
Camera	Sony HDR-1500R
Camera movement	No
Rig	TS-2 (3Ality)
Characteristics	
Subject movement	Yes
Image	



Near distance (m)	**Far distance (m)**	**Focal length(mm)**
1	8.4	7.80
IOD (%)	**Convergence point (‘fit “inch)**	**Focus Point (‘fit “inch)**
0	7’ 70“(Front of the desk)	12’ 15“ (Face of the female subject)

(c) Depth budget images

After commentary at the desk, a female announcer comes forth and presents a final greeting

Higher resolution 1 920 × 1 080 side by side videos (mov(h.264)) of these sequences can be downloaded from the ITU site via this link http://www.itu.int/oth/R0A07000034/en.

FIGURE 34

Motion depth images used in the experiments

(a) Depth motion (loop) (b) Depth motion(once)

2.2 Subjective assessment method of visual discomfort

1) Subjects

One hundred adults between 18 and 55 years old and with the corrected vision of at least 0.8 volunteered for this experiment. The age and sex distributions were considered to be even.

TABLE 18

Subject group characteristics

Group	18 ~ 29 years old		30 ~ 39 years old		40 ~ 55 years old		Total
	Male	Female	Male	Female	Male	Female	
Number of subjects	16	16	18	18	16	16	100

2) Measurement of stereovision

In general, there is a stereo anomaly for people who do not perceive the stereo visual depth from images with various disparities. People with ophthalmological problems such as strabismus are categorized as stereo blind because they cannot perceive stereo visual depth from 3D images [4].

To exclude such participants from the experiment, a screening test was performed to find stereo anomalies by measuring near-distance and far-distance stereovision. The "stereo fly test" was used to test the near-distance stereovision. The test equipment was composed of nine circles with different stereo visual resolutions similar to the stereo visual assessment tools recommended in Recommendation ITU-R BT.1438. The visual angles of each stereovision had a magnitude of 40 ~ 800 seconds, as shown in the following Figure. For the far-distance stereovision test, participants wearing 3D glasses were asked to watch 3D videos from 3DTV from a distance of three meters from the screen.

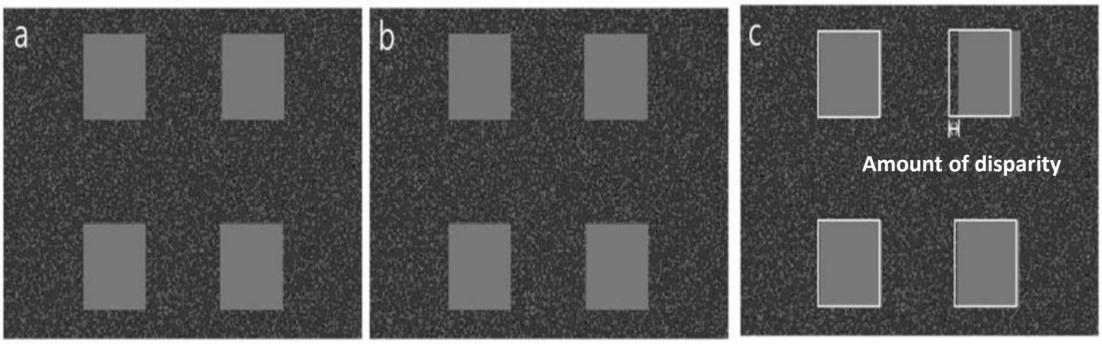
The screen displayed four grey rectangles or randomized dot rectangles, and the participants were asked to choose one rectangle with a different depth from the other rectangles, and to fill in the questionnaire with the answer. A total of 48 (2 stimulus × 6 disparity × 4 repetition) 3D images were presented in randomized order.

FIGURE 35

Near-distance stereovision test equipment and the angle of stereovision

Test	Angle of Stereopsis at 16 inches
1	800 seconds
2	400 seconds
3	200 seconds
4	140 seconds
5	100 seconds
6	80 seconds
7	60 seconds
8	50 seconds
9	40 seconds

FIGURE 36



Far-distance stereovision test (a) and (b) are the images presented to the left and right eyes respectively. Image (c) is the image showing the level of disparity when (a) and (b) were presented to both eyes at the same time. In (c), the white rectangle implies the location of the grey picture for the right eye overlapping the picture for the left eye. In all the stereoscopic images, one randomized rectangle appears to have different depth than other rectangles. For example, the upper right rectangle from (c) has a different disparity level than those of the other rectangles, and hence it is perceived to have different depth.

3) Experiment

Subjects were presented with 45 randomized video clips. They filled in 5-point scaled questionnaires on dizziness and/or visual discomfort while watching those video clips. Comfort/discomfort assessment while 3D content watching was the viewing safety evaluation. Questions were used to evaluate test images designed with five levels for each question item in the ACR-HR (Absolute Category Rating-Hidden Reference) method of ITU-T P.910. The specific answers were on a 5-point scale (high discomfort, mild discomfort, nil, mild comfort, and high comfort) for each test video clip.

FIGURE 37

ACR-HR (absolute category rating-hidden reference)

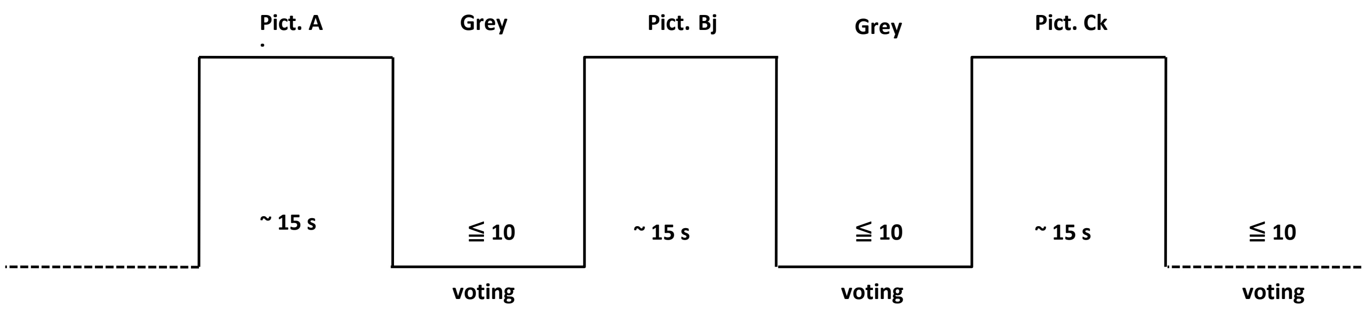


FIGURE 38

Categorical scales that assess the overall level of visual discomfort

(Questionnaire) Please evaluate your comfort/discomfort level while watching 3D video clips.

High discomfort	Mild discomfort	Nil	Mild comfort	High comfort
①	②	③	④	⑤

2.3 Experimental results and discussion

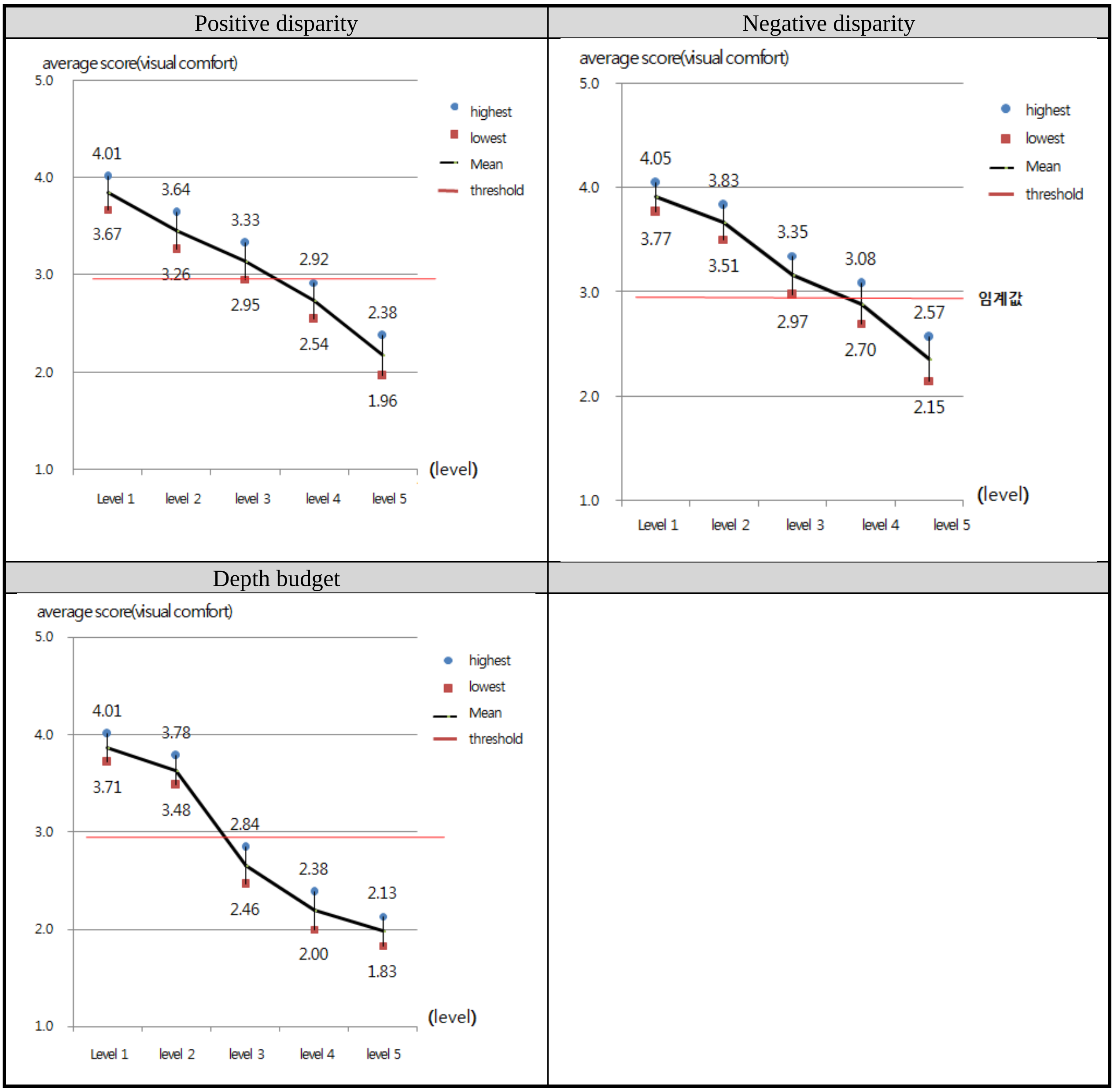
1) Binocular disparity

Generally, an increase of binocular disparity within a certain range increases the level of stereoscopic depth. However, when the amount of disparity passes over the range, the change of stereoscopic depth is perceived in the form of a double image [5][6].

In this way, the level of stereoscopic depth determines whether the stereoscopic image appears single or double. Furthermore, the amount of visual discomfort increases with an increase of binocular disparity since it is caused by the inconsistency of accommodation and vergence. In this experiment, the threshold value of MOS was set to 3, the middle point of the five-point scale, to suggest the allowable range of visual discomfort. The result showed that the MOS of positive disparity based on the threshold dropped from the fourth level image (3.5%). For 3D content with negative disparity, the index showing visual discomfort dropped below the threshold level from the fourth level image (3.0%) just like for positive disparity. For 3D content with depth budget, the index dropped from the third level (3.0%). As a result, it is estimated that the allowable range of positive disparity is 2.5~3.5%, negative disparity is 2.0~3.0%, and depth budget is 2.0~3.0%.

FIGURE 39

Visual fatigue caused by disparity



2) Motion depth

Most 3D content consists of videos containing certain types of motion rather than static images. Hence, the change rate of binocular disparity as well as the binocular disparity itself may affect visual discomfort, and this can be more important in certain situations. From the viewpoint of inconsistency of accommodation and vergence, which is the origin of visual discomfort, visual discomfort caused by stereoscopic images containing an object moving in the direction of depth differs from the discomfort caused by images without any motion.

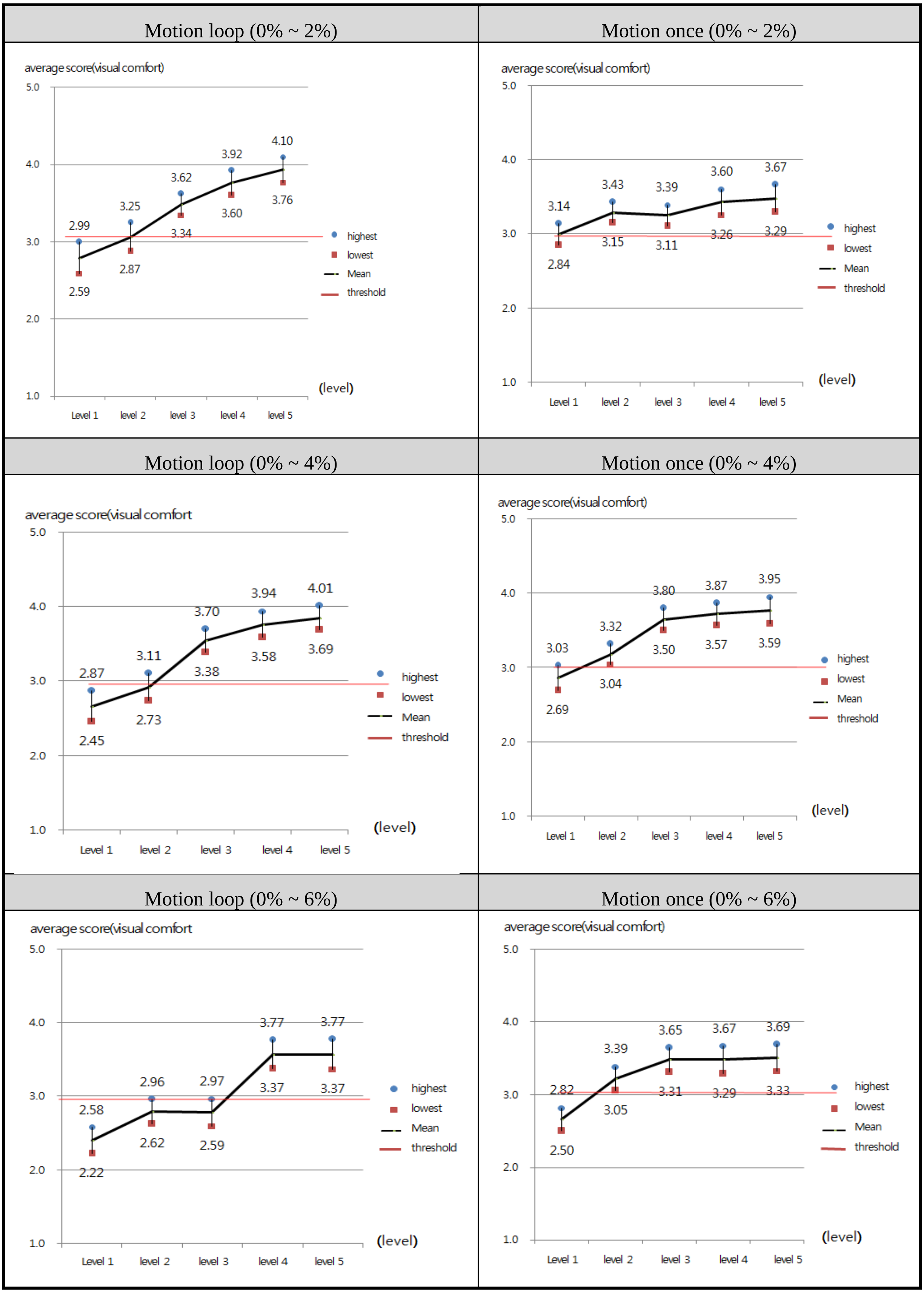
With static stereoscopic images, ocular movements are required to move just once to a specific vergence angle, while such vergence movements happen repeatedly when an object in a stereoscopic video moves in the depth direction. Furthermore, the vergence angle of the object and actual vergence angle of eyes do not exactly match [7], and this error can increase with the movement speed in the depth direction.

In this experiment, the MOS threshold of visual discomfort was set to 3 to suggest the allowable range of visual discomfort by the change of binocular disparity. Based on this threshold value, the motion depth for visual discomfort was set to 2%, 4% and 6%, and the amount of visual discomfort increased with an increase of motion depth and with an increase of the depth change rate of binocular disparity.

Moreover, the visual discomfort level from images with persisting stimuli of the change of binocular disparity was higher for images with one-time change. When the motion depth was 6%, the difference of visual discomfort depending on the change rate of binocular disparity depth changed significantly for each stimulus level. Figure 39 shows the allowable range of binocular disparity from the viewpoint of visual fatigue. The images with a change of disparity of 0~2% and 0~4% among the repeated stimuli caused visual discomfort if the change rate of binocular disparity was higher than one second.

The 0~6% image caused visual discomfort when the change rate of binocular disparity was higher than two seconds. The image with one-time stimulus caused visual discomfort for all cases when the change rate of binocular disparity was higher than 0.5 seconds.

FIGURE 40



Visual fatigue caused by motion depth

3) Limitations

This research was performed to provide a production guideline for the safety of 3D watching. However, 3D content involves more variables than just the content itself, for example, viewer and/or environmental factors, and those variables all affect each other. This implies that it is difficult to measure the allowable range as an independent variable, and further study is required. Even though the research result is limited to true values in an actual production environment, it still can be used as baseline data to set the default values of stereoscopic variables in 3D content production.

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Annex 9

Liaison statement to the WHO

Source: Document 6/316

Working Party 6C

DRAFT COMMUNICATION FROM STUDY GROUP 6 TO
THE WORLD HEALTH ORGANIZATION

Visual fatigue and other possible health hazards due to prolonged viewing of stereoscopic (3D) television presentations

ITU-R Study Group 6 (“Broadcasting Service”) has initiated studies on the specifications to be recommended for stereoscopic (3D) television for broadcast use, which is currently attracting some interest on the part of some television broadcasters and of their audiences.

Some ITU members have pointed out that there are indications in the medical literature to the effect that extended viewing of stereoscopic programme material, as displayed on currently available

3D presentation devices, can cause, for example, viewers’ eye fatigue, nausea, dizziness, discomfort, headache and other possible health hazards.

We ask the World Health Organization to kindly advise us on any evidence that they may have on whether viewing stereoscopic 3D television presentations that would be typical of normal television home viewing using currently available displays[7] may cause any possible medical issues and to which extent.

We look forward to the WHO kind reply and we thank them for their help on this matter.

[Please address your reply to (Counsellor)…]

Annex 10

The Influence of Alzheimer’s Dementia on dynamic 3D perception and fatigue while watching 3D Television

Subjects and methods

Subjects included Alzheimer’s dementia (AD) patients and an age-matched normal control group. All subjects had stereo acuity levels of under 800 arcsec. Informed consent was obtained from all of the patients.

	AD patients	**Control group**	***P*-value**
Sex (man: woman)	17:20	11:18	NS
Age	73.73 ± 6.79	68.14 ± 7.47	.002
MoCA score	14.86 ± 4.37	24.48 ± 2.91	< .001
Corrected visual acuity (Left)	0.57 ± 0.27	0.73 ± 0.32	NS
Corrected vVisual acuity (Right)	0.55 ± 0.26	0.75 ± 0.30	NS
Log seconds of arc of Titmus test	168.38 ± 169.09	175.86 ± 258.85	NS

[7] It is also known that all currently available stereoscopic displays for television viewing in the home require the use of special 3D glasses, and some 3D viewing uses shuttered “active glasses”.

The amount of visual acuity and number of refractive errors were measured. The angle of ocular deviation was obtained with the alternate prism-cover test. The level of stereo acuity was examined with the Stereo Fly test (Stereo Optical Co., Chicago, IL, USA) for near stereopsis.

The 3D video, which was produced by the national broadcasting system of South Korea, was shown for 18 minutes on a 55-inch 3D high-definition television. The viewing distance was 2.7 metres. After watching 3DTV, a survey was performed to evaluate the degree of subjective 3D perception and the symptoms. The questionnaire was comprised of 6 items, which included the degree of 3DTV perception and frequently reported symptoms after watching 3D TV (as shown in Table 19). Each item was answered according to a five-category scale (1-5). A value of 1 corresponded to no impact and a value of 5 corresponded to an impact too severe to watch 3DTV. The degree of subjective 3D perception and level of discomfort were also compared.

For statistical analysis, the Independent-Samples Kruskal-Wallis Test and Kendall’s Taucorrelation were used with SPSS 20.0K for Windows.

TABLE 19

Discomfort questionnaire

Item	1	2	3	4	5
Dizzy					
Headache					
Nausea					
Eye fatigue					
Cold sweat					
Feel stereoscopic vision					

* 1: Never experienced, 2: mild impact, 3: moderate impact, 4, severe impact, 5: very severe impact.

Experimental results and discussion

Sixty-six subjects were enrolled in this study, 37 with AD and 29 age-matched subjects without AD. The mean age between the two groups was 73.73 ± 6.79 and 68.14 ± 7.47 years, respectively. The mean cognitive function test (MoCA) between the two groups was 14.86 ± 4.37 and 24.48 ± 2.91, respectively. A cognitive function test showed significant differences between the AD and the control subjects ($p < .001$).

The mean stereo acuity levels examined with the Stereo Fly test did not differ. However, the mean subjective dynamic 3DTV perception scores of the AD group were significantly different from those of the control group (3.05 ± 1.49 vs. 3.79 ± 1.37, respectively) (Fig. 41).

The scores show that the AD group could not sufficiently perceive dynamic 3D content as well as the control patients. Furthermore, the degree of 3DTV perception was correlated with the scores on a cognitive test (Korean version of Montreal Cognitive Assessment, K-MoCA) (Fig. 42).

There was no difference in the amount of 3D discomfort between the two groups. Therefore, in terms of safety, it can be concluded that 3DTV is not harmful for those with AD (Fig. 43).

Summary

In the preliminary experiments, it was observed:

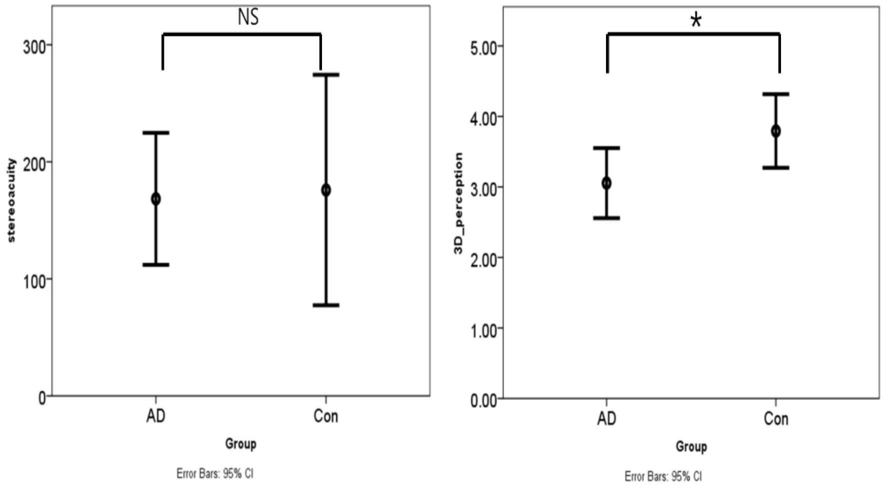
- 3D perception decreased more in the dementia group than in the control group even when there was no structural difference between their eyes.

- Watching 3DTV did not cause any different level of discomfort for the control group nor for those in the AD group.
- In terms of safety, watching 3DTV did not harm the AD patients as long as they complied with the "3D video safety guidelines".

All of the above observations should be considered when developing viewing safety guidelines of stereoscopic 3D systems.

FIGURE 41

Differences when using the Titmus fly test and the 3D perception questionnaire in the AD group and the control group



NS; not significant, *p < 0.05

FIGURE 42

Correlation 3D perception questionnaire with K-MoCA scores (p < 0.01)

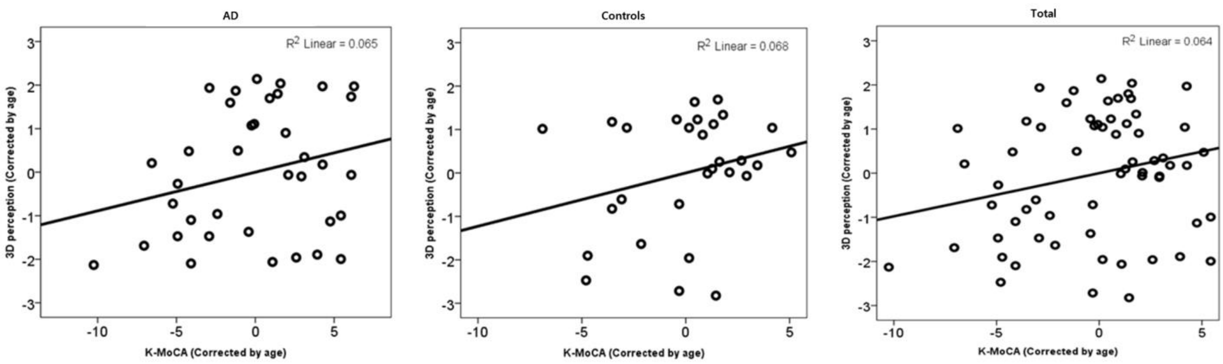
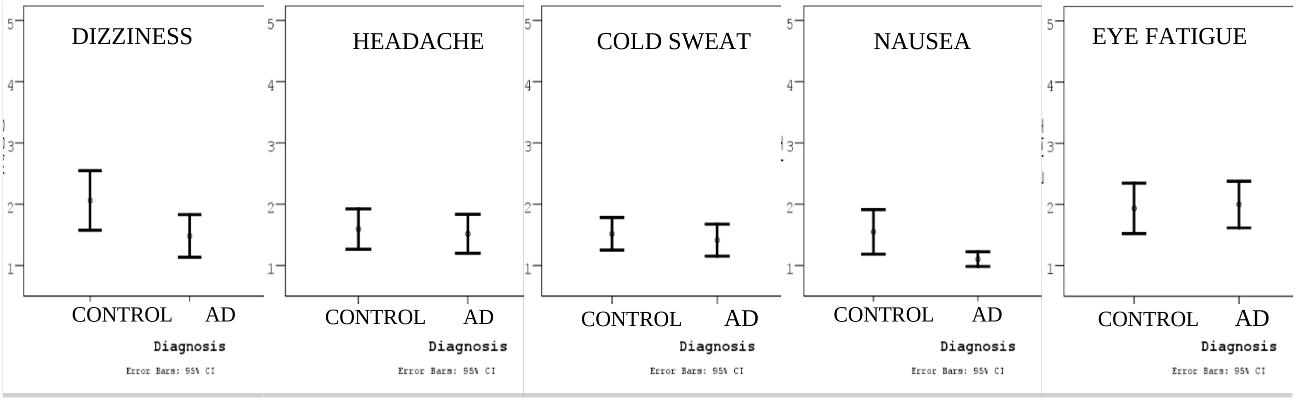


FIGURE 43

No significant difference in the components of the 3D TV discomfort scale



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Annex 11

The role of 3D Television in terms of refractive errors in children

Subjects and methods

Healthy volunteers aged 6 to 12 years were recruited. Informed consent was obtained from the parents of all the subjects. Before enrolment, manifest refraction, slit lamp examination, fundus evaluation with fundus camera, alternate prism-cover test and near stereopsis test with the Stereo Fly (Stereo Optical Co., Chicago, IL, USA) were performed. Volunteers with strabismus, best corrected Snellen visual acuity less than 20/20, near stereoacuity worse than 60 seconds of arc, anisometropia more than 2.00 D or with any structural abnormalities in the cornea, lens, retina or optic nerve were excluded.

A 3D video was shown for 50 minutes on a 3D high-definition television (UN55C7000WF, Samsung Electronics, Suwon, South Korea) with a diagonal screen size of 139 cm. Subjects wore liquid-crystal shutter glasses. The illumination of the room was 5 lux and the viewing distance was 2.8 metres. The viewing distance and duration were set following the recommendations of the TV manufacturer and the International Telecommunication Union (2.2 metres or more for a 55 inch HDTV, respectively).

The 3D content used in this study was produced with the true 3D shooting technique by the national broadcasting system of South Korea for 3D test-run broadcasts. The image disparity ranged from −1 to 1 degree and the reference depth was zero screen disparity.

Refractive errors were obtained objectively with an autorefractor (RK-F1, Canon, Tokyo, Japan) before and immediately after watching 3DTV. It was rechecked after a 10-minute rest. At each point, the measurement of the refractive errors was repeated until we obtained the same value for three consecutive measurements of each subject. The repeatability of the autorefractor was assessed using a coefficient of variation (0.64%), and it was highly reliable as we reported in the previous study. Spherical equivalent (sphere + 1/2 cylinder) of the right eye was used in this study. The refractive errors before and after watching 3DTV were compared. The subjects whose spherical equivalent of baseline refractive error was worse than –0.75 diopters (D) were included in the myopia group, and the other subjects were in the non-myopia group. The number of refractive changes after watching 3DTV was compared between the two groups. The refractive changes of the subjects who showed myopic shifts were compared between each point to assure that the myopic shift persisted after 10 minutes of rest.

Results

The mean age of the subjects was 9.23 ±1.75 years.

1 Normal subjects

Sixty normal subjects were enrolled. Their mean age was 9.23 + 1.75 years (6~12).

The refractive errors before and after watching 3DTV are shown in Table 20. There were no statistically significant differences between each time point.

TABLE 20

The changes of refractive errors after watching 3DTV

<table>
<tr><th></th><th>Refractive errors
(diopters, mean±SD)</th><th>Difference
(diopters)</th><th>P</th></tr>
<tr><td>Before watching</td><td>–1.70 ± 1.79</td><td rowspan="2">–0.05</td><td rowspan="2">0.387</td></tr>
<tr><td>Immediately after watching</td><td>–1.75 ± 1.85</td></tr>
<tr><td>After 10 minutes of rest</td><td>–1.69 ± 1.80</td><td>+0.06</td><td>0.279</td></tr>
</table>

The myopic group consisted of 34 subjects (56.7%). Table 21 shows a comparison of the change of refractive error between the myopia and non-myopia group. The refractive errors did not change significantly for either of the groups. Also, the mean change of refractive errors immediately after watching 3DTV did not differ between the two groups (P = 0.541).

TABLE 21

The refractive errors of the non-myopia and myopia group before & after watching 3DTV

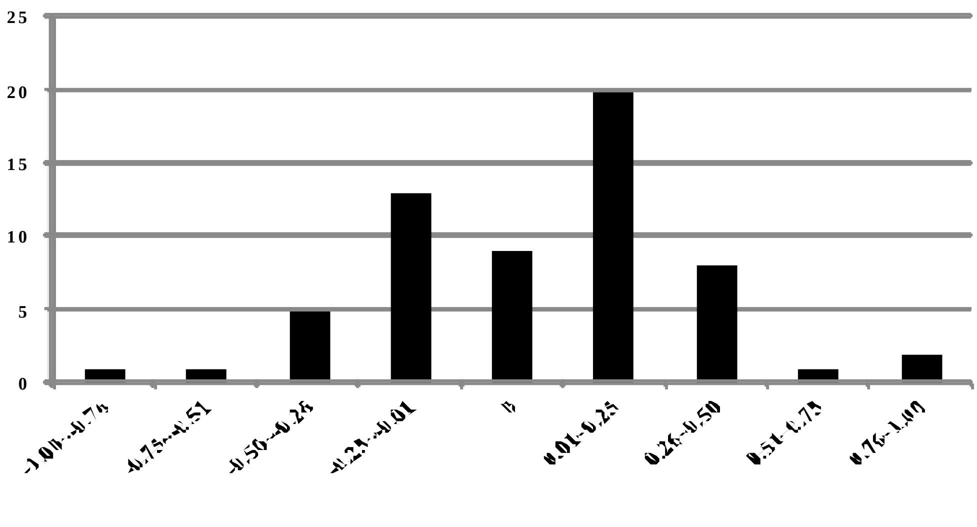
<table>
<tr><th></th><th>Non-myopia group
(n = 26, < –0.75D)</th><th>P</th><th>Myopia group
(n = 34, > –0.75D)</th><th>P</th></tr>
<tr><td>Before watching</td><td>–0.10 ± 0.56</td><td rowspan="2">0.963</td><td>–2.93 ± 1.39</td><td rowspan="2">0.184</td></tr>
<tr><td>Immediately after watching</td><td>–0.10 ± 0.69</td><td>–3.01 ± 1.41</td></tr>
</table>

After 10 minutes of rest	–0.10 ± 0.62	0.978	–2.92 ± 1.42	0.124

The distribution of refractive changes before and immediately after watching 3DTV is shown in Fig. 44.

FIGURE 44

The distribution of the changes of refractive errors after watching 3DTV



The myopic shift was observed in 31 subjects. The refractive errors before watching 3DTV in these subjects (–1.83 ± 1.92 D) did not differ from those in the others who did not show any myopic shift (–1.53 ± 1.68 D; *P* = 0.636). The ages of the subjects did not differ either (*P* = 0.994). In subjects with myopic shift, the refractive errors significantly changed immediately after watching 3DTV (*P* < 0.001) and the mean amount of myopic shift was 0.29 ± 0.23 (0.13-1.00) D. However, it was resolved after 10 minutes of rest and the refractive errors before watching 3DTV and after 10 minutes of rest did not differ significantly (*P* = 0.122).

2 Subjects with exodeviation

There was no significant change in terms of exodeviation and refractive errors after watching 3DTV. Table 22 shows the changes in refractive errors and the angle of deviation after watching 3DTV.

TABLE 22

Changes of refractive errors (D) and angle of exodeviation (PD) after watching 3DTV

	Before	**After**	**Difference (diopters)**	***P***
Angle of exodeviation (PD)	13.04 ± 5.25	12.96 ± 5.11	–0.09 ± 2.45	0.672
Refractive errors in the right eye (D)	–2.15 ± 1.55	–2.14 ± 1.57	0.01 ± 0.22	0.838

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