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Ergonomics of human-system interaction —

Part 392:
Ergonomic recommendations for the reduction of visual fatigue from stereoscopic images

Ergonomie de l'interaction homme-système —

Partie 392: Exigences ergonomiques pour diminuer la fatigue visuelle induite par des images stéréoscopiques

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT), see the following URL: Foreword — Supplementary Information.

The committee responsible for this document is ISO/TC 159, *Ergonomics*, Subcommittee SC 4, *Human-system interaction*.

ISO 9241 consists of the following parts, under the general title *Ergonomic requirements for office work with visual display terminals (VDTs)*:

— *Part 1: General introduction*

— *Part 2: Guidance on task requirements*

— *Part 5: Workstation layout and postural requirements*

— *Part 6: Guidance on the work environment*

— *Part 11: Guidance on usability*

— *Part 12: Presentation of information*

— *Part 13: User guidance*

— *Part 14: Menu dialogues*

— *Part 15: Command dialogues*

— *Part 16: Direct manipulation dialogues*

ISO 9241 also consists of the following parts, under the general title *Ergonomics of human-system interaction*:

— *Part 20: Accessibility guidelines for information/communication technology (ICT) equipment and services*

— *Part 110: Dialogue principles*

— *Part 129: Guidance on software individualization*

— *Part 143: Forms*

— *Part 151: Guidance on World Wide Web user interfaces*

— *Part 154: Interactive voice response (IVR) applications*

— *Part 171: Guidance on software accessibility*

— *Part 210: Human-centred design for interactive systems*

— *Part 300: Introduction to electronic visual display requirements*

— *Part 302: Terminology for electronic visual displays*

— *Part 303: Requirements for electronic visual displays*

— *Part 304: User performance test methods for electronic visual displays*

— *Part 305: Optical laboratory test methods for electronic visual displays*

— *Part 306: Field assessment methods for electronic visual displays*

— *Part 307: Analysis and compliance test methods for electronic visual displays*

— *Part 308: Surface-conduction electron-emitter displays (SED)*

— *Part 309: Organic light-emitting diode (OLED) displays*

— *Part 310: Visibility, aesthetics and ergonomics of pixel defects*

— *Part 331: Optical characteristics of autostereoscopic displays*

— *Part 400: Principles and requirements for physical input devices*

— *Part 410: Design criteria for physical input devices*

— *Part 420: Selection of physical input devices*

— *Part 910: Framework for tactile and haptic interaction*

— *Part 920: Guidance on tactile and haptic interactions*

For the other parts under preparation, see Annex A.

Introduction

When a person views a three-dimensional object, the lateral distance between the eyes provides each with a slightly different retinal image. The fusion of these retinal images by the brain provides a single percept with an associated sense of depth termed as stereopsis. Recent advances in the imaging technology have created a notable increase in our chances of viewing artificially-created stereoscopic images. The technology creates two different images, one of which is seen by one eye and the other by the other eye. Their fusion results in the sensation of stereopsis.

Stereoscopic images are appealing because of their heightened sense of reality compared with the traditional 2D images. Presentations of stereoscopic images also provide clear depth information and, for this reason, the broad use of stereoscopic images is anticipated in fields such as medicine and industry. However, there are scientific data indicating that without careful consideration of the properties of the human visual system, the stereoscopic presentation of images might induce undesirable effects.

This part of ISO 9241 describes the basic and minimal conditions for comfortable viewing of stereoscopic images. It is intended to promote an environment in which viewers can enjoy the benefits of stereoscopic images without adverse effects. In such an environment, new technologies for stereoscopic images can also be actively developed and applied in various fields. This part of ISO 9241 is not intended to restrict the freedom of expression or artistic creativity in the image culture.

This part of ISO 9241 is based on scientific findings related to the possible undesirable effects of viewing stereoscopic images and in the future, this part of ISO 9241 can be revised as new scientific data.

This part of ISO 9241 specifies human–system interaction standards. Readers who need guidance on other aspects of human–system interaction can therefore refer to other documents in ISO 9241 (see Annex A for an overview of the entire ISO 9241 series).

Ergonomics of human-system interaction —

Part 392:
Ergonomic recommendations for the reduction of visual fatigue from stereoscopic images

1   Scope

This part of ISO 9241 establishes recommendations for reducing the potential visual discomfort and visual fatigue experienced during viewing of stereoscopic images under defined viewing conditions. Visual fatigue and discomfort might be produced by the stereoscopic optical stimulus of disparate images that were presented binocularly.

This part of ISO 9241 is also applicable to the final products of stereoscopic presentations which depend on stereoscopic image content and stereoscopic displays when viewed under appropriate defined conditions. Therefore, the recommendations are intended for people responsible for the design, development, and supply of stereoscopic image content as well as stereoscopic displays.

NOTE 1   See Annex B for appropriate viewing conditions.

The recommendations in this part of ISO 9241 are applicable to stereoscopic displays such as those with glasses and two-view autostereoscopic displays, stereoscopic head-mounted displays, and stereoscopic projectors. Moreover, they are applicable to stereoscopic image content intended to be presented on the above-mentioned stereoscopic displays and stereoscopic presentations that are realized by the combinations of these images and displays.

NOTE 2   Annex C presents numerical criteria as an informative reference.

NOTE 3   Other guidance might need to be established by referring to this part of ISO 9241 when requirements and recommendations specific to each type of stereoscopic image content or stereoscopic display become necessary.

NOTE 4   ITU generally sets the standards for broadcasting.

NOTE 5   ISO 9241-303:2011, Annex E provides guidelines for virtual displays which are intended for stereoscopic head-mounted displays.

2   Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9241-303, *Ergonomics of human-system interaction — Part 303: Requirements for electronic visual displays*

3   Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
stereopsis
binocular, visual perception of depth or three-dimensional space

Note 1 to entry: See ISO 9241-302:2008, 3.3.40.

3.2
binocular parallax
apparent difference in the position of an object as seen separately by one eye and by the other while the head remains in a fixed position

Note 1 to entry: See ISO/TR 9241-331:2012, 2.2.1.

Note 2 to entry: Extent of binocular parallax of a point is equivalent to the optic angle between the visual axes of both eyes when they are fixated on the point.

3.3
horizontal disparity
difference in the relative position of visual images of an object on the two retinas

Note 1 to entry: See ISO 9241-302:2008, 3.5.26.

3.4
vergence angle
angle between the visual axes of the left and right eyes

Note 1 to entry: See ISO 9241-302:2008, 3.5.55.

3.5
accommodation
adjustment of the optics of an eye to keep an object in focus on the retina as its distance from the eye varies

Note 1 to entry: Accommodation can also be a process of adjusting the focal length of a lens.

Note 2 to entry: Accommodation can also refer to an increase in the power of a lens of an eye.

Note 3 to entry: See ISO 9241-302:2008, 3.5.1.

3.6
visual global motion
wide spatial range of visual motion composed of different velocities and directions that are systematically aligned in a moving image

Note 1 to entry: There are generally six types of visual global motion that correspond to the different types of motion of a camera during the shooting of images which are rotation around and translation along the pitch, yaw, and roll axes.

3.7
stereoscopic display
display device or system that makes depth perception possible as a result of *binocular parallax* (3.2)

Note 1 to entry: People perceive depth owing to the retinal disparity produced by binocular parallax.

3.8
stereoscopic image content
set of image information that results in *stereoscopic images* (3.9) when shown on a *stereoscopic display* (3.7)

3.9
stereoscopic images
set of images presented on a stereoscopic display

3.10
stereoscopic presentation
presentation of stereoscopic images on a stereoscopic display

3.11
stereoscopic view
single sight produced as a consequence of fusion of left and right views of a *stereoscopic presentation* (3.10) which induces *stereopsis* (3.1)

3.12
interocular vertical misalignment
difference between vertical positions of the left and right views of a stereoscopic presentation

3.13
interocular rotational misalignment
difference between rotational positions of the left and right views of a stereoscopic presentation

3.14
interocular magnification difference
difference between apparent size of the left and right views of a stereoscopic presentation

3.15
interocular geometrical difference
geometrical misalignment of the left and right views of a stereoscopic presentation including *interocular vertical misalignment* (3.12), *interocular rotational misalignment* (3.13), and *interocular magnification difference* (3.14)

3.16
interocular luminance difference
difference between the luminance values of the left and right views of a stereoscopic presentation

3.17
interocular contrast difference
difference between the luminance contrast values of the left and right views of a stereoscopic presentation

3.18
interocular chromaticity difference
difference between the chromaticity values of the left and right views of a stereoscopic presentation

3.19
interocular photometric difference
photometric mismatch between the left and right views of a stereoscopic presentation including *interocular luminance difference* (3.16), *interocular contrast difference* (3.17), and *interocular chromaticity difference* (3.18)

3.20
accommodation-convergence mismatch
difference in distance information indicated by *accommodation* (3.5) and convergence stimuli of an object

Note 1 to entry: Accommodation-convergence mismatch can be produced when stereoscopic images are presented on a depth plane (e.g. stereoscopic display surface) which is well nearer or further from the viewers than where the images are simulated.

3.21
design viewing distance
distance or range of distances between the viewers' eyes and the screen of a stereoscopic display that is designed for stereoscopic presentation

Note 1 to entry: Design viewing distance can be specified for both *stereoscopic image content* (3.8), stereoscopic displays, and stereoscopic presentation.

4 Guiding concepts

4.1 Framework

To reduce the potential visual discomfort and visual fatigue experienced during viewing of stereoscopic images, the recommendations in this part of ISO 9241 are established based on the review of the factors (see 4.2) that are considered in terms of the stereoscopic optical stimulus of disparate images

presented binocularly. Therefore, other standards specific to each type of stereoscopic image content or stereoscopic display could be established by referring to this part of ISO 9241.

4.2 Review of factors

4.2.1 General

This part of ISO 9241 focuses on the major factors that have the potential to induce visual discomfort and visual fatigue during viewing of stereoscopic images. These factors, listed below, have been empirically determined and are widely recognized in the scientific literature. Since these factors are affected by the viewing conditions, such as the viewing distance, the viewing conditions should also be specified.

1) Interocular geometrical differences: Interocular vertical misalignment, interocular rotational misalignment, and interocular magnification difference.

2) Interocular photometric differences: Interocular luminance difference, interocular contrast difference, and interocular chromaticity difference.

3) Accommodation-convergence mismatch.

4) Other factors to be considered for stereoscopic presentation: Interocular temporal asynchrony, visual motion-induced motion sickness, and vergence limits.

In establishing guidance, the above-mentioned factors must be considered in light of their level of importance by reviewing the four items listed below.

a) Efficacy of factor: The probability that a factor will cause visual discomfort or visual fatigue in the viewers of stereoscopic images.

b) Inevitability of factor: The extent to which the effect of a factor can be reduced especially when the origin of the factor might be related to the principle of stereoscopic presentation.

c) Accumulation of scientific knowledge: Whether a sufficient amount of scientific data which determine the relation between each of the factors and visual fatigue, and/or discomfort, have been collected as well as their practical applicability to ergonomic guidance.

d) Availability of measurement methods: Whether measurement methods are readily available for assessing products.

In the following subsections, the major factors listed above (items 1 to 4) are reviewed in terms of items A to D.

4.2.2 Interocular geometric differences

4.2.2.1 General

Interocular geometric differences refer to the geometrical misalignment of the left and right views of a stereoscopic presentation such as interocular vertical misalignment, interocular rotational misalignment, and interocular magnification difference which are generally thought to induce visual fatigue and discomfort. The geometrical misalignment of the left and right views of a stereoscopic presentation is determined by the interaction between such differences in stereoscopic images and stereoscopic displays.

4.2.2.2 Efficacy of factor

Even a relatively small interocular geometrical difference can easily induce discomfort and make binocular fusion difficult.

4.2.2.3 Inevitability of factor

Interocular geometric differences can be caused by misalignment of the left and right cameras in the shooting of stereoscopic images and/or by misalignment of the left and right displayed images of a stereoscopic display that does not present those images within the same spatial frame. The differences can be reduced to some extent by making adjustments during the editing of images by adjusting devices and by carefully setting the viewing conditions.

4.2.2.4 Accumulation of scientific knowledge

Although there are no scientific data about the condition of the stereoscopic image size generally used at home, fundamental data have been collected which determine the relation between each of the factors and discomfort (e.g. see References [13] and [19]) and can serve as useful references.

4.2.2.5 Availability of measurement methods

Depending on necessity and feasibility, measurements can be taken separately for stereoscopic image content and stereoscopic displays or for final products of stereoscopic presentations. Firstly, measurements of stereoscopic image content can be performed by geometrical analysis by which the factors of interocular vertical misalignment, interocular rotational misalignment, and interocular magnification difference can be extracted separately as the factor of optical distortion caused by lens aberration (e.g. Hartly and Zisserman, 2004). Secondly, measurements of stereoscopic displays can be performed using generally available optical measurement devices.[30] Thirdly, measurements of stereoscopic presentations can be performed by combining the optical measurements of a whole stereoscopic image and geometrical analysis of the image.

4.2.3 Interocular photometric differences

4.2.3.1 General

Interocular photometric differences refer to the photometric mismatch between the left and right views of a stereoscopic presentation such as the interocular luminance difference, interocular contrast difference, and interocular chromaticity difference which are generally thought to induce visual fatigue and discomfort. Photometric mismatch between the left and right views of a stereoscopic presentation is determined by the interaction between such differences in stereoscopic images and in stereoscopic displays.

4.2.3.2 Efficacy of factor

Interocular photometric differences might induce discomfort when present to a relatively large degree (e.g. see References [2] and [11]).

4.2.3.3 Inevitability of factor

An interocular photometric difference can be caused by a photometric difference between the left and right cameras during the shooting of stereoscopic images and/or by a photometric difference between the left and right displayed images of a stereoscopic display. The difference can be reduced to some extent by making adjustments during the editing of images and by adjusting the devices. Since luminance, contrast, and chromaticity in a stereoscopic presentation are, in general, mutually related, they generally cannot be manipulated independently.

4.2.3.4 Accumulation of scientific knowledge

There are few scientific data determining the relation between interocular photometric difference and discomfort (e.g. see References [2] and [11]). A number of conditions can be considered as major contributory factors such as the display size, the surrounding lighting conditions, and the duration and frequency of the presentation of the factors.

4.2.3.5 Availability of measurement methods

Depending on necessity and feasibility, measurement can be taken separately for stereoscopic image content and stereoscopic displays, or for final products of stereoscopic presentations. Firstly, measurements of stereoscopic image content can be performed by comparing the photometric results obtained for corresponding points in the left and right image content. Secondly, measurements of stereoscopic displays can be performed using generally available optical measurement devices, whereas the measurements usually differ depending on the type of stereoscopic display. Thirdly, the measurement of stereoscopic presentations can be performed by combining the optical measurements of a whole stereoscopic image and comparing the photometric results obtained for the corresponding points in the left and right images.

4.2.4 Interocular photometric interaction

4.2.4.1 General

Interocular photometric interaction refers to unwanted photometric interaction, such as crosstalk, which affects the view in one eye through information about the image in the other eye.

4.2.4.2 Efficacy of factor

Crosstalk is recognized as "a primary factor affecting the image quality" of stereoscopic image presentation[24] and might induce discomfort (e.g. see References [11] and [26]).

4.2.4.3 Inevitability of factor

Crosstalk can occur in the capture, transmission, storage, editing, display, and separation stages, but most of the literature focuses on the display and separation stages[24] which can be the major stages of crosstalk occurrence. Crosstalk can be reduced to some extent by adjusting the devices.

4.2.4.4 Accumulation of scientific knowledge

Although crosstalk in stereoscopic image presentation has been widely studied (e.g. Reference [24] for review and References [11], [25], [26], [27], and [28]), the literature does not necessarily contain reports about the effects on visual fatigue and discomfort. Moreover, the numerical range of quantitative characteristics varies widely more than tenfold among the literature and sometimes experimental conditions relating to visual images, devices, and so forth, are not clear. The conditions of binocular disparity and contrast can be considered major contributory factors[28]. For quantifying crosstalk, several methods have been proposed. However, they are not necessarily perceptually relevant. Finally, crosstalk is quantified by using various equations which might sometimes lead to miscommunications.

4.2.4.5 Availability of measurement methods

Optical measurement devices can be used to measure crosstalk. In fact, measurement methods have been reported to use various optical devices.[24] However, the measurement methods differ by type of stereoscopic display (see ISO/TR 9241-331). The measurement methods using grayscale charts have yet to be established for stereoscopic displays in which the crosstalk process is highly non-linear.

4.2.5 Accommodation-convergence mismatch

4.2.5.1 General

In stereoscopic presentations, when visual targets are simulated as being in front of or behind the stereoscopic display surface, there can be a difference between the distance information of accommodation and convergence. The factor of accommodation-convergence mismatch, thus, refers to a mismatch between the accommodation and convergence stimuli and can possibly induce visual discomfort.

4.2.5.2 Efficacy of factor

Discomfort associated with a large extent of simulated depth has been well established empirically and has also been observed experimentally (e.g. see References [4], [5], [17], and [22]). Although there are large individual differences in the effect of accommodation-convergence mismatch on discomfort, the obtained results are basically consistent among the literature.

4.2.5.3 Inevitability of factor

Stereoscopic displays included in the scope of this part of ISO 9241 in principle include this factor for stereoscopic presentation. There are insensitive regions of accommodation and convergence that appear as depth of focus and fixation disparity respectively. Therefore, the effect of this factor can be reduced to some extent by reducing the simulated depth of visual objects from the stereoscopic display surface.

4.2.5.4 Accumulation of scientific knowledge

Various experimental data have been reported for accommodation-convergence mismatch (e.g. see References [1], [13], [15], and [21]). However, a number of conditions remain to be explored further such as the spatial distribution of simulated depth (especially in relation to edge violation), temporal variation, size, and duration of presented images.

4.2.5.5 Availability of measurement methods

The measurements are performed basically for both stereoscopic displays and stereoscopic image content. The relative disparity in stereoscopic displays and that of stereoscopic image content in terms of the display surface can be evaluated through optical measurements and/or geometrical analysis of image content.

4.2.6 Other factors to be considered for stereoscopic presentation

4.2.6.1 General

There are other factors to be considered as well such as interocular temporal asynchrony, visual motion-induced motion sickness, and vergence limits. These factors are respectively defined as follows: (i) the temporal difference of corresponding left and right images presented stereoscopically; (ii) visual global motion and other spatially wide ranges of motion that could induce motion sickness; (iii) the limits of vergence which is the point at which the visual axes of the two eyes diverge beyond the point of being parallel.

4.2.6.2 Interocular temporal asynchrony

4.2.6.2.1 Efficacy of factor

Interocular temporal asynchrony possibly raises multiple other factors such as interocular geometrical and photometric differences.

4.2.6.2.2 Inevitability of factor

Interocular temporal asynchrony can be induced when the left and right images of stereoscopic presentation are not optimally synchronized. This asynchrony can occur in the capture, transmission, storage, editing, display, and separation stages. It can also be reduced to some extent by adjusting the devices.

4.2.6.2.3 Accumulation of scientific knowledge

Basic experiments have been reported for interocular temporal asynchrony and visual motion-induced motion sickness.

4.2.6.2.4 Availability of measurement methods

Depending on necessity and feasibility, measurements can be performed separately for stereoscopic image content and stereoscopic displays, or for final products of stereoscopic presentations. However, the measurement methods of interocular temporal asynchrony are not yet established.

4.2.6.3 Visual motion-induced motion sickness

4.2.6.3.1 Efficacy of factor

Visually induced motion sickness, which can also be caused by traditional two-dimensional images, is thought to be enhanced by the stereoscopic images, though this has not yet been fully documented in scientific experiments.

4.2.6.3.2 Inevitability of factor

Dynamic visual motion, which is thought to induce motion sickness, is independent of the principle of stereoscopic presentation. Thus, visually induced motion sickness is not inevitably induced by stereoscopic images.

4.2.6.3.3 Accumulation of scientific knowledge

The conditions affecting visually induced motion sickness by stereoscopic images have not been fully reported on.

4.2.6.3.4 Availability of measurement methods

The visual motion contained in stereoscopic images can be measured. However, it is necessary to further clarify the conditions other than visual motion that produce visually induced motion sickness.

4.2.6.4 Vergence limits

4.2.6.4.1 Efficacy of factor

Discomfort is thought to be easily induced by stereoscopic images that cause the visual axes of the two eyes to diverge beyond the point of being parallel. At the same time, there are thought to be large individual differences in the degree of these effects.

4.2.6.4.2 Inevitability of factor

Conditions under which the visual axes of the two eyes diverge beyond the point of being parallel can be caused by the following: (i) maladjustments during the production of stereoscopic image content or during stereoscopic presentation using a projection method; (ii) stereoscopic presentation at a larger presentation size than that assumed during the production of the stereoscopic image content. This factor can be reduced to some extent, by making adjustments during the editing of images, by adjusting devices, and by adjusting settings for an appropriate presentation size.

4.2.6.4.3 Accumulation of scientific knowledge

Few reports in the scientific literature have covered the effects of the relative disparity that causes the visual axes of the two eyes to diverge beyond the point of being parallel.

4.2.6.4.4 Availability of measurement methods

Measurements are performed for stereoscopic images that are presented on stereoscopic displays. In general, it is rather difficult to consider the effect of this factor separately for stereoscopic image content and stereoscopic displays. However, if a combination of conditions, such as the presentation size

of stereoscopic image content and stereoscopic displays is considered, this factor can be estimated by measuring the corresponding points in the stereoscopic image content and the stereoscopic displays.

4.2.7 Summary

The review of factors in 4.2.2 to 4.2.6 made it clear that the influence of various factors has been examined to only a limited extent and that it is necessary to further investigate the effects of those factors before numerical criteria for requirements and recommendations can be determined. In this summary, the appropriateness of providing or not providing numerical criteria as reference information is described below for each factor.

The effects of interocular geometrical differences are relatively larger than the effects of other factors due to the fact that even a small interocular geometrical difference can easily induce discomfort. However, this factor is not an inevitable result of stereoscopic presentation and can be eliminated to some extent. The factor can also be measured relatively, easily, and its effect on discomfort has been reported in the scientific literature. Although there are various conditions to be further considered, basic data on discomfort induced by interocular geometrical differences have been reported. It is therefore possible to determine the numerical criteria for interocular geometrical differences as reference information.

Interocular photometric differences can readily induce discomfort. This factor is not an inevitable result of stereoscopic presentation and can be eliminated to some extent. Although there are various conditions to be further considered, basic data on discomfort induced by interocular luminance difference have been reported. Therefore, it is possible to determine the numerical criteria for interocular luminance difference as reference information.

Crosstalk, a factor of interocular photometric interaction, is a primary factor affecting the image quality of stereoscopic image presentation and can induce discomfort. Crosstalk mainly occurs in display stages and can be reduced to some extent by adjusting the devices. However, the reported characteristics of perceptual effects vary widely in quantitative terms, possibly because of the different types of measurements (perceptual threshold, subjective image quality, and discomfort), different methods of quantification, different types of stereoscopic displays, and different visual image conditions (luminance contrast and binocular disparity). Due to the variations, it is very important to clarify the effects of the different visual image conditions and display types before the numerical criteria can be determined.

Various experimental data have been reported for accommodation-convergence mismatch. The measurement of this factor can be performed by analysing the disparities in image content. The effect of this factor can be reduced to some extent by reducing the simulated depth of visual objects from the stereoscopic display surface. Although this factor has been examined to only a limited extent, various scientific data have been reported that confirm discomfort is induced by this factor when the mismatch is rather extreme. Thus, it is possible to determine the numerical criteria for accommodation-convergence mismatch as reference information.

Interocular temporal asynchrony and visual motion that induce motion sickness can be measured and their effects can be reduced to some extent by adjusting the images and devices. However, this factor has been examined to only a limited extent. Although it is therefore premature to determine numerical criteria for these factors, it is important to take relevant precautions. The factor of vergence limit can be measured and reduced to some extent in a stereoscopic presentation. However, there appears to be large individual differences in the effects it produces and almost no experimental data have been reported regarding its effect on discomfort. It is therefore important to further examine the effect of this factor before numerical criteria can be determined.

Based on the descriptions given above, for the items indicated with 'numerical criteria,' the numerical criteria are then presented in Annex C and referenced in Clause 5. For the items indicated with 'cautions,' the precautions to be taken are presented in Clause 5.

Interocular geometrical differences

— Interocular vertical misalignment – numerical criteria

— Interocular rotational misalignment – numerical criteria

— Interocular magnification difference – numerical criteria

Interocular photometric differences

— Interocular luminance difference – numerical criteria

— Interocular contrast difference – caution

— Interocular chromaticity difference – caution

Interocular photometric interaction

— Crosstalk – caution

Accommodation-convergence mismatch – numerical criteria

Other factors to be considered for stereoscopic presentation

— Interocular temporal asynchrony – caution

— Visual motion-induced motion sickness – caution

— Vergence limits – caution

5 Ergonomic recommendations

5.1 General

This part of ISO 9241 intends to reduce the potential for visual discomfort and visual fatigue induced in the viewers who watch stereoscopic images in appropriate viewing conditions which are described in Annex B. Therefore, the case where stereoscopic images happen to be viewed by a person who does not intend to watch the images is beyond the scope of this part of ISO 9241.

To reduce the potential for visual discomfort and visual fatigue during the viewing of stereoscopic images, the provider of stereoscopic image content, stereoscopic displays, and the final products of stereoscopic presentation should evaluate the content described in 5.3, 5.4, and 5.6.

5.2 Viewing conditions

5.2.1 General

It is important to consider the viewing conditions for stereoscopic presentations. In this regard, the design viewing distance, the associated viewing size of the stereoscopic presentation, and the assumed interpupillary distance are important, not only in terms of the perceived extent of depth perception, but also in terms of visual fatigue and discomfort.

5.2.2 Design viewing distance

The design viewing distance of a stereoscopic presentation is determined according to how stereoscopic images will be used as well as with the conditions of the stereoscopic presentation such as the presentation size and resolution. For some types of stereoscopic displays, such as head-mounted displays, the distance equivalent to the design viewing distance (i.e. distance to virtual screen [refer to ISO 9241-305:2008, Figure 74]) can be used. The design viewing distance (or equivalent design viewing distance) should be specified for stereoscopic image content and stereoscopic displays.

5.2.3 Interpupillary distance

For stereoscopic presentations, the extent of perceived depth can be affected by the assumed interpupillary distance. Although a distance of approximately 60 mm is generally assumed, it should

be taken into consideration that there are large individual differences in interpupillary distance[14][23] and that the interpupillary distance of children and teenage individuals is generally shorter than that of adults.[14] For the adjustment of stereoscopic displays, such as head-mounted displays, the range of distances is described in ISO 9241-303:2011, Annex E.14.

5.3 Interocular geometrical differences

5.3.1 Interocular vertical misalignment

Interocular vertical misalignment is produced by the interaction between such vertical misalignment in stereoscopic image content and in stereoscopic displays.

For stereoscopic image content, interocular vertical misalignment is the difference between the vertical position of the left and right images of each image frame. For stereoscopic displays, interocular vertical misalignment is the apparent difference between the vertical positions of the left and right display areas.

For the numerical criteria used as a reference for interocular vertical misalignment of a stereoscopic presentation, C.3 should be referred to.

5.3.2 Interocular rotational misalignment

Interocular rotational misalignment is produced by the interaction between such rotational misalignment in stereoscopic image content and in stereoscopic displays.

For stereoscopic image content, interocular rotational misalignment is the difference between the rotational position of the left and right images of each image frame. For stereoscopic displays, interocular rotational misalignment is the apparent difference between the rotational positions of the left and right display areas.

For the numerical criteria used as a reference for interocular rotational misalignment of a stereoscopic presentation, C.4 should be referred to.

5.3.3 Interocular magnification difference

Interocular magnification difference is produced by the interaction between such magnification differences in stereoscopic image content and in stereoscopic displays.

For stereoscopic image content, interocular magnification difference is the difference between the sizes of the left and right images in each image frame. For stereoscopic displays, interocular magnification difference is the apparent difference between the size of the left and right display areas.

For the numerical criteria used as a reference for interocular magnification difference of a stereoscopic presentation, C.5 should be referred to.

5.4 Interocular photometric differences

5.4.1 Interocular luminance difference

Interocular luminance difference is produced by the interaction between such luminance differences in stereoscopic image content and in stereoscopic displays.

For stereoscopic image content, interocular luminance difference is the difference between the luminance values of the corresponding left and right images in each image frame and can be expressed as the difference between the luminance level of the left and right image content. For stereoscopic displays, interocular luminance difference is the apparent difference between the luminance level of the left and right display areas. For stereoscopic displays with glasses, interocular luminance difference is considered to be the difference in luminance level in the display area as seen through the glasses. For autostereoscopic displays, interocular luminance difference can be affected by the positions of the

left and right eyes relative to the light ray distribution from the display and thus, can be affected by interpupillary distance and viewing distance.

For the numerical criteria used as a reference for interocular luminance difference in a stereoscopic presentation, C.6 should be referred to.

5.4.2   Interocular contrast difference

Interocular contrast difference is produced by the interaction between such contrast differences in stereoscopic image content and in stereoscopic displays.

For stereoscopic image content, interocular contrast difference is the difference between the luminance contrast values of the corresponding left and right images in each image frame. For stereoscopic displays, interocular contrast difference is the apparent difference between the luminance contrast level (dynamic range of luminance) of the left and right display areas.

Due to the interocular contrast difference in stereoscopic image content being affected by the interocular differences in luminance, black level, and gamma characteristics, it is rather difficult to control. Adjustments should be made to reduce the difference as low as reasonably achievable.

NOTE   Monocular contrast is also an important factor that can affect visual fatigue. See the relevant sections of ISO 9241-303:2011, 5.4.4, 5.5.2, and Annex D for the factor of monocular contrast.

5.4.3   Interocular chromaticity difference

Interocular chromaticity difference is produced by the interaction between such chromaticity differences in stereoscopic image content and in stereoscopic displays.

For stereoscopic image content, interocular chromaticity difference is the difference between the chromaticity values of the corresponding left and right images in each image frame. For stereoscopic displays, interocular chromaticity difference is the apparent difference between the chromaticity values of the left and right display areas.

Because the interocular chromaticity difference in stereoscopic image content is affected by the interocular differences in luminance, black level, and gamma characteristics, it is rather difficult to control. Hue and saturation should be adjusted to reduce[16] the interocular chromaticity difference as low as reasonably achievable.

5.5   Interocular photometric interaction

5.5.1   Crosstalk

Crosstalk is the condition in which the optical stimulus presented in one eye is contaminated by the optical stimulus presented to the other eye in stereoscopic presentation. Crosstalk might not only reduce the quality of stereoscopic image presentation and depth perception,[25][26] but might also induce discomfort.[11][25] It is important to take into consideration that the effect of crosstalk on visual discomfort can be affected by binocular disparity and luminance contrast.[28] Adjustments should be made to reduce crosstalk as low as reasonably achievable.

5.6   Accommodation — convergence mismatch

In a stereoscopic presentation, the visual objects in the stereoscopic images can be perceived either in front of or behind the surface of the stereoscopic display depending on the horizontal disparity which is, in effect, a relative horizontal shift between the objects in the left and right images on the display. When the horizontal disparity is defined as zero for an object whose position is simulated to be at the depth of the surface of the stereoscopic display, the positive and negative values of horizontal disparity are, in general, defined as follows: (i) the horizontal disparity in the simulation of an object in front of the display surface is defined as a negative value; (ii) the horizontal disparity in the simulation of an object behind the display surface is defined as a positive value.

When visual objects with some degree of horizontal disparity are simulated in front of or behind the surface of a stereoscopic display, the distance information of accommodation and convergence can be different. When the difference in this distance information exceeds the insensitive region (i.e. depth of focus and fixation disparity), the difference can be the factor in visual fatigue and discomfort. Thus, this factor needs to be carefully considered.

It is thought that visual fatigue and discomfort might be affected by the duration of a certain extent of horizontal disparity and by the spatial distribution and temporal variation of the disparity. The horizontal disparity should be considered with respect to these possibilities. The possible effects of horizontal disparity on visual fatigue and discomfort are described in C.7 in which numerical criteria are presented for reference.

5.7   Other factors to be considered for stereoscopic presentation

Other factors to be considered for stereoscopic presentation are interocular temporal asynchrony, visual motion-induced visual fatigue, and vergence limits.

Interocular temporal asynchrony might influence interocular geometrical and photometric differences, owing to pseudo-matching between the left and right images which can induce visual fatigue and discomfort (see D.1). To reduce the potential for interocular temporal asynchrony, maintaining the temporal synchrony of two corresponding images in a stereoscopic presentation should be considered.

Visual global motion and other visual motion that covers a wide area on a stereoscopic display might induce motion sickness depending on the conditions. Visual global motion depends on the image content and is generally caused by motion of the camera during the shooting of images that involve combinations of rotation around and translation along three axes namely pitch, yaw, and roll. The types of global motion and their undesirable effects are summarized in D.2.

The vergence angle is the angle between the visual axes of the left and right eyes (see C.7.1). The value of this angle is 0 ° when viewing an object at an infinite distance and is a positive value when viewing an object at a shorter distance. When visual objects in a stereoscopic presentation are displayed separately in the left and right images, viewers converge both their eyes to fuse the images into a single percept. Convergence demand is the vergence angle that is required for this fusion of images. A vergence angle with a negative value, which indicates that the two visual axes diverge beyond the point of being parallel, is not usually required under natural viewing conditions. Stereoscopic images that require the two visual axes to diverge further beyond that point should be avoided.

6   How to use the ergonomic recommendations

6.1   General

For developing products of stereoscopic presentation, stereoscopic image content, and stereoscopic displays, this part of ISO 9241 provides general guidelines for reducing visual fatigue and discomfort experienced during viewing of stereoscopic images.

When performing the evaluation recommended in 5.1, the procedure described in 6.2 can be followed.

6.2   Report

For reference purposes, the subclauses in 5.3, 5.4.1, and 5.6 are listed in Annex E.2. Users of this part of ISO 9241 should evaluate the applicability of each subclause. If a product is claimed to have met the applicable items in those subclauses of this part of ISO 9241, the procedure used in evaluating the product should be specified.

Annex E provides an example of both determining and recording the applicability of all the content in 5.3, 5.4.1, and 5.6 and for reporting that they have been evaluated. Other equivalent forms of reporting are also acceptable.

Annex A
(informative)

Overview of the ISO 9241- series

This annex presents an overview of the structure of ISO 9241. For an up-to-date overview of its structure, subject areas, and the current status of both published and projected parts, please refer to

ISO 9241- series.

The structure reflects the numbering of the original ISO 9241 standard, for example, displays were originally Part 3 and are now the 300 series. In each section, the "hundred" is an introduction to the section, for example, Part 100 gives an introduction to the software-ergonomics parts.

Table A.1 — Structure of ISO 9241, *Ergonomics of human–system interaction*

Part	Title
1	Introduction
2	Job design
11	Hardware and software usability
20	Accessibility and human-system interaction
21-99	Reserved numbers
100	Software ergonomics
200	Human-system interaction processes
300	Displays and display-related hardware
400	Physical input devices — Ergonomics principles
500	Workplace ergonomics
600	Environment ergonomics
700	Control rooms
900	Tactile and haptic interactions

Annex B
(informative)

Viewing conditions

B.1 General

To reduce the potential for visual discomfort and visual fatigue while viewing stereoscopic images, appropriate viewing conditions are important. It is useful for the providers of stereoscopic image content, stereoscopic displays, and final products of stereoscopic presentation to inform the viewers of the following information regarding viewing conditions. It is also important to be aware that refraction anomalies might be an additional reason for visual fatigue and discomfort while viewing stereoscopic images.

B.2 Setting viewing position and posture

It is generally assumed that stereoscopic images are viewed from directly in front of a stereoscopic display. When stereoscopic images are viewed at an angle, it might be difficult to achieve stereoscopic perception because of the resulting increase in the trapezoidal distortion of images. It is also assumed that stereoscopic images are viewed at a certain distance. If the viewing distance is shorter than assumed, horizontal disparity will increase, and if it is longer than assumed, the disparity will decrease. Some of the experimental data that have been reported were obtained using high-definition images and at a viewing distance that is triple the height of the display area (3H, or 3 × height).[9] However, other experimental data that were reported were based on a different viewing distance.[11] Whatever the viewing distance might be, it is useful for viewers to be informed of the assumed viewing distance.

In this part of ISO 9241, for stereoscopic presentation, the interocular axis of the viewers' eyes and the horizontal axis of stereoscopic images are assumed to remain on the same plane which is usually a horizontal surface. When the interocular axis of the viewers' eyes is inclined to a certain extent relative to the horizontal axis of stereoscopic images, it may be difficult to achieve the binocular fusion that produces stereopsis.

B.3 Confirmation of clear and appropriate stereoscopic depth perception

If the viewer experiences double-vision or does not experience stereopsis while viewing stereoscopic images, it is appropriate that the viewer stops viewing the images and checks the settings of the stereoscopic image content, stereoscopic display, and viewing conditions. If the viewer experiences discomfort while watching stereoscopic images, pseudostereopsis might have occurred in which the left and right images are reversed, thus, resulting in reversed binocular parallax. If the viewer finds that pseudostereopsis occurs, it is advisable to obviate the cause of the pseudostereopsis or to stop watching the stereoscopic images.

There are individual differences on how people experience stereopsis, visual fatigue, and discomfort when viewing stereoscopic images. If the viewer does not experience stereopsis or feels discomfort even while viewing appropriately adjusted stereoscopic images and displays, it is advisable to stop watching the stereoscopic images.

B.4 Viewing period

Even when the conditions described in B.2 and B.3 are taken into account, a long period of viewing stereoscopic images might induce visual fatigue and discomfort. Moreover, the presence of refraction anomalies as well as other visual deficits might potentiate the induced visual fatigue and discomfort. If

the viewer experiences visual fatigue, discomfort, or double-vision while viewing stereoscopic images, it is advisable to take a break.

Annex C
(informative)

Numerical values to be considered for assessment of visual fatigue and discomfort

C.1 General

Annex C provides the maximum values as reference values (or recommended values) of the limits for viewing stereoscopic images with as little visual fatigue and discomfort as possible. They are shown as summaries of scientific data previously reported in the literature regarding the influence of the factors of interocular geometrical differences (interocular vertical misalignment, interocular rotational misalignment, and interocular magnification difference), interocular photometric difference (interocular luminance difference), and accommodation-convergence mismatch (see Table C.1). These values are shown for each of the typical contexts of use based on the experimental conditions used in the studies from which the reference values are taken. The typical contexts of use are as follows: (i) watching a large screen in a small hall; (ii) watching a large display at home; (iii) working with a desktop monitor; (iv) using a mobile display indoors.

When referring to the reference values shown in this annex, the user of this part of ISO 9241 needs to refer the experimental conditions used in obtaining these values in the literature. These conditions are summarised for each of the influential factors. For the experimental conditions, the duration of the presentation of each influential factor is also indicated. Since these durations are at least five seconds, it is accepted that the stereoscopic images include influential factors that are presented within that range of duration.

NOTE 1   The reference values presented in this annex are for the final products of stereoscopic presentation. When a part (stereoscopic image content, stereoscopic display, etc.) of the final product has a value almost equivalent to the reference value, the total values for the final products of stereoscopic presentation can be larger than the reference value.

NOTE 2   One should be aware that the scientific data that are the basis of this part of ISO 9241 were obtained primarily by subjective scoring which might insufficiently reflect the real use cases and actually induced symptoms.

Table C.1 — Factors presented with reference values in this Annex

Clause/subclause of this part of ISO 9241		Typical context of use				Page
		Watching large screen in a small hall	Watching large display at home	Working with desktop monitor	Using mobile display in a room	
Interocular geometrical difference						
C.3	Vertical misalignment	X				18
C.4	Rotational misalignment	X				19
C.5	Interocular magnification difference	X				19
Interocular photometric difference						
C.6	Interocular luminance difference	X				19
Accommodation – convergence mismatch						

Table C.1 *(continued)*

Clause/subclause of this part of ISO 9241			Typical context of use				Page
			Watching large screen in a small hall	Watching large display at home	Working with desktop monitor	Using mobile display in a room	
	C.7.3	Horizontal disparity relative to stereoscopic display surface	X	X	X		22

C.2 Image analysis method for interocular geometrical difference

When interocular geometrical differences are included in stereoscopic images, they exist in general as the combination of interocular vertical misalignment, interocular rotational misalignment, and interocular magnification difference. Using geometrical analysis, they can be analysed and extracted separately as an optical distortion caused by lens aberration. An example of such analysis is described below.

When two cameras shooting the left and right images are allocated at points O and O', as shown in Figure C.1, interocular vertical misalignment, interocular rotational misalignment, and interocular magnification difference can be formulated using arbitrary points **X** and **X'** on the imaging areas of the two cameras at points O and O', respectively.

Interocular vertical misalignment is expressed as:

$$|\theta - \theta'| \tag{C.1}$$

with

$$\theta = \arcsin(\mathbf{X} \times \mathbf{n})$$
$$\theta' = \arcsin(\mathbf{X'} \times \mathbf{n}) \tag{C.2}$$
$$\mathbf{X'} = R(1,0,0)^T$$

where

  n   is a normal vector of the surface including the Y and Y' axes;

  X and **X'**   are unit vectors along the X and X' axes, respectively.

Interocular rotational misalignment is expressed as:

$$|\Psi - \Psi'| \tag{C.3}$$

with

$$\Psi = \arcsin(\mathbf{Y} \times \mathbf{n})$$
$$\Psi' = \arcsin(\mathbf{Y'} \times \mathbf{n}) \tag{C.4}$$
$$\mathbf{Y'} = R(0,1,0)^T$$

where

  n   is a normal vector of the surface including the Y and Y' axes;

  Y and **Y'**   are unit vectors along the Y and Y' axes, respectively.

Interocular magnification difference is expressed as:

$$k(f/z) \div (f'/z') \tag{C.5}$$

where

k   is a constant;

f and f'   are the focal distances of the left and right cameras, respectively;

z and z'   are depths from the left and right cameras to each of the imaging area.

For the formulae above, the assumptions are made as below:

— the intersection point of the optical axis and image plane is at the centre of the image frame;

— the aspect ratio of a pixel is unity;

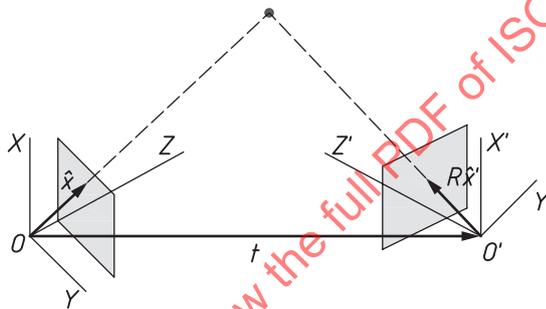— the angle between longitudinal and quadrature axes is 90 °.

Figure C.1 — Camera positions and stereoscopic images

C.3   Interocular vertical misalignment

The reference value (or recommended value) for interocular vertical misalignment is as follows:

   For stereoscopic presentations on a large screen in a small hall, 30 arc min or less.

References [19] and [11].

The experimental conditions used in the references are shown below:

Ref. #	Display type	Display resolution	Display size	Viewing distance	Diff. between vergence and accommodation	Indices	Duration	Exp. Env.	Lumiance of disp.	Lumiance of target
[19]	HDTV		160 inches	3H (597 cm)	0,3 to 0,1 D	Subjective scoring	Ref. 10 s, Test 10 s	–	–	–
[11]	LCD	1 024× 768 pix	170× 128 cm	185 cm	14 to 31 arcmin	Subjective scoring	Ref. 3,5 s, Test 5 s	in a dimly lit room	–	–

Under the conditions of the design viewing distance of stereoscopic image content and the assumed presentation size, interocular vertical misalignment of stereoscopic image content in the viewing angle is expressed as:

$$2 \times \arctan\left(\text{VMI}/(2 \times \text{DVDI})\right) \tag{C.6}$$

where

VMI   is the interocular vertical misalignment of stereoscopic image content, expressed in meters, for the assumed presentation size;

DVDI   is the design viewing distance for stereoscopic image content, in meters.

Under the condition of the design viewing distance of stereoscopic displays, interocular vertical misalignment of stereoscopic displays in the viewing angle is expressed as:

$$2 \times \arctan\left(\text{VMD}/(2 \times \text{DVDD})\right) \tag{C.7}$$

where

VMD   is the interocular vertical misalignment of a stereoscopic display, expressed in meters;

DVDD   is the design viewing distance for stereoscopic display, in meters.

C.4 Interocular rotational misalignment

The reference value (or recommended value) for interocular rotational misalignment is as follows:

For stereoscopic presentations on a large screen in a small hall, 2 ° or less.

References [19] and [11].

The experimental conditions used in the references are shown below:

Ref. #	Display type	Display resolution	Display size	Viewing distance	Diff. between vergence and accommodation	Indices	Duration	Exp. Env.	Lumiance of disp.	Lumiance of target
[19]	HDTV		160 inches	3H (597 cm)	0,3 to 0,1 D	Subjective scoring	Ref. 10 s, Test 10 s	–	–	–
[11]	LCD	1 024× 768 pix	170× 128 cm	185 cm	14 to 31 arcmin	Subjective scoring	Ref. 3,5 s, Test 5 s	in a dimly lit room	–	–

C.5 Interocular magnification difference

The reference values (or recommended values) for the interocular magnification difference are as follows:

For stereoscopic presentations on a large screen in a small hall, 5 % or less for artificial images and 10 % or less for natural images.

References [19] and [11]

NOTE   The ratio of the interocular magnification difference is expressed as the percentage of the difference between the size of the left and right images relative to the size of the right or left image, whichever is larger.

The experimental conditions used in the references are shown below:

Ref. #	Display type	Display resolution	Display size	Viewing distance	Diff. between vergence and accommodation	Indices	Duration	Exp. Env.	Lumiance of disp.	Lumiance of target
[19]	HDTV		160 inches	3H (597 cm)	0,3 to 0,1 D	Subjective scoring	Ref. 10 s, Test 10 s	–	–	–
[11]	LCD	1 024× 768 pix	170× 128 cm	185 cm	14 to 31 arcmin	Subjective scoring	Ref. 3,5 s, Test 5 s	in a dimly lit room	–	–

C.6 Interocular luminance difference

The reference value (or recommended value) for the ratio of the interocular luminance difference is as follows:

For stereoscopic presentations on a large screen in a small hall, 50 % or less

Reference [2] and [11].

NOTE 1   The ratio of the interocular luminance difference is expressed as the percentage of the difference between the luminance of the left and right images relative to the luminance of the right or left image, whichever is higher.

The interocular luminance difference of a stereoscopic presentation can be obtained using the following:

$$100 \times \left(\left(\Pi \left(ILD_i \right) \right)^{(1/N)} - 1 \right) \tag{C.8}$$

with

$$ILD_i = 1 + \left| LCR_i - LCL_i \right| / LCLR_i \tag{C.9}$$

where

Π is the product operator indicating the product of a numerical sequence;

i is the i-th corresponding point pair of the left and right images;

N is the total number of corresponding point pairs obtained for the left and right images;

LCR_i is the luminance of the right image of the i-th pair of corresponding points and their proximities (see Figure C.2);

LCL_i is the luminance of left image of the i-th pair of corresponding points and their proximities (see Figure C.2);

$LCLR_{ii}$ is either LCR_i or LCL_i, if the average luminance of the right image is higher than that of the left image, then LCR_i is chosen and vice versa.

NOTE 2   A local luminance difference caused by a difference in apparent shading between the left and right views might be perceived as shining and might not induce discomfort as discussed in Reference [11], section 2.3.

The experimental conditions used in the references are shown below:

Ref. #	Display type	Display resolution	Display size	Viewing distance	Diff. between vergence and accommodation	Indices	Duration	Exp. Env.	Lumiance of disp.	Lumiance of target
[11]	LCD	1 024× 768 pix	170× 128 cm	185 cm	14 to 31 arcmin	Subjective scoring	Ref. 10 s, Test 10 s	in a dimly lit room	–	–

Ref. #	Display type	Display resolution	Display size	Viewing distance	Diff. between vergence and accommodation	Indices	Duration	Exp. Env.	Lumiance of disp.	Lumiance of target
[2]	Projector		150× 112 cm	4,2 m		Subjective scoring	12 s	–	–	–
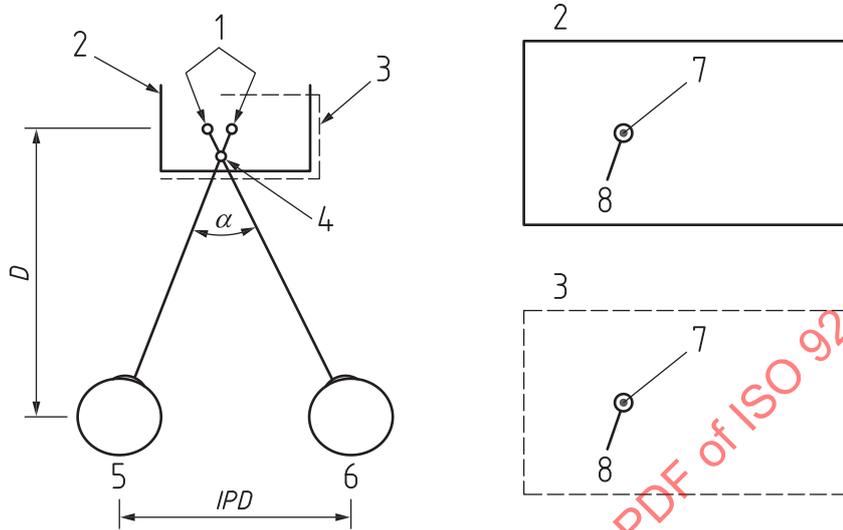
Key

1   corresponding point for right eye and left eye
2   image for right eye
3   image for left eye
4   virtually simulated point
5   left eye
6   right eye
7   corresponding point
8   corresponding point and its proximity

Figure C.2 — Pair of corresponding points and their proximities

C.7   Accommodation — convergence mismatch

C.7.1   Vergence angle

The vergence angle is the angle between the left and right visual axes which is expressed as:

$$\alpha = 2\arctan\left(IPD/2D\right) \tag{C.10}$$

where

    D   is the distance from the nodal point of the eye along the midsagittal plane to the fixation point, F, in space (see Figure C.3);

    IPD   is the interpupillary distance (see Figure C.3).
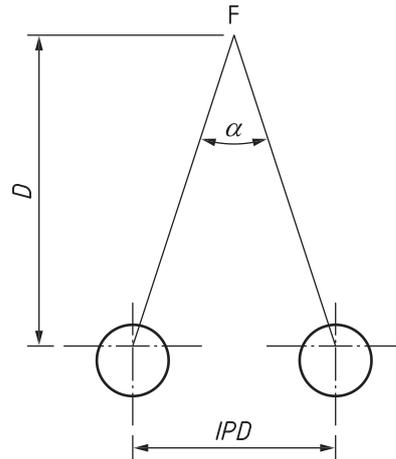
Figure C.3 — Convergence angle

C.7.2 Geometry of accommodation-convergence mismatch

The corresponding point in a visual image that has a certain horizontal disparity relative to the surface of a stereoscopic display simulates a point that is either in front of or behind the surface of the display. For example, in Figure C.4, point P, which has a horizontal disparity $(\alpha_2 - \alpha_1)$, simulates the depth, d, in front of the display surface. Whereas in point Q, which has a horizontal disparity $(\alpha_1 - \alpha_3)$, it simulates the depth, d', behind the display surface.
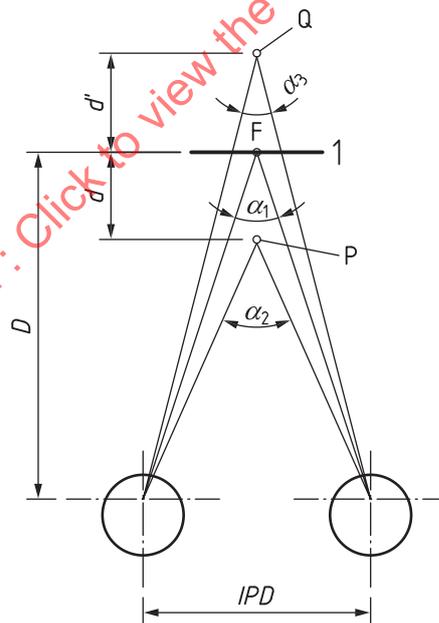
Key

1   screen

**Figure C.4 — Binocular disparity and accommodation-convergence mismatch**

For a visual object in a stereoscopic image that has a certain horizontal disparity, the simulated position is either in front of or behind the surface of the stereoscopic display. In this case, the distance information for accommodation and convergence is inconsistent. For example, for point P, the distance information for convergence is $D-d$, whereas the distance information for accommodation is generally the distance from the eyes to the display surface, D. There are insensitive regions of accommodation and convergence that appear as depth of focus and fixation disparity respectively, and there is virtually

no potential for visual fatigue or discomfort in these regions. However, when the difference of the distance information exceeds the insensitive region, that difference can be a factor that causes visual fatigue or discomfort. Visual fatigue and discomfort possibly depend on spatio-temporal components of stereoscopic information and the susceptibility of individual viewers.

C.7.3 Discomfort condition of accommodation-convergence mismatch

Several reports have offered subjective evaluations of visual fatigue and discomfort when the difference in the distance information for accommodation and convergence becomes large to some extent.[3] [5] [10] These researchers varied the difference in the distance information for accommodation and convergence by changing the horizontal disparity or by changing the convergence stimulus relative to the surface of a stereoscopic display in which distance information for accommodation and convergence was consistent.

When the distance of the accommodation information is plotted against the distance of the convergence information, the Donders' line is a line that is inclined 45 ° on which the distance information for accommodation and convergence is consistent. Within that plot, Percival's zone of comfort is the middle third of the region in which the distance information for accommodation and convergence provides clear single binocular vision.[2] [9] [14] Although there have been reports on the effects on discomfort of viewing distance and duration of viewing,[9] the effects of temporal variation of the accommodation-convergence mismatch that exceeds the zone of comfort remain unclear. Considering the literature, it is suggested that for stereoscopic presentations on a desktop monitor, on a large display at home, and on a large screen in a small hall, the horizontal disparity should be within ± 1 °.[20]
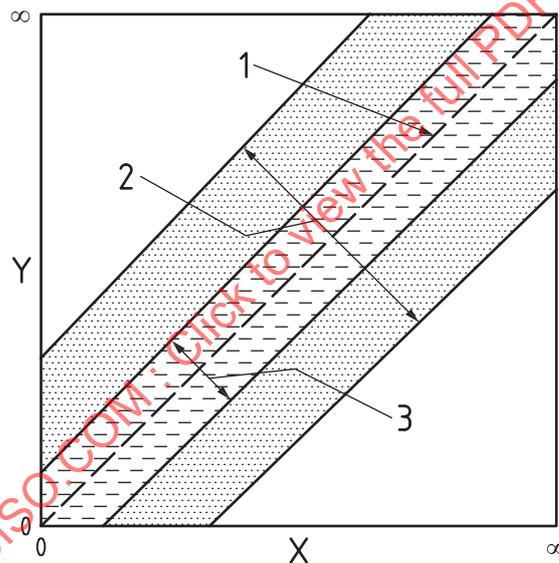
Key

1   Donders' line
2   zone of clear single-binocular vision
3   Percival's zone of comfort
X   vergence stimulus (D)
Y   accommodation stimulus (D)

Figure C.5 — Donders' line and Percival's zone of comfort

The experimental conditions used in the References [3], [5], [10], [12], [17], [18], and [22] are shown below:

Ref #	Display type	Display resolution	Display size	Viewing distance	Diff. between vergence and accommodation	Indices	Duration	Exp. Env.	Lumiance of disp.	Lumiance of target
[3]	HDTV master monitor CRT	HDTV	32 inches	1,2 m (3H)	8 conditions were prepared based on the ratio of individual ability for vengeance (relative vengeance limits)	Relative vengeance limits	Subjective scoring after approx. 1h observ.	–	–	–
[10]		921 600 pix	10,4 inches	0,5 m	± 0,5 °	Accommodation	80 s per session × 5 sessions	–		4, 40, 8 cd/m^2
[5]	Volumetric disp (TFT)	1 920 × 1 200 pix	22,2 inches	31,1; 39,4; 53,6 cm (3,21; 2,54; 1,87 °)	0; ± 0,33; ± 0,67; ± 1,33 °	Visual function	Variable (at least 6min approx. 0,634 s × 293 trial × 2 sessions	–	–	–
[5]	Volumetric disp (TFT)	3 840 × 2 400 pix	22,2 inches	31,1; 39,4; 53,6 cm (3,21; 2,54; 1,87 °)	0; ± 0,33; ± 0,67; ± 1,33 °	Visual function	Variable (at least 10min approx. 1 s × 293 trial × 2 sessions	–	–	–
[5]	Volumetric disp and conventional CRT	1 600 × 1 024 pix (CRT)	22,2 inches	31,1; 39,4; 53,6 cm (3,21; 2,54; 1,87 °)	0; ± 0,33; ± 0,67; ± 1,33 °	Psychometric function	Variable (at least 15min approx. 3 s × 100 trial × 3 stimuli	the room was dimly lit	–	–
[5]	Volumetric disp (TFT)	1 920 × 1 200 pix	22,2 inches	31,1; 39,4; 53,6 cm (3,21; 2,54; 1,87 °)	0; ± 0,33; ± 0,67; ± 1,33 °	Subjective scoring	5,6 s per trial (totally 90 min approx.. 45 min × 2 days)	–	–	–
[17]	CRT	1 600 × 1 200 pix	22,2 inches (for each eye)	–	combinations of (0,25; 0,4; 0,77; 10 m) for vengeance and focal	Subjective scoring	30 min (20 min trials + 10 min competition question-naire) per day × 3 days	–	–	The space average luminance was 0,13 cd/m^2
[17]	CRT	1 600 × 1 200 pix	22,2 inches (for each eye)	–	combinations of (0,3; 0,77; 1,11;2,0; 10, inf m) for vengeance and (0,4; 0,77; 10) focal	Subjective scoring	By 2 min × 10 times (for time course of visual fatigue)	–	–	The space average luminance was 0,13 cd/m^2
[22]	HDTV	1 920 × 1 080 pix	28 inches	108 cm (3H)	0; ± 0,82; ± 1,36; ± 1,90 °	Subjective scoring	After 1h observ.	–	–	–
[12]	HMD	–	–	2 m; 33,75 °	–	Subjective scoring	By 20 min × 3 times	–	–	–
[12]	TV	–	14 inches	60 cm	–	Subjective scoring	By 20 min × 3 times	–	–	–

Ref #	Display type	Display resolution	Display size	Viewing distance	Diff. between vergence and accommodation	Indices	Duration	Exp. Env.	Lumiance of disp.	Lumiance of target
[12]	HMD	–	–	2 m; 33,75 °	–	Subjective scoring	By 20 min × 3 times	–	–	–
[12]	TV	–	20 inches	60 cm	–	Subjective scoring	By 20 min × 3 times	–	–	–
[12]	screen with shaky video	–	90 inches	2,3 m	–	Subjective scoring	After approx. 20 min observ.	–	–	–
[12]	screen with LDP	–	90 inches	2,0 m	–	Subjective scoring	After 140 min observ.	–	On the white area, luminance was 100 cd/m2 (DLP) and 103 cd/m2 (LCD) and on the black area 4 cd/m2 (DLP) and 7 cd/m2 (LCD)	–
[12]	screen with LCD	–	90 inches	2,0 m	–	Subjective scoring	After 140 min observ.	–	–	–

C.7.4   Other related factors

There is a range of disparities relative to the left and right eyes' retinae, within which two images are fused and perceived as single. This range is called Panum's fusional area. Outside this area, the images are perceived as double and this might also be considered a cause of visual fatigue and discomfort especially when the double images are experienced often during viewing stereoscopic images. The range expressed in angular subtense depends on various factors, for example, the characteristics of the images (spatiotemporal components, luminance, etc.) and the characteristics of the surrounding environment.