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Ergonomics of human-system interaction —

Part 331:
Optical characteristics of autostereoscopic displays

Ergonomie de l'interaction homme-système —

Partie 331: Caractéristiques optiques des écrans autostéréoscopiques

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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ISO/TR 9241-331 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 4, *Ergonomics of 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 4: Keyboard requirements*
- *Part 5: Workstation layout and postural requirements*
- *Part 6: Guidance on the work environment*
- *Part 9: Requirements for non-keyboard input devices*
- *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 100: Introduction to standards related to software ergonomics* [Technical Report]
- *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)* [Technical Report]
- *Part 309: Organic light-emitting diode (OLED) displays* [Technical Report]
- *Part 310: Visibility, aesthetics and ergonomics of pixel defects* [Technical Report]
- *Part 331: Optical characteristics of autostereoscopic displays* [Technical Report]
- *Part 400: Principles and requirements for physical input devices*
- *Part 410: Design criteria for physical input devices*
- *Part 411: Evaluation methods for the design of physical input devices* [Technical Specification]
- *Part 420: Selection of physical input devices*
- *Part 910: Framework for tactile and haptic interaction*
- *Part 920: Guidance on tactile and haptic interactions*

User-interface elements, requirements, analysis and compliance test methods for the reduction of photosensitive seizures, ergonomic requirements for the reduction of visual fatigue from stereoscopic images, and the evaluation of tactile and haptic interactions are to form the subjects of future Parts 161, 391, 392 and 940.

Introduction

Recent developments in display technologies have made it possible to render highly realistic content on high-resolution colour displays. The developments include advanced 3D display technologies such as autostereoscopic displays. The new 3D displays extend the capabilities of applications by giving the user more-realistic-than-ever perception in various application fields. This is valid not only in the field of leisure but also in the fields of business and education, and in medical applications.

Nevertheless, 3D displays have display-specific characteristics originating from the basic principles of the image formation applied for the different 3D display designs. Among negative characteristics are imperfections that affect the visual quality of the displayed content and the visual experience of the users. These imperfections can induce visual fatigue for the users, which is one of the image safety issues described in IWA 3:2005. Nevertheless, it is important for the end user to be able to enjoy of the benefits of the 3D display without suffering any undesirable biomedical effects. It is therefore necessary that a standardized methodology be established which characterizes and validates technologies in order to ensure the visual quality of the displays and the rendered content. The development of such a methodology has to be based on the human perception and performance in the context of stereoscopic viewing.

The negative characteristics, by nature, originate from both 3D displays and 3D image content. In this part of ISO 9241, however, attention is focussed only on 3D display, for simplicity of discussion and as a first step.

In ISO 9241-303, performance objectives are described for virtual head-mounted displays (HMDs). This is closely related to autostereoscopic displays, but not directly applicable to them.

Considering the growing use of autostereoscopic displays, and the need for a methodology for their characterization in order to reduce visual fatigue caused by them, this Technical Report presents basic principles for related technologies, as well as optical measurement methods required for the characterization of the current technologies and for a future International Standard on the subject.

Since this Technical Report deals with display technologies that are in continual development, its content will be updated if and as necessary. It includes no content intended for regulatory use.

Ergonomics of human-system interaction —

Part 331:
Optical characteristics of autostereoscopic displays

1 Scope

This part of ISO 9241 establishes an ergonomic point of view for the optical properties of autostereoscopic displays (ASDs), with the aim of reducing visual fatigue caused by stereoscopic images on those displays. It gives terminology, performance characteristics and optical measurement methods for ASDs.

It is applicable to spatially interlaced autostereoscopic displays (two-view, multi-view and integral displays) of the transmissive and emissive types. These can be implemented by flat-panel displays, projection displays, etc.

2 Terms and definitions

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

2.1 General terms

2.1.1
3D display
display device or system including a special functionality for enabling depth perception

2.1.2
stereoscopic display
3D display where depth perception is induced by binocular parallax

NOTE 1 People perceive depth from the retinal disparity provided by binocular parallax.

NOTE 2 Stereoscopic displays include stereoscopic displays requiring glasses, stereoscopic HMDs and autostereoscopic displays.

NOTE 3 See ISO 9241-302:2008, 3.5.5, *binocular display device*.

2.1.3
autostereoscopic display
ASD
stereoscopic display that requires neither viewing aids such as special glasses nor head-mounted apparatus

NOTE Autostereoscopic displays includes two-view displays, multi-view displays and integral displays, as well as other types of display not discussed in this part of ISO 9241, such as holographic displays and volumetric displays.

2.1.4
two-view display
two-view autostereoscopic display
autostereoscopic display that creates two monocular views with which the left and right stereoscopic images are coupled

2.1.5
multi-view display
multi-view autostereoscopic display

autostereoscopic display that creates more than two monocular views with which the stereoscopic images are coupled

NOTE 1 It becomes an autostereoscopic display when the number of stereoscopic images is increased from two to more than two.

NOTE 2 Principally, one of multiple stereoscopic images corresponds to one of multiple stereoscopic views, yet not necessarily excluding one-to-multi correspondence.

2.1.6
integral display
integral autostereoscopic display

autostereoscopic display that is intended to optically reproduce three-dimensional objects in space

NOTE Since, at present, it is not easy to make the optical reproduction perfect, integral displays are not necessarily free from such factors of undesirable biomedical effect as accommodation-vergence inconsistency (see 3.7, 4.1).

2.1.7
stereoscopic images

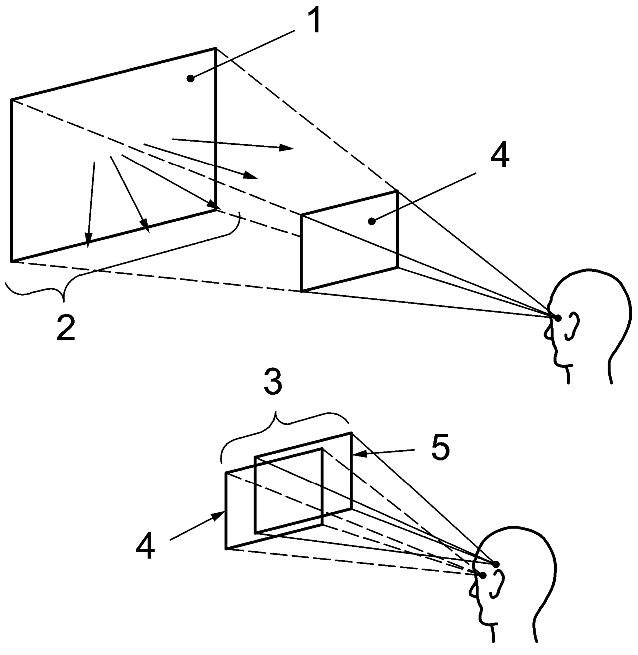
set of images with parallax shown on a stereoscopic display

NOTE See 2.1.8.

2.1.8
stereoscopic views

pair of sights provided by a stereoscopic display, which induce stereopsis

NOTE See Figure 1.



Key

1	autostereoscopic display	3	stereoscopic views	5	monocular view (right eye)
2	stereoscopic images	4	monocular view (left eye)		

Figure 1 — Relation between stereoscopic images, stereoscopic views and monocular view

2.1.9
monocular view
one stereoscopic view

NOTE See 2.1.8.

2.1.10
number of views
number of monocular views with which stereoscopic images are coupled

2.2 Human factors

2.2.1
binocular parallax
apparent difference in the direction of a point as seen separately by one eye and by the other, while the head remains in a fixed position

NOTE 1 See IWA 3:2005, 2.15.

NOTE 2 Binocular parallax is equivalent to the optic angle between the visual axes of both eyes, when they are fixated to a single point.

2.2.2
visual fatigue
eyestrain or asthenopia, which shows a wide range of visual symptoms, including tiredness, headache and soreness of the eyes, caused by watching images in a visual display

NOTE 1 Adapted from IWA 3:2005, 2.13.

NOTE 2 See also ISO 9241-302:2008, 3.5.3.

2.2.3
accommodation
adjustment of the optics of an eye to keep an object in focus on the retina as its distance from the eye varies

[SOURCE: ISO 9241-302:2008, 3.5.1, modified — the Note to the definition has not been included.]

NOTE Adapted from IWA 3:2005, 2.18.

2.2.4
convergence
turning inward of the lines of sight toward each other as the object of fixation moves toward the observer

[SOURCE: ISO 9241-302:2008, 3.5.10]

NOTE See also IWA 3:2005, 2.19.

2.3 Performance characteristics

2.3.1
3D crosstalk
leakage of an unwanted image data to each eye

2.3.2
interocular crosstalk
leakage of the stereoscopic image(s) from one eye to the other

2.3.3
interocular luminance difference
difference in luminance between stereoscopic views

2.3.4
interocular chromaticity difference
difference in chromaticity between stereoscopic views

2.3.5
interocular contrast difference
difference in contrast between stereoscopic views

2.3.6
3D moiré
periodical irregularity of luminance or chromaticity in space or angular directions on a 3D display

2.3.7
pseudoscopic images
pseudo-stereoscopic images
set of images with inverted parallax shown on a stereoscopic display

2.3.8
3D image resolution
spatial resolution of the image with depth shown on a stereoscopic display

NOTE The term “spatial resolution” refers to horizontal and vertical resolution, as shown in the ISO 9241 300 series.

2.3.9
qualified viewing space
QVS
⟨autostereoscopic displays⟩ space for the eye in which image(s) is observed at an acceptable level of visual fatigue

NOTE 1 See also ISO 9241-302, 3.5.42.

NOTE 2 QVS is defined separately for each eye as the measurement result is unambiguous and equally valid for all observers, whereas the measured QBVS and QSVS results as such are only valid for people with average eye separation.

NOTE 3 This term still needs discussion, because “monocular” viewing space is insufficient for determining the characteristics of autostereoscopic displays that require “binocular” viewing.

2.3.10
qualified binocular viewing space
QBVS
space in which images on a stereoscopic display are observed by both eyes at an acceptable level of visual fatigue

NOTE 1 This term is based on the concept that there should be space where visual fatigue caused by pseudo-stereoscopy is small enough.

NOTE 2 This term still needs discussion, because it is not clear whether there can exist a space larger than QSVS, which would still satisfy the visual fatigue requirements.

2.3.11
qualified stereoscopic viewing space
QSVS
space in which images on a stereoscopic display induce stereopsis at an acceptable level of visual fatigue

NOTE This term is based on the concept that there should be space where visual fatigue caused by stereoscopic images is small enough.

3 Autostereoscopic display technologies

3.1 General

In this clause, technological features of autostereoscopic displays are described. Firstly, information for people to perceive depth provided by autostereoscopic displays is explained. This is essential for understanding the basics of autostereoscopic display technologies. Secondly, the autostereoscopic displays are classified according to their technological aspects. Three different display technologies are presented based on their principles, structures and features. Finally, to establish optical measurement methods for evaluating visual fatigue caused by these autostereoscopic displays, the related matters are discussed in the light of both, ergonomics and technologies.

3.2 Cues for depth perception

People usually perceive the three-dimensional visual world based on retinal images of two eyes. The cues for such depth perception are not only binocular cues but also monocular cues. These cues are shown in Table 1.

Table 1 — Classification of depth cues

	Binocular	**Monocular**
Absolute depth	Convergence/Binocular parallax	Accommodation Motion parallax
Relative depth	Binocular disparity	Motion disparity Pictorial depth cues [a]

[a] Pictorial depth cues

Geometrical perspective

Relative/familiar size

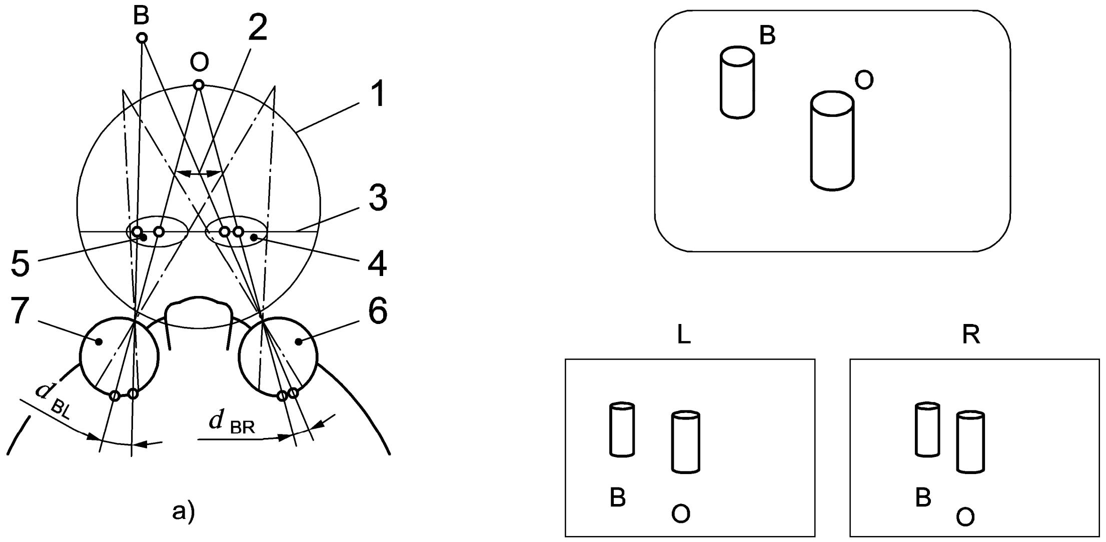
Shading/Shadow

Occlusion

Texture

Aerial perspective, etc.

For autostereoscopic displays, the device itself provides binocular and monocular parallax as absolute distance cues, and binocular and monocular disparity as relative depth cues. Binocular parallax is presented as interocular differences in apparent direction of a target, while binocular disparity is presented as in relative position of retinal images of two different objects. Both concepts are shown in Figure 2.



a)

b)

Key

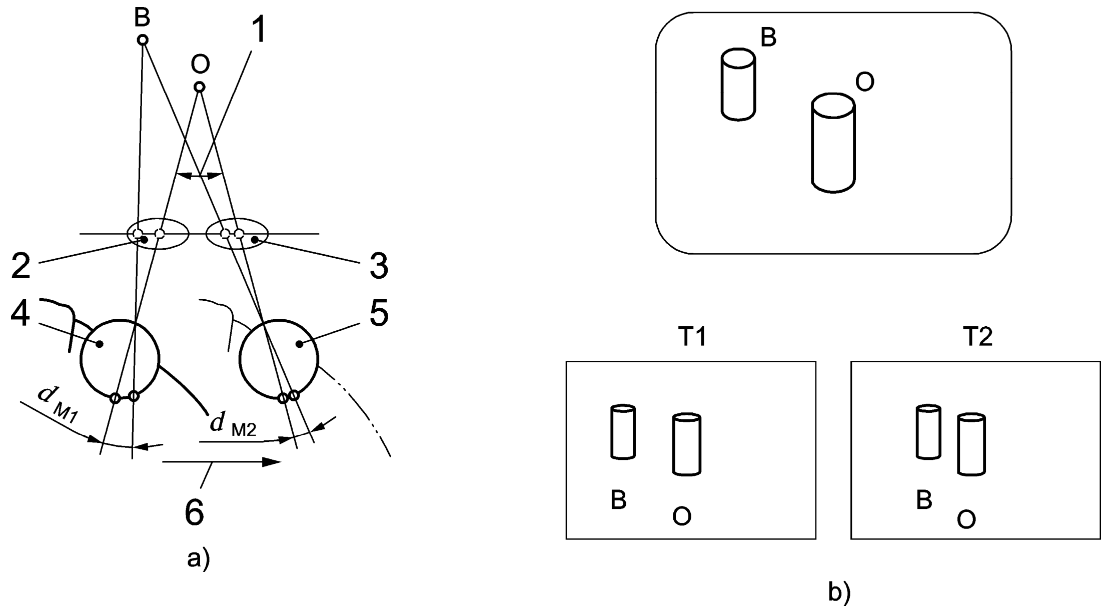
1	Vieth Muller circle	5	image for left eye	O	fixated object
2	binocular parallax θ_{LOR}	6	right eye	L	left eye image
3	display surface	7	left eye	R	right eye image
4	image for right eye	B	target object	$d_{BR} - d_{BL}$	= binocular disparity

Figure 2 — Binocular parallax and disparity

If an object, (e.g. object “O” in Figure 2a), is fixated by the two eyes, the apparent direction of the object relative to the right eye is different from the direction relative to the left eye. This difference is called binocular parallax. Moreover in Figure 2a, when the other object, such as “B”, exist, the apparent gap between the two objects “O” and “B” is different in the views of the left and the right eye (see Figure 2b). This difference originates in binocular parallax. This difference, binocular disparity, is described as the difference in angle between d_{BL} and d_{BR} as shown in Figure 2.

In Figure 2, the circle connecting three points, two nodes of the eyes and the fixation point “O”, is the Vieth-Müller circle, which is the theoretical horopter. Any point on the horopter builds up its retinal image on corresponding points of the two retinae, thus are viewed single. Therefore, none of the points on the circle produce binocular disparity with each other including the fixated point “O”. The actual horopter, or empirical horopter, has been measured, and is known as slightly different in its shape from the theoretical horopter.

Motion parallax and disparity are caused when different images are observed from different positions. As the head moves from left to right, the absolute and relative positions of object images change, which creates motion parallax and disparity, respectively, as shown in Figure 3.



a)

b)

Key

1	motion parallax θ_{M12}	4	right eye position at time T1	B	target object
2	image position at time T1	5	right eye position at time T2	O	fixated object
3	image position at time T2	6	head movement		$d_{M1} - d_{M2} =$ motion disparity

Figure 3 — Motion parallax and disparity

When an object (e.g. object “O” in Figure 3) is fixated by a single eye during head movements, the apparent direction of the object relative to the eye varies depending on the eye’s position. This variation of apparent direction is called motion parallax. Moreover, when the two objects, “O” and “B” in Figure 3, are seen during head movements, the apparent adjacency changes, for example, between the views at time T1 and time T2 (see Figure 3). This change is produced because of motion parallax. This difference is described as the difference in angle between d_{M1} and d_{M2}, or motion disparity.

The term “motion parallax” is used for motion disparity. For example, motion parallax is defined as the relative movement of images across the retina resulting from movement of the observer.

3.3 Stereoscopic display classification

A stereoscopic display is defined as a 3D display, for which depth perception is induced by binocular parallax. The binocular parallax provides disparity between retinal images, which induces stereopsis.

Stereoscopic displays can be classified into three types:

- autostereoscopic displays;
- stereoscopic Head-Mounted Displays (HMDs); and
- stereoscopic displays requiring glasses.

Stereoscopic viewing has traditionally required users to wear special viewing devices, like glasses with polarizing or colour filters. In contrast, autostereoscopic displays do not require special viewing devices. Whether glasses are required or not is an important factor in ergonomics. The visual factors of HMDs are also different from those of autostereoscopic displays or stereoscopic displays using glasses. This is the reason why these three display types are classified in three separate categories. In this part of ISO 9241, only autostereoscopic displays are covered.

Until now, many types of autostereoscopic displays have been developed and various concepts of classification have been proposed according to their related factors. Figure 4 shows the classification of autostereoscopic displays in this part of ISO 9241. In this taxonomy, ergonomics aspects of autostereoscopic display hardware are the basis for the classification. There exist other stereoscopic display technologies, that are not shown in this taxonomy – some of which are not yet even known.

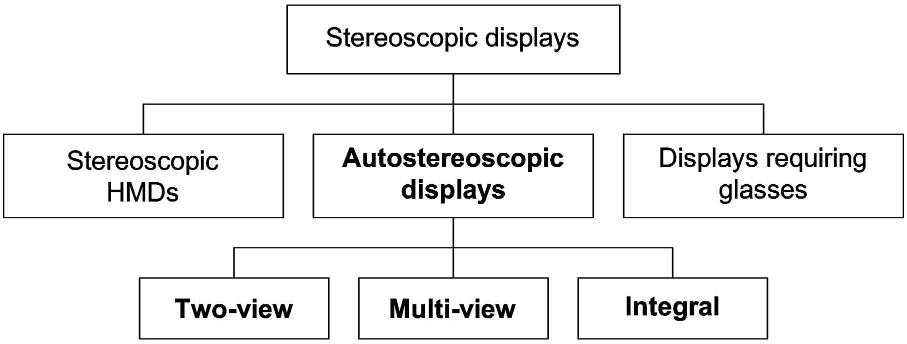


Figure 4 — Taxonomy of stereoscopic displays

Autostereoscopic displays can be classified into two-view, multi-view and integral displays according to the viewpoints of visual ergonomics. In this classification, the integral display belongs to autostereoscopic displays, as it fulfils the definition of autostereoscopic displays.

Autostereoscopic displays could also be classified into spatially and temporally interlaced types. Human factors for the spatially interlaced type are generally different from those for the temporally interlaced type. Compared to the spatially interlaced type, the temporally interlaced type can have discriminative characteristics, such as temporal changes in luminance and colour, and flicker, which can affect the visual quality of the displayed content and the visual experience of the users.

An autostereoscopic display is able to produce, at least, two different images which are perceived by the two eyes of the user, respectively. Those images are used for producing binocular parallax and disparity to simulate depth among the observer and objects. Examples of producing different images are shown in Figure 2 and Figure 3.

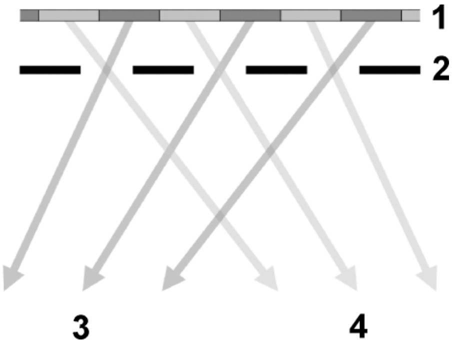
For the multi-view and integral displays, lateral head movements parallel to display surface can derive parallax images, which simulate motion parallax and disparity also for simulating depth among observer and objects.

Autostereoscopic displays have some principle differences in their optical characteristics compared to conventional two-dimensional (2D) displays:

- Binocular difference;
  - An autostereoscopic display is able to show a different image for each eye, while a 2D display is not.
- Directional non-uniformity;
  - An autostereoscopic display provides different images in different angular directions, and thus, angular directional characteristics are not made to be uniform. For a 2D display, angular uniformity is tried to be maintained.
- Lateral non-uniformity.
  - In some cases, in order to improve some of the characteristics, all spatial screen locations are not made to have the same characteristics.

Some of the autostereoscopic displays can provide not only horizontal but also vertical parallax/disparity. In this part of ISO 9241, mainly one-dimensional parallax in the horizontal direction is discussed.

A typical spatially interlaced autostereoscopic display consists of a base 2D display panel and some additional (electro-)optical components for controlling the light output angles, such as parallax barrier or lenticular sheet. In spatially interlaced displays, the displayed picture elements, pixels or sub-pixels, are multiplexed into two or more sections with slightly different stereoscopic views of the displayed content. The parallax barrier or lenticular structure conveys the information to the space in front of the display. A parallax barrier has an array of light blocking opaque barriers, each slit between the barriers corresponding to each certain pixel group. In lenticular type autostereoscopic displays, semi-cylindrical lenses are used instead of the slits to lessen the absorption of display illumination. In addition, many other possibilities exist for the creation of a two-view spatially interlaced display. When the two eyes of the user receive the binocular parallax resulting from these arrangements, depth perception is induced. The basic principle of the parallax barrier type autostereoscopic display is illustrated in Figure 5. In this figure, the arrow represents the main direction of light from each pixel. For simplicity, descriptions and drawing of autostereoscopic displays henceforth refer to the parallax barrier type autostereoscopic display.



Key

1	display (sub)pixels	3	light rays from pixels for the left eye
2	parallax barrier	4	light rays from pixels for the right eye

Figure 5 — Conceptual illustration of basic display technology in a two-view display

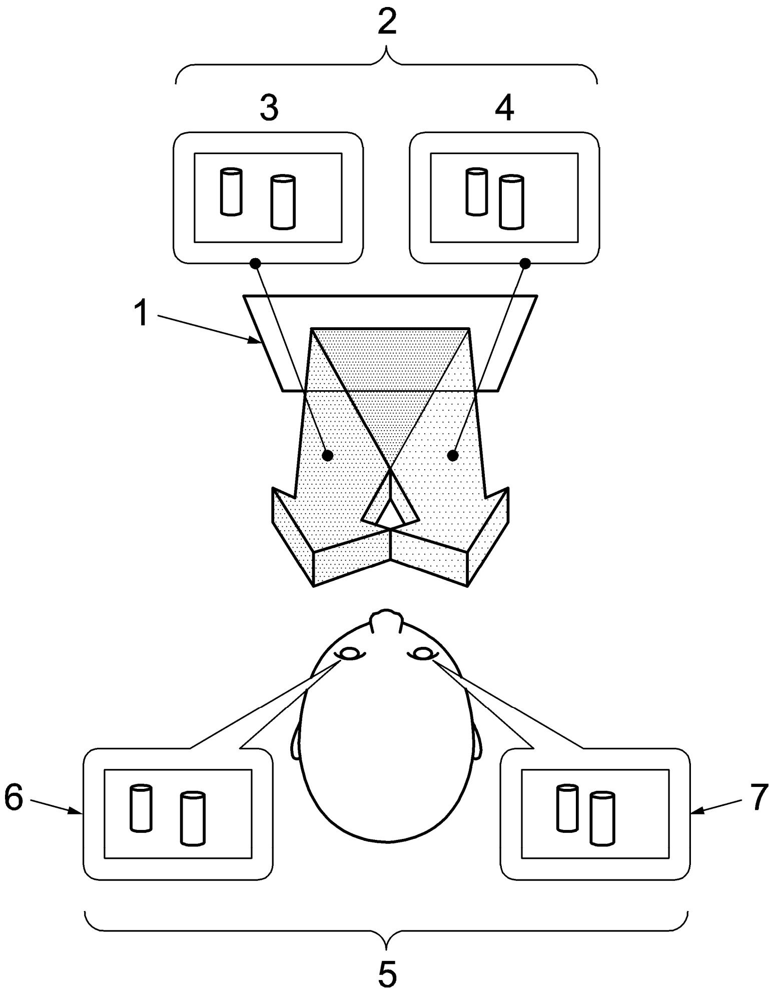
Parallax barrier or lenticular array structures are necessary to be aligned with the display pixels. Content of the display pixels or sub-pixels should be interlaced according to these structures. Vertical structures typically result in reduced observed resolution in horizontal direction. Slanted or step barrier structures can divide the resolution drop both in horizontal and vertical direction.

An autostereoscopic display can generally be used as a 2D display by showing images without binocular parallax. Some autostereoscopic displays have a 2D/3D selection switch by which they are turned to 2D mode, if needed.

3.4 Two-view (autostereoscopic) display

3.4.1 Definition and principle

A two-view display is defined as an autostereoscopic display, that creates two monocular views with which the left and right stereoscopic images are coupled. On a two-view display, left and right images are shown. The left part of stereoscopic images is observed by the left eye, while the right part is observed by the right eye, as illustrated in Figure 6. As a result, binocular parallax for depth perception can be created.



Key

1 two-view display

2 stereoscopic images

3 left image

4 right image

5 stereoscopic views

6 monocular view (left eye)

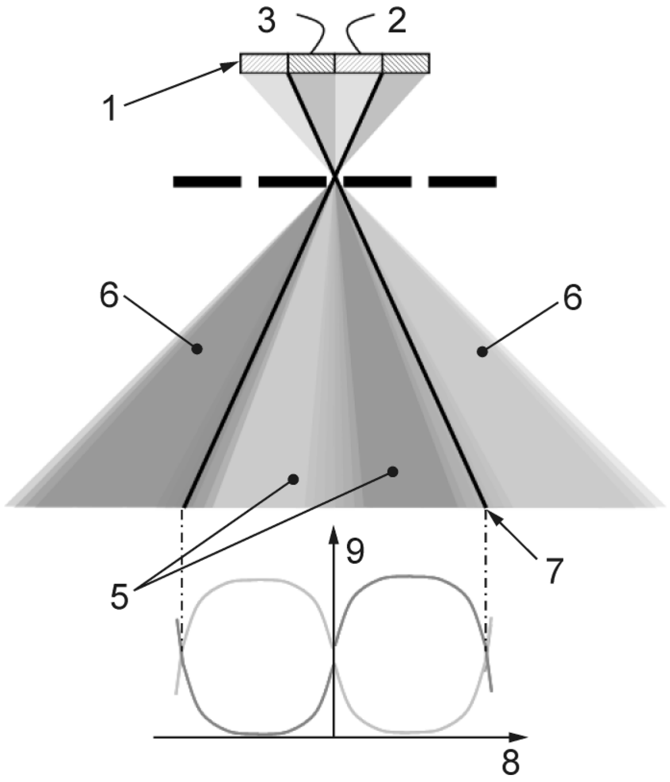
7 monocular view (right eye)

Figure 6 — Basic working principle of a two-view display

3.4.2 Structure and optical property

This subclause describes the optical properties of two-view displays, while different types of qualified viewing spaces for the display are described in clause 6 based on the optical properties and performance characteristics described in Clause 4.

In a two-view display, the display panel has two kinds of pixel or sub-pixel groups for showing left and right images (left-eye pixels and right-eye pixels), as shown in Figure 7. On the display panel, an optical component for distributing the light from each pixel group, such as a parallax barrier, is attached. Each slit of the parallax barrier corresponds to each pixel set of left- and right-eye pixels. The light from each pixel set and the light from its adjacent pixel set passing through the corresponding slit will generate main and side lobes, respectively. The lobe can be defined as a segment formed by a set of light rays that are emitted from the screen for producing stereoscopic images. On the boundary of lobe, the luminance of the right set is the same as that of the left set.

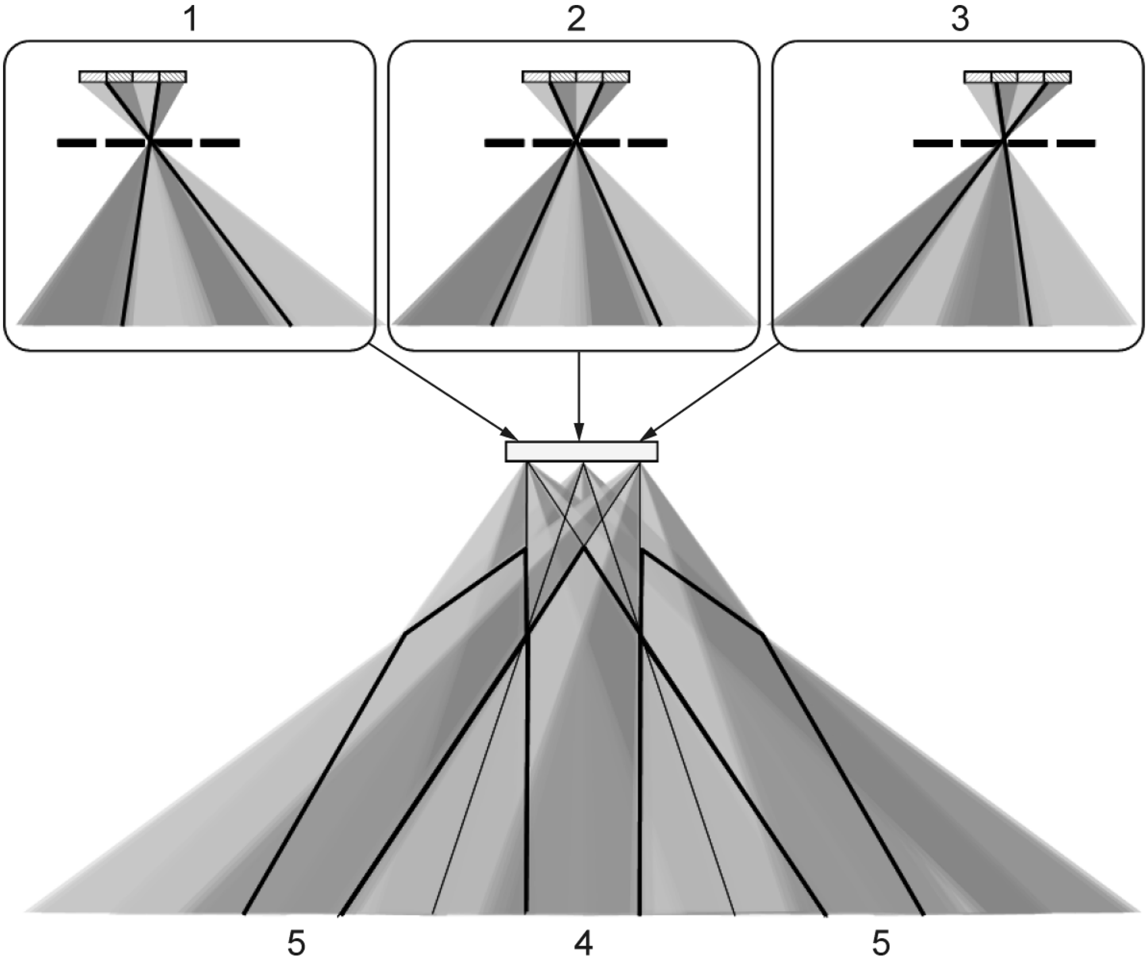


Key

1 two-view display
2 left eye pixel
3 right eye pixel
4 parallax barrier
5 light for main lobe
6 light for side lobe
7 boundary of lobe
8 angle
9 luminance

Figure 7 — Angular luminance output of a two-view (parallax barrier) display

For widening each lobe, generally the angular distributions on each display location are made to be different. This is illustrated in Figure 8, as well as the generation of lobes. The recurring lobes can be applicable to simultaneous multi-user viewing.



Key

1 left location

2 centre location

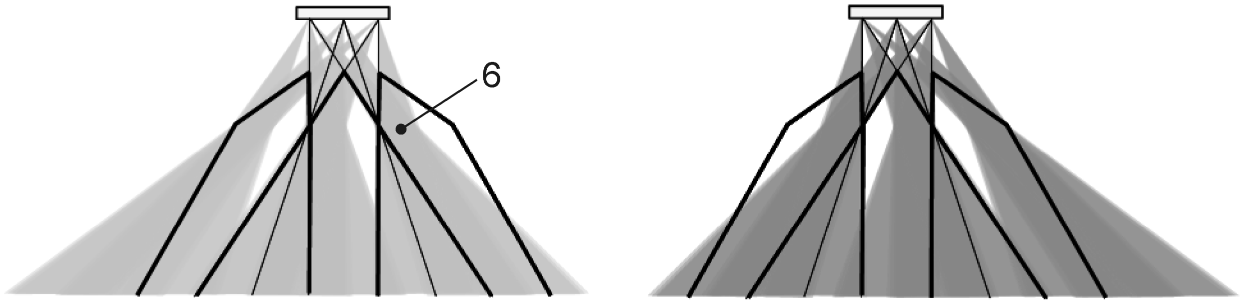
3 right location

4 main lobe

5 side lobe

Figure 8 — Varying angular light distributions in different screen locations and the generation of main lobe and side lobes

As shown in Figure 9, when pixels of only one of the two stereoscopic images are on (=white), light all over the screen area from these pixels concentrates into the space. In this space, each part of stereoscopic images can be seen. This important space or position is sometimes called a “viewpoint”.

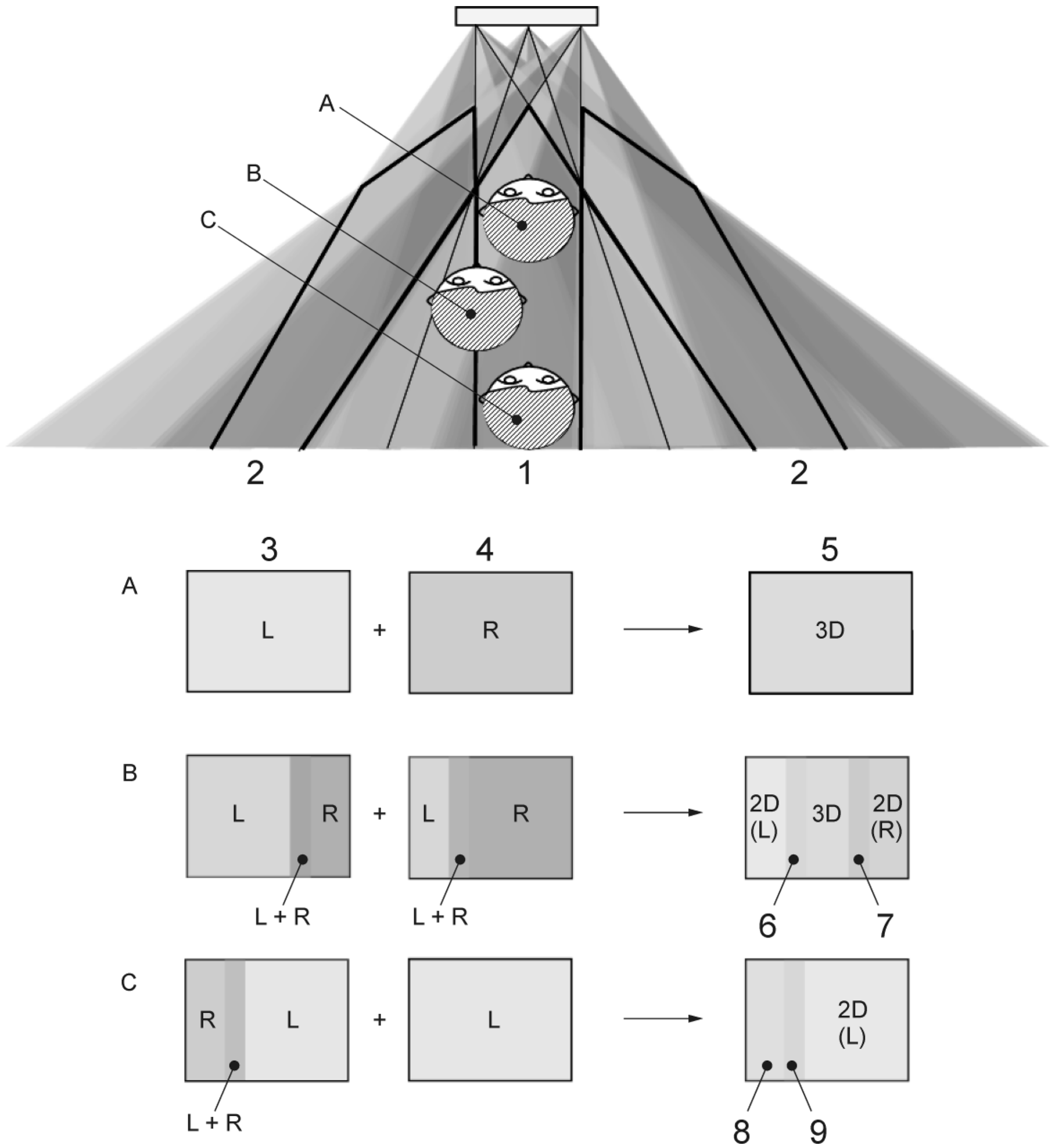


Key

6 space, where the light from left-eye pixels concentrates

Figure 9 — Concentration of light from left-eye and right-eye pixels

When both eyes are placed inside the same lobe space, pseudoscopy does not occur. For example, at position (A) in Figure 10, the observer can see stereoscopic images on the whole screen. At position (B), stereoscopic images can be seen in the centre of the screen, while left and right next to it, 2D images are seen. At position (C) partially outside the lobe, the observer perceives pseudoscopy on the left side of the screen.

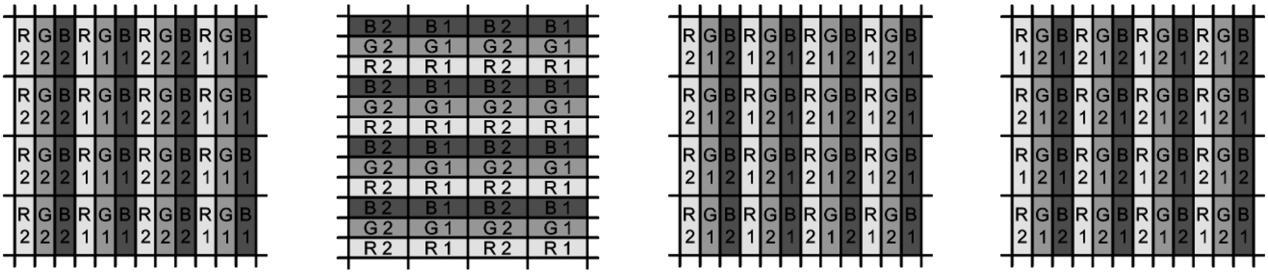


Key

1 main lobe
2 side lobe
3 left-eye view
4 right-eye view
5 superimposed images of left and right eyes
6 left eye/left and right eye
7 left and right eye/right eye
8 right eye/left eye/pseudoscopy
9 left and right eye/left eye/pseudoscopy
L left image
R right image
3D stereopsis

Figure 10 — Relation between observer's position and the observed view

Figure 11 shows some display interlacing method examples for two-view displays. The light-directing optical component is aligned with the pixels typically in vertical direction, but other solutions are possible, as well. Both vertical and slanted structures mainly create parallax in the horizontal direction.



R2	G2	B2	R1	G1	B1	R2	G2	B2	R1	G1	B1
R2	G2	B2	R1	G1	B1	R2	G2	B2	R1	G1	B1
R2	G2	B2	R1	G1	B1	R2	G2	B2	R1	G1	B1
R2	G2	B2	R1	G1	B1	R2	G2	B2	R1	G1	B1

a) Pixel interlacing with horizontal sub-pixel arrays

B 2	B 1	B 2	B 1
G 2	G 1	G 2	G 1
R 2	R 1	R 2	R 1
B 2	B 1	B 2	B 1
G 2	G 1	G 2	G 1
R 2	R 1	R 2	R 1
B 2	B 1	B 2	B 1
G 2	G 1	G 2	G 1
R 2	R 1	R 2	R 1
B 2	B 1	B 2	B 1
G 2	G 1	G 2	G 1
R 2	R 1	R 2	R 1

b) Pixel interlacing with vertical sub-pixel arrays

R2	G1	B2	R1	G2	B1	R2	G1	B2	R1	G2	B1
R2	G1	B2	R1	G2	B1	R2	G1	B2	R1	G2	B1
R2	G1	B2	R1	G2	B1	R2	G1	B2	R1	G2	B1
R2	G1	B2	R1	G2	B1	R2	G1	B2	R1	G2	B1

c) Sub-pixel interlacing with horizontal sub-pixel arrays

R1	G2	B1	R2	G1	B2	R1	G2	B1	R2	G1	B2
R2	G1	B2	R1	G2	B1	R2	G1	B2	R1	G2	B1
R1	G2	B1	R2	G1	B2	R1	G2	B1	R2	G1	B2
R2	G1	B2	R1	G2	B1	R2	G1	B2	R1	G2	B1

d) Slanted or step interlacing with horizontal sub-pixels

Figure 11 — Different pixel interlacing example illustrations assuming square (R,G,B) pixels in two-view displays

Optionally, a combination of relative head position tracking and mechanically, electrically or optically adjustable display components can be used in order to change the location and/or shape of the lobes to match with the user position.

NOTE A general description of tracking technology is comprised in Annex B.

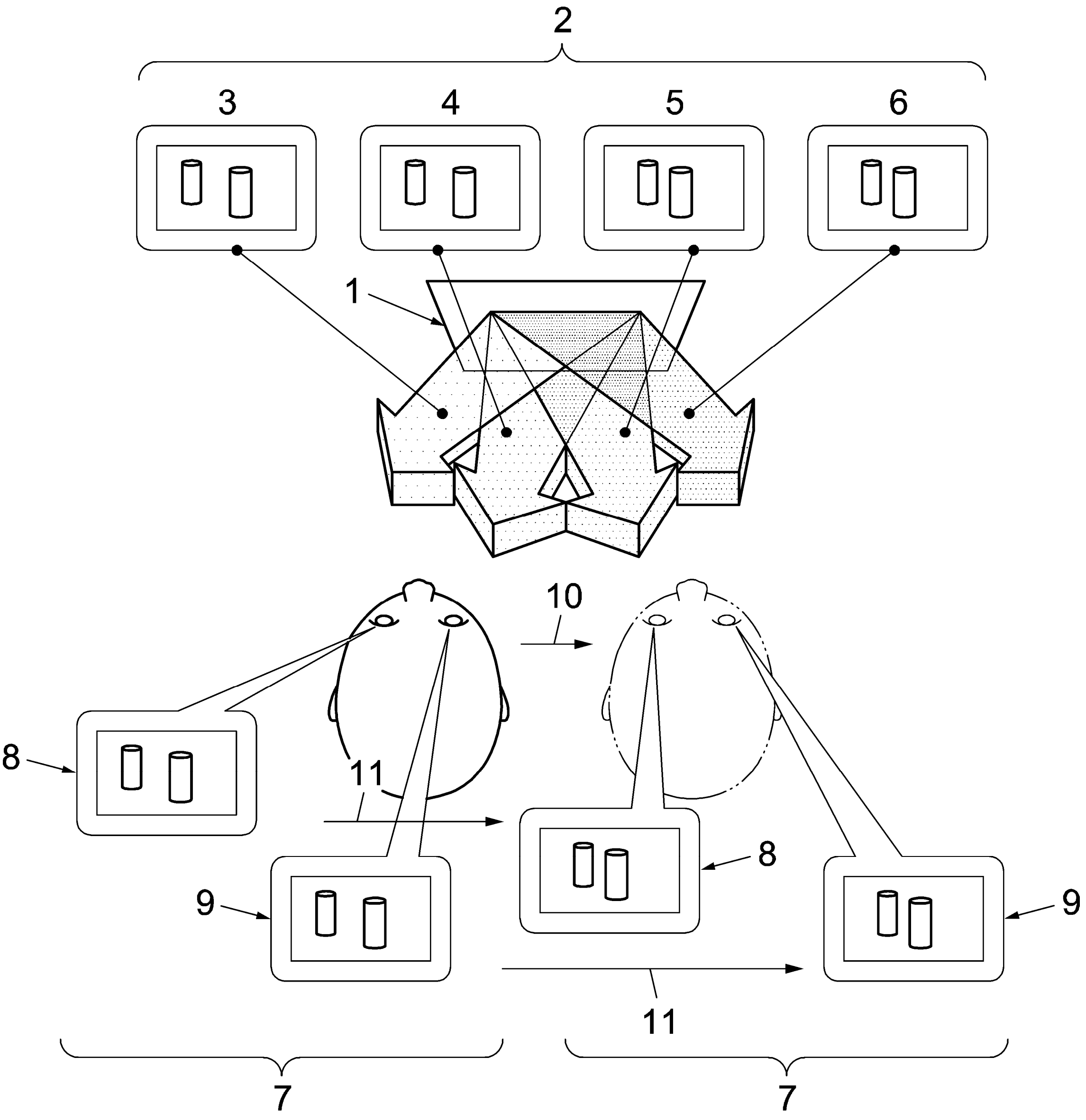
3.4.3 Features

A two-view display satisfies the minimum requirements for being classified as autostereoscopic display. It is a comparatively simple stereoscopic method and the preparation and obtaining of contents is fairly easy. Furthermore, high resolution results in clear 3D views and large stereo effect. As a drawback, the display technology itself does not support simulation of motion parallax and the viewing space is rather small.

3.5 Multi-view (autostereoscopic) display

3.5.1 Definition and principle

A multi-view display is defined as an autostereoscopic display that creates more than two monocular views with which the stereoscopic images are coupled. Figure 12 shows a typical multi-view display, whose number of views is four. The number of views is defined as the number of monocular views, with which stereoscopic images are coupled. On the multi-view display, four stereoscopic images (image 1, 2, 3 and 4), are shown. When the left eye sees image 1 and the right eye sees image 2, binocular parallax for depth perception can be created. In addition, when each eye sees the other images, binocular parallax can also be created. This means that motion parallax can be obtained, when the head moves from left to right and vice versa.



Key

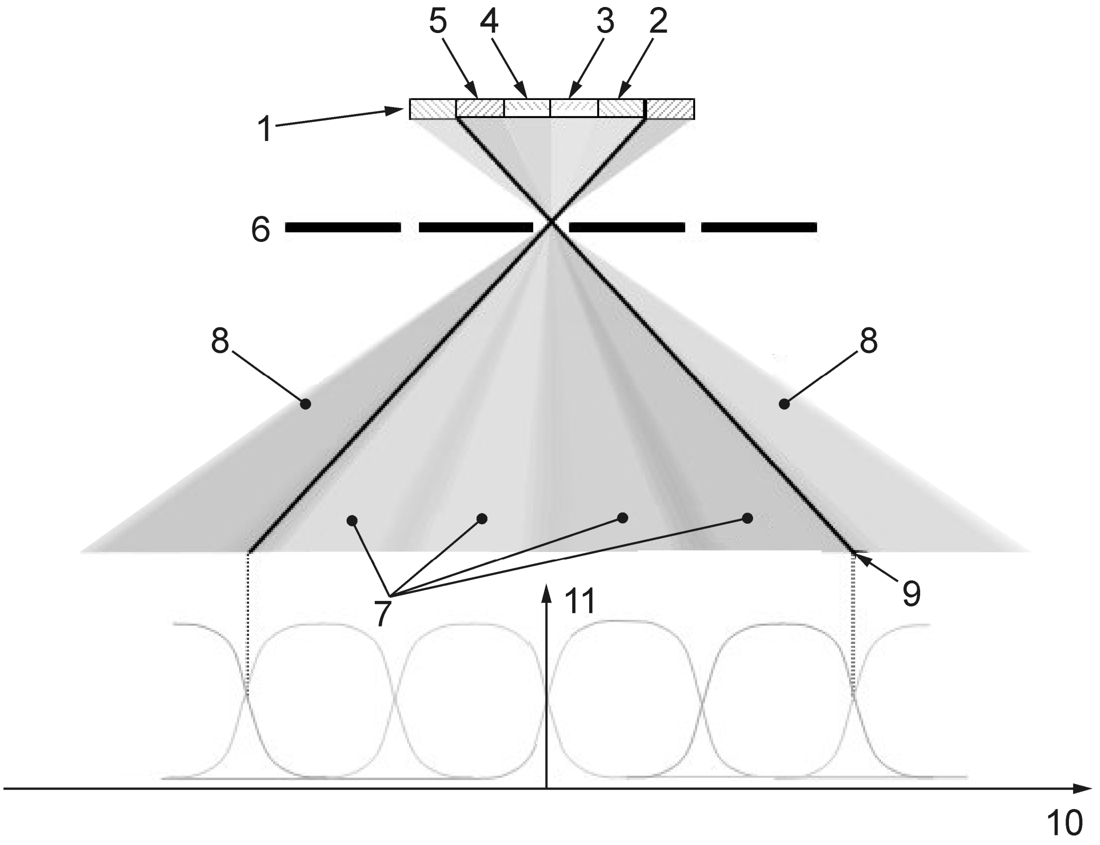
1	multi-view display
2	stereoscopic images
3	image 1
4	image 2
5	image 3
6	image 4
7	stereoscopic views
8	monocular view (left eye)
9	monocular view (right eye)
10	head movement
11	motion parallax

Figure 12 — Principle of multi-view display

3.5.2 Structure and optical property

This subclause describes the optical properties of multi-view displays, while different types of qualified viewing spaces for the display are described in Clause 6, based on the optical properties and performance characteristics described in Clause 4.

In a multi-view display, the display panel is equipped with more than two kinds of pixel groups for showing stereoscopic images. Similar to two-view displays, a sheet of parallax barrier or lenticular lens is generally used for distributing the light from each pixel group. For example, in the parallax barrier type as shown in Figure 13, each slit of parallax barrier corresponds to each set of pixels (pixels for images 1, 2, 3 and 4). The light from each pixel set going through the corresponding slit forms the main lobe, while the light going through the adjacent slit forms the side lobe.

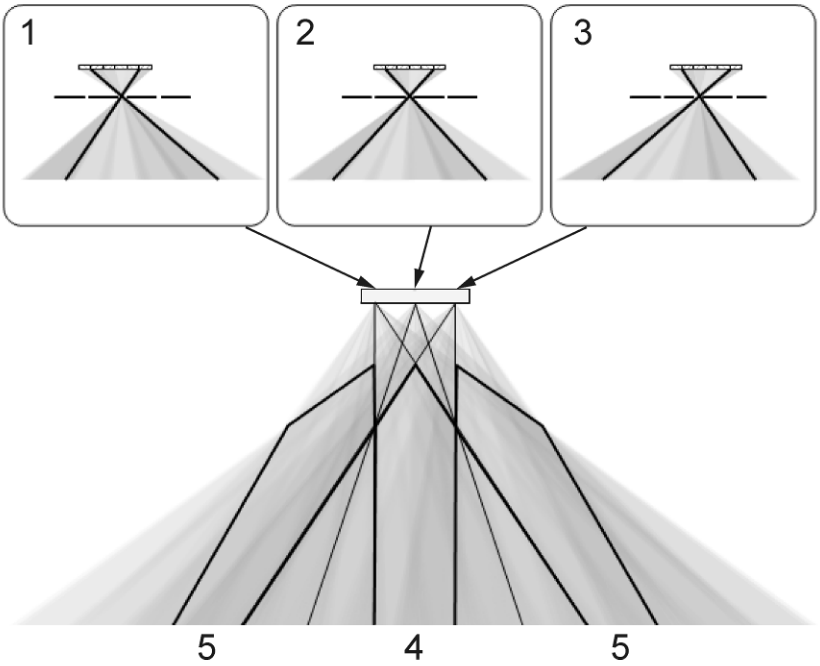


Key

1	multi-view display	5	pixel for image 4	9	boundary of lobe
2	pixel for image 1	6	parallax barrier	10	angle
3	pixel for image 2	7	light for main lobe	11	luminance
4	pixel for image 3	8	light for side lobe		

Figure 13 — Structure of a multi-view display

Due to the nature of lobe shape as shown in Figure 14, the angular distribution of light generally varies depending on each screen location, similar to two-view displays.



Key

1 left location

2 centre location

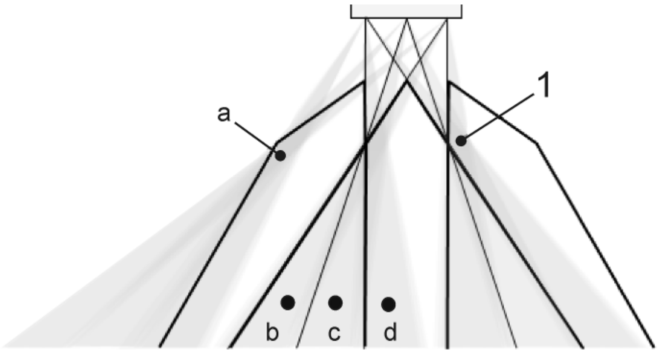
3 right location

4 main lobe

5 side lobe

Figure 14 — Formation of main lobe and side lobe

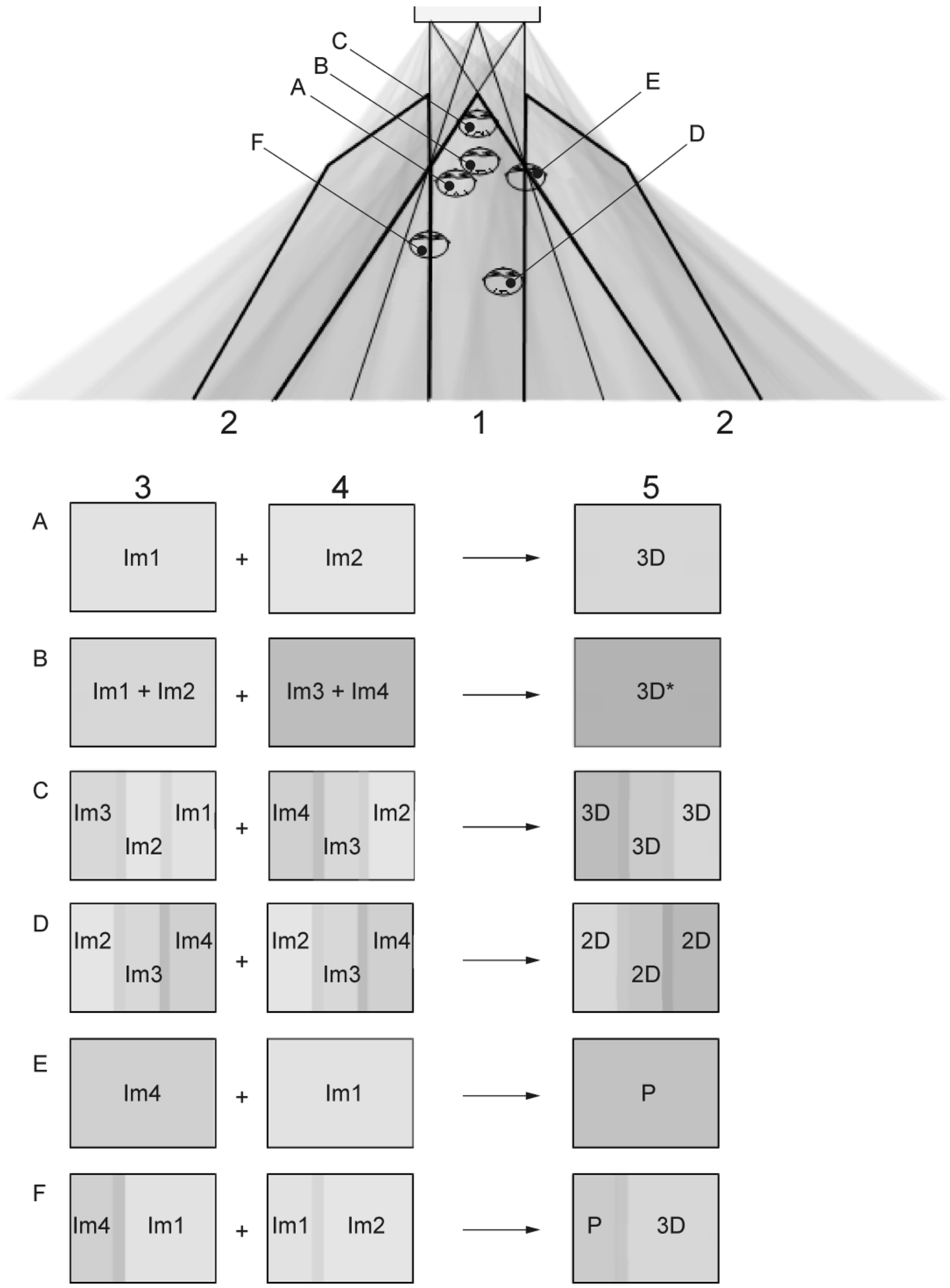
As shown in Figure 15, when only one pixel group is on, light all over the screen originating from the pixel group concentrates towards one point in space. For example, at position (a), which is inside the space, when only one pixel group of image 1 is white, the entire screen will be white. At positions (b), (c) and (d), only a part of screen will be white. There, one of the stereoscopic images can be seen on the entire screen. The spaces around these positions feature a multi-view display. This space or position is sometimes called a “viewpoint”.



Key

1 space where the light from pixels for image 1 concentrates

Figure 15 — Concentration of light from pixels for image 1



Key

1 main lobe

2 side lobe

3 left-eye view

4 right-eye view

5 superimposed images of left and right eyes

Im1 image 1

Im2 image 2

Im3 image 3

Im4 image 4

3D stereopsis

P pseudoscopy

3D* In case of B, although each eye sees overlapped image, stereopsis can be induced because both eyes see the different images. Overlapped image will cause blur, but it depends on the simulated depth (see 3.7.1).

Figure 16 — Relation between observer's position and the observed views

The structure of the multi-view display is similar to that of the two-view display. However, optical properties are quite different between the two display types. When each eye (pupil) is correctly placed inside the diamond shaped viewing spaces, as shown in Figure 16 position (A), the left eye sees one part of the stereoscopic images, and the right eye sees another part. As a result, binocular parallax for depth perception is created.

At position (B) in Figure 16, each of the eyes sees a double or blurred image. For example, the left eye sees image 1 and image 2, and right eye sees image 3 and image 4. In this situation, one monocular view corresponds to two stereoscopic images. Although each eye sees an overlapped image, stereopsis can be induced because both eyes see different images. Overlapping can cause a double image, but it depends on the amount of simulated depth. When the depth is small, neither the double image nor the blurred image will be apparent. This is also related to the number of views per interpupillary distance (IPD).

EXAMPLE Larger number of views per IPD will decrease the parallax on adjacent stereoscopic images (see 3.7.1).

In addition, in a two-view display, when both eyes see double images, stereopsis can not be induced, because the double image contains pseudoscopic images. However, in a multi-view display, since the double images do not always contain pseudoscopic images, stereopsis can be achieved. Therefore, the effect of pseudoscopic images should be carefully considered.

At position (C) in Figure 16, stereopsis can be created, although each of stereoscopic views consists of three stereoscopic images.

At position (D), stereopsis can not be achieved.

At position (E), pseudoscopy is observed all over the screen.

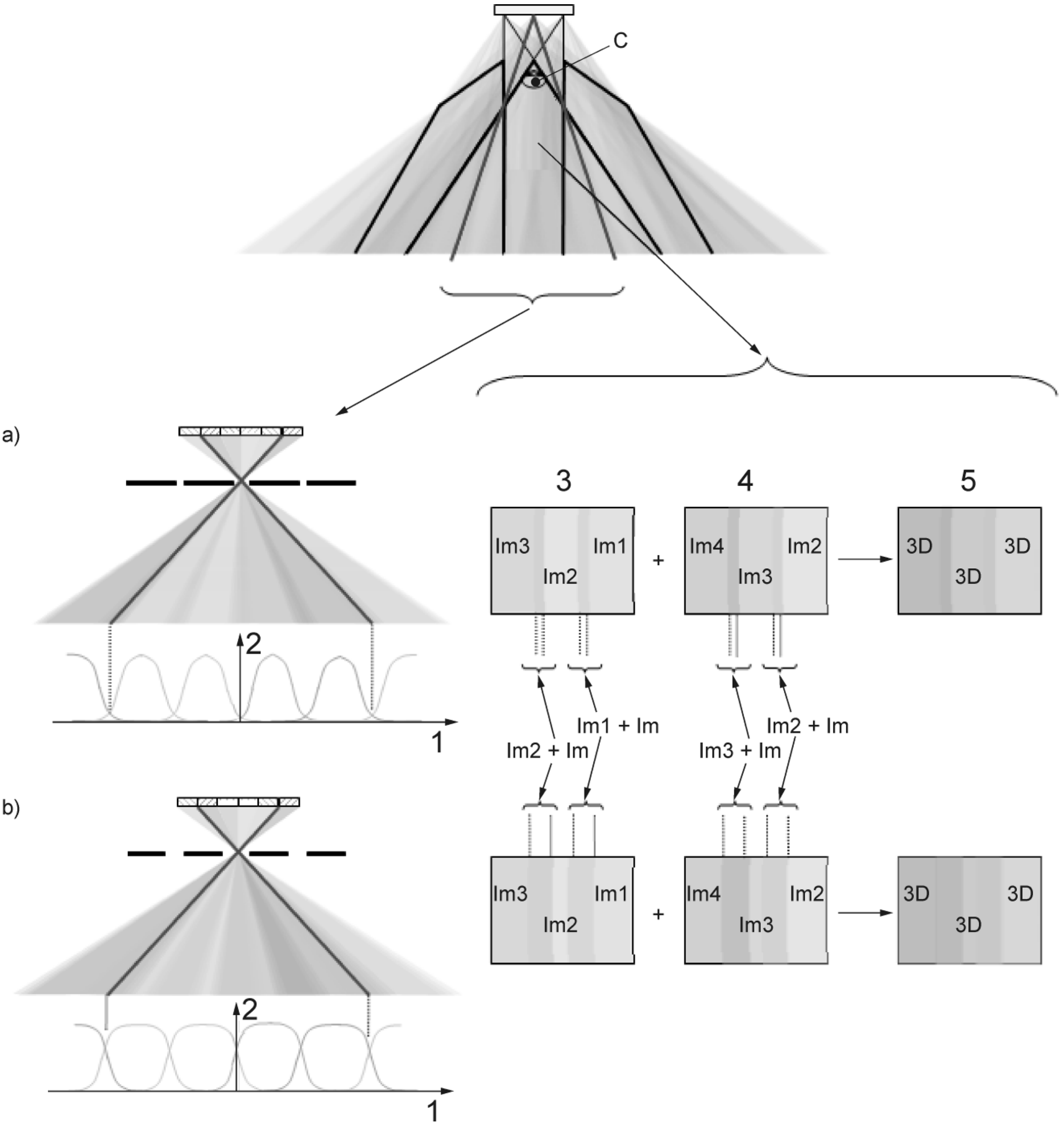
At position (F), pseudoscopy is observed on a part of the screen.

The luminance angular profile is also related to the screen view. As shown in Figure 17, the larger the overlapping of the profile, the wider is the region of double image and the smaller is the luminance fluctuation.

Figure 18 shows a multi-view display, whose number of views is eight. Compared to the multi-view display in Figure 16 (whose number of views is four), the multi-view display in Figure 18 has smaller angular-pitch of light from each pixel. At position (A), the left eye sees image 1 and the right eye sees image 3, so that binocular parallax is created. At position (B), although the viewing distance is larger than that of position (D) in Figure 16, stereopsis can still be induced.

Pixel assignment in a multi-view display is an important issue, because the number of pixel groups required for showing stereoscopic images is large. Figure 19 illustrates an example of a pixel assignment in a multi-view display. In Figure 19 (b), sub-pixels of the same colour are arranged vertically. In this case, same number of sub-pixels are arranged vertically, since the parallax barrier with vertical slits is used as shown in Figure 19 (a). As a result, as shown in Figure 19 (c), the horizontal resolution becomes 1/4, yet the vertical resolution is unchanged. This decreases the image quality and can be a source of visual fatigue. The situation is worsened by a further increase of number of views.

In response to this issue, some technologies, such as step barrier technology, slanted barrier technology and slanted lenticular technology, have been proposed. In the step barrier technology, the parallax barrier has tiny rectangular holes arranged in a slanted line like stairs, as shown in Figure 20 (a). RGB sub-pixels on the slanted line can be treated as one pixel, as shown in Figure 20 (c). As a result, the horizontal resolution will be 1/3, and the vertical resolution will be 3/4. This means that the step barrier technology can lessen the resolution issue, as the decrease of resolution in horizontal can be reduced. In general, the aspect ratio of each pixel is 9 to n, whereas n is the number of views. In theory, vertical parallax can be introduced to multi-view displays.

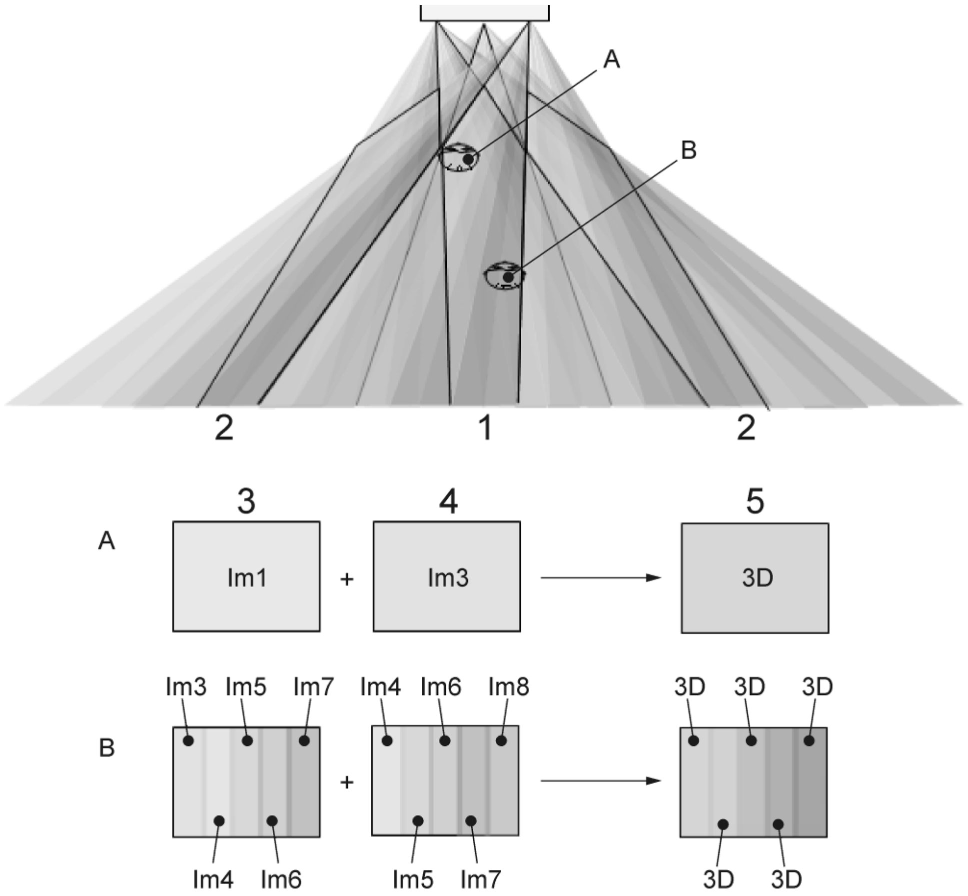


Key

1	angle	4	right-eye view	Im2	image 2	3D	stereopsis
2	luminance	5	superimposed images of left and right eyes	Im3	image 3		
3	left-eye view	Im1	image 1	Im4	image 4		

a) shows a smaller overlapping, b) a larger overlapping.

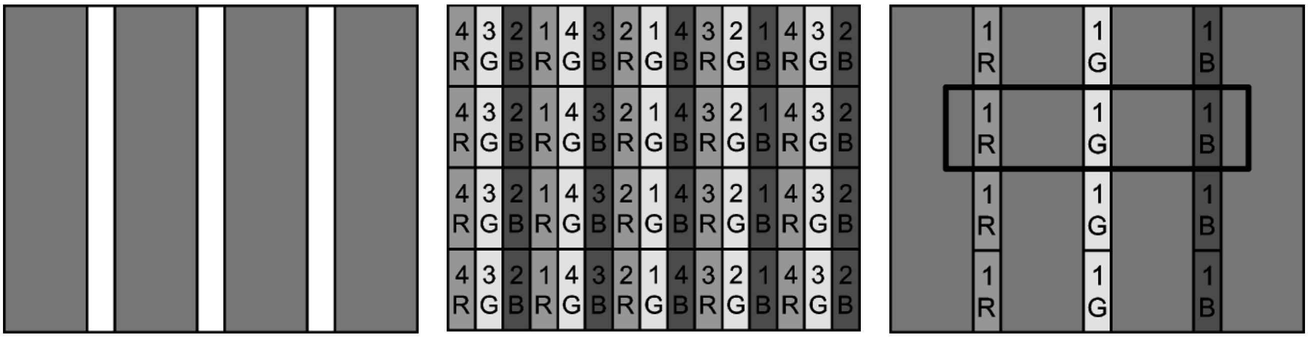
Figure 17 — Luminance profile overlapping and screen view



Key

1	main lobe	Im1	image 1	Im6	image 6
2	side lobe	Im2	image 2	Im7	image 7
3	left-eye view	Im3	image 3	Im8	image 8
4	right-eye view	Im4	image 4	3D	stereopsis
5	superimposed images of left and right eyes	Im5	image 5		

Figure 18 — Multi-view display with improved motion smoothness (number of views: eight)



4 R	3 G	2 B	1 R	4 G	3 B	2 R	1 G	4 B	3 R	2 G	1 B	4 R	3 G	2 B
4 R	3 G	2 B	1 R	4 G	3 B	2 R	1 G	4 B	3 R	2 G	1 B	4 R	3 G	2 B
4 R	3 G	2 B	1 R	4 G	3 B	2 R	1 G	4 B	3 R	2 G	1 B	4 R	3 G	2 B
4 R	3 G	2 B	1 R	4 G	3 B	2 R	1 G	4 B	3 R	2 G	1 B	4 R	3 G	2 B

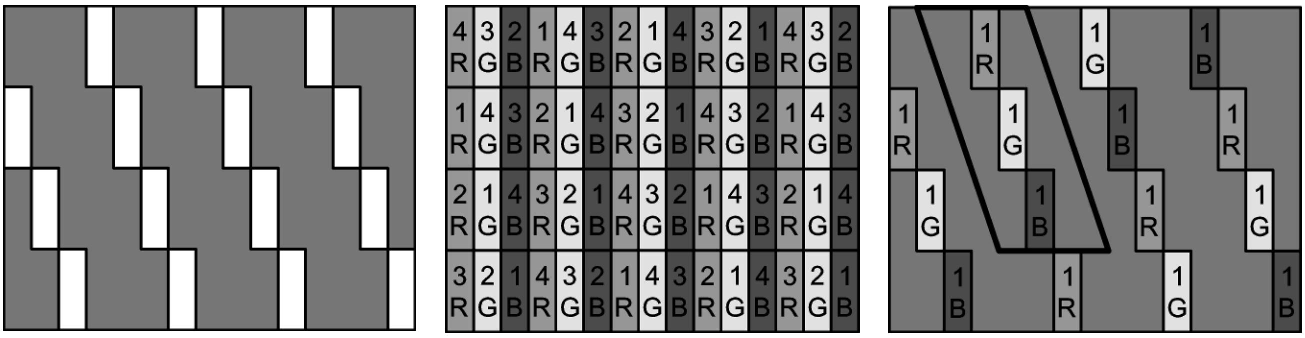
a) Parallax barrier

b) viewing point numbers given to the sub-pixels on the display device

c) condition where the parallax barrier is placed on the display device and the image "1" is seen through the apertures

NOTE This figure shows an image view of the conventional four-view system.

Figure 19 — Pixel assignment in multi-view display



4 R	3 G	2 B	1 R	4 G	3 B	2 R	1 G	4 B	3 R	2 G	1 B	4 R	3 G	2 B
1 R	4 G	3 B	2 R	1 G	4 B	3 R	2 G	1 B	4 R	3 G	2 B	1 R	4 G	3 B
2 R	1 G	4 B	3 R	2 G	1 B	4 R	3 G	2 B	1 R	4 G	3 B	2 R	1 G	4 B
3 R	2 G	1 B	4 R	3 G	2 B	1 R	4 G	3 B	2 R	1 G	4 B	3 R	2 G	1 B

a) Parallax barrier

b) viewing point numbers given to the sub-pixels on the display device

c) condition where the parallax barrier is placed on the display device and the image "1" is seen through the apertures

Figure 20 — Image view of the step barrier technology

3.5.3 Features

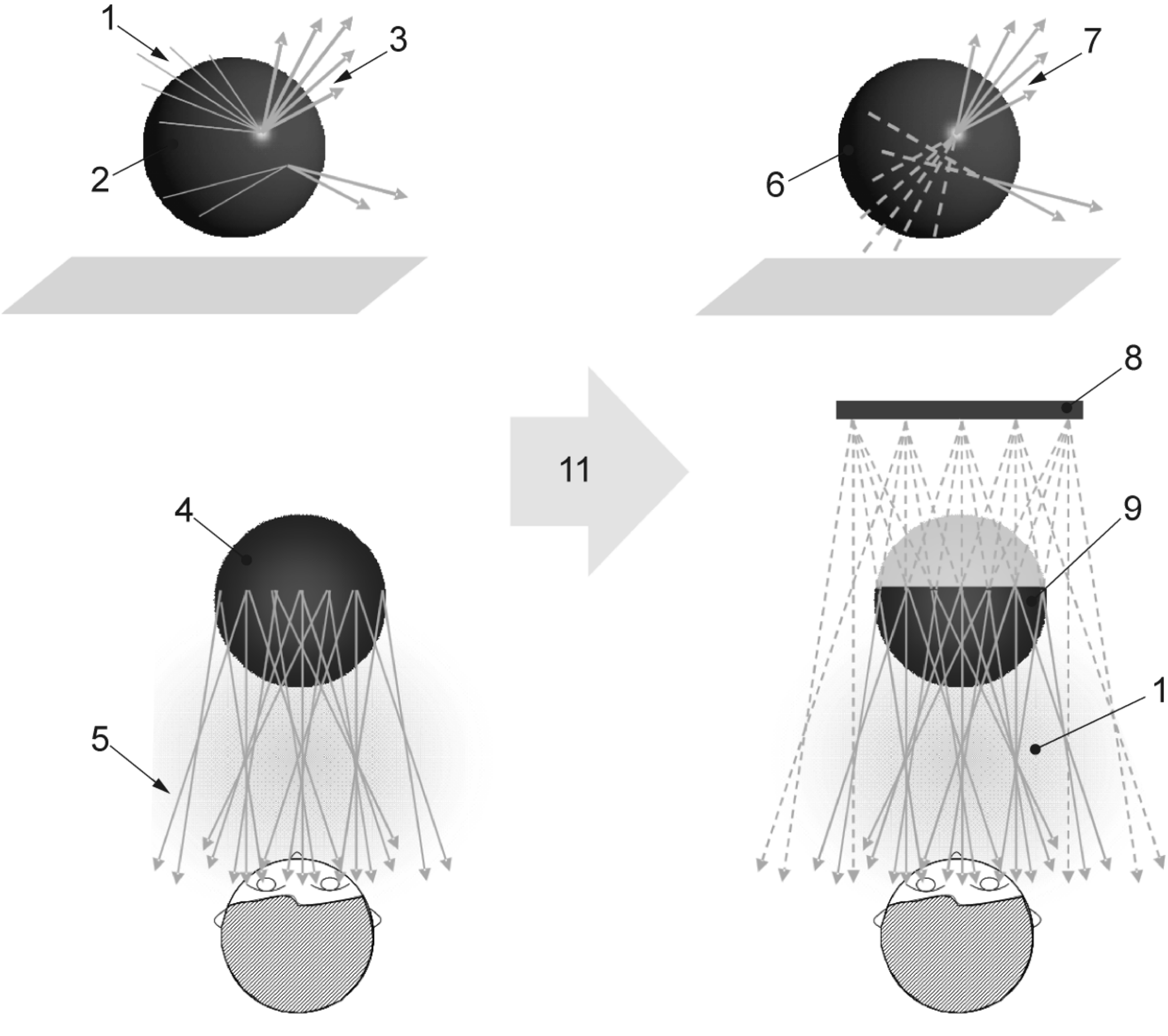
In theory, multi-view display technology can produce wide viewing spaces for observing 3D images. Consequently, the problem of pseudoscopic images is decreased for multi-viewing. Even if the viewer moves from the optimum viewing distance, the pseudoscopic image space generated in the screen is decreased compared to the two-view observation. As a drawback, typically the observed resolution is decreased along with the increased amount of views.

3.6 Integral (autostereoscopic) display

3.6.1 Definition and principle

An integral display is based on the method of spatial image reproduction, which optically reproduces an object surface in space. When a real object in space is illuminated with light, it shines due to reflected light. The integral display simulates the reflected light so that plural observers can see the surface of the displayed object. Therefore, it is necessary that the surface of the real object is optically sampled and that the obtained small images are projected in the space where the real object is removed. Observers perceive a reproduced object as if it exists in space with binocular or motion parallax. Spatial image reproduction is illustrated in Figure 21.

For the sampling and projection shown in Figure 21, a fly-eye lens – a sheet of two-dimensionally arranged lenslets – is generally used. A real object is sampled with the light through a lenslet in an analogous capturing device. The obtained small images, which are called elemental images, are projected into the space in front of the display.



Key

1 Incident light illuminating real object

2 Real object

3 Reflected light on real object

4 Real object

5 Reflected light from real object

6 Optically reproduced object (virtual object)

7 Optically simulated reflected light

8 3D display

9 Virtual object

10 Light from 3D display

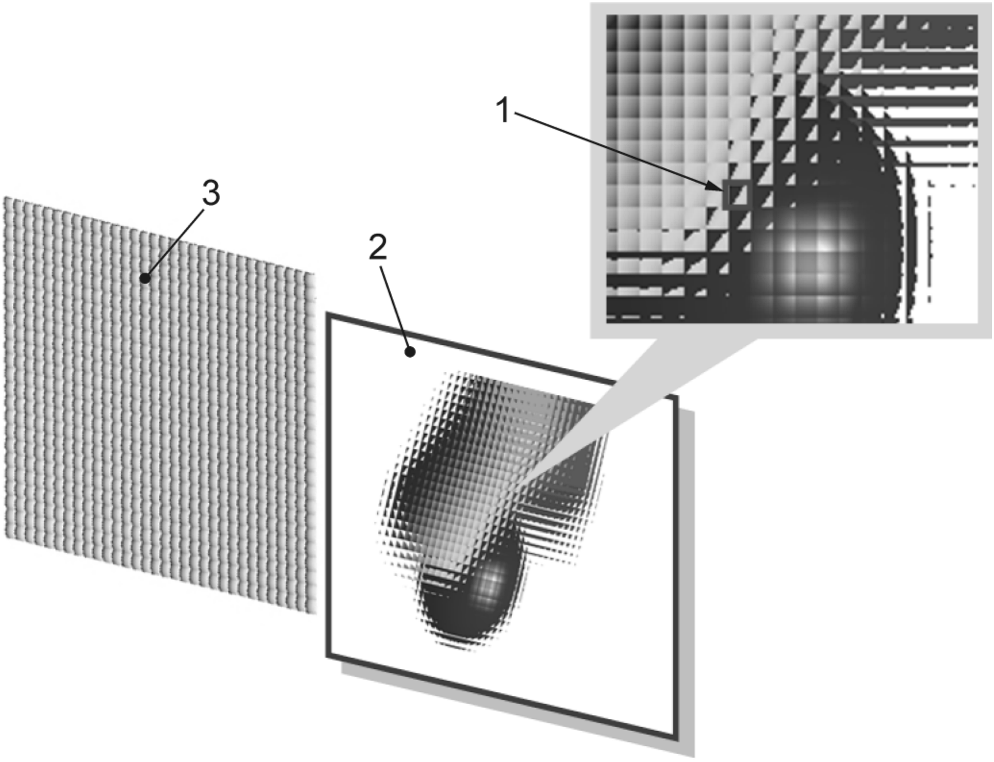
11 Spatial image reproduction by simulating reflected light

Figure 21 — Spatial image reproduction

3.6.2 Structure and optical property

This subclause describes optical properties of integral displays, while different types of qualified viewing spaces of the display appear in Clause 6 based on the optical properties and performance characteristics. Performance characteristics are described in Clause 4.

The most popular structure of the integral display is a combination of a fly-eye lens sheet and a high-resolution Flat-Panel Display (FPD), as illustrated in Figure 22. Instead of the fly-eye lens, a pinhole array can be applied as a variation. Another alternative is a one-dimensional structure, that adopts a lenticular sheet or a parallax barrier instead of the fly-eye lens to provide only horizontal parallax. Despite the decrease of the resolution, this variation results in simpler display components.

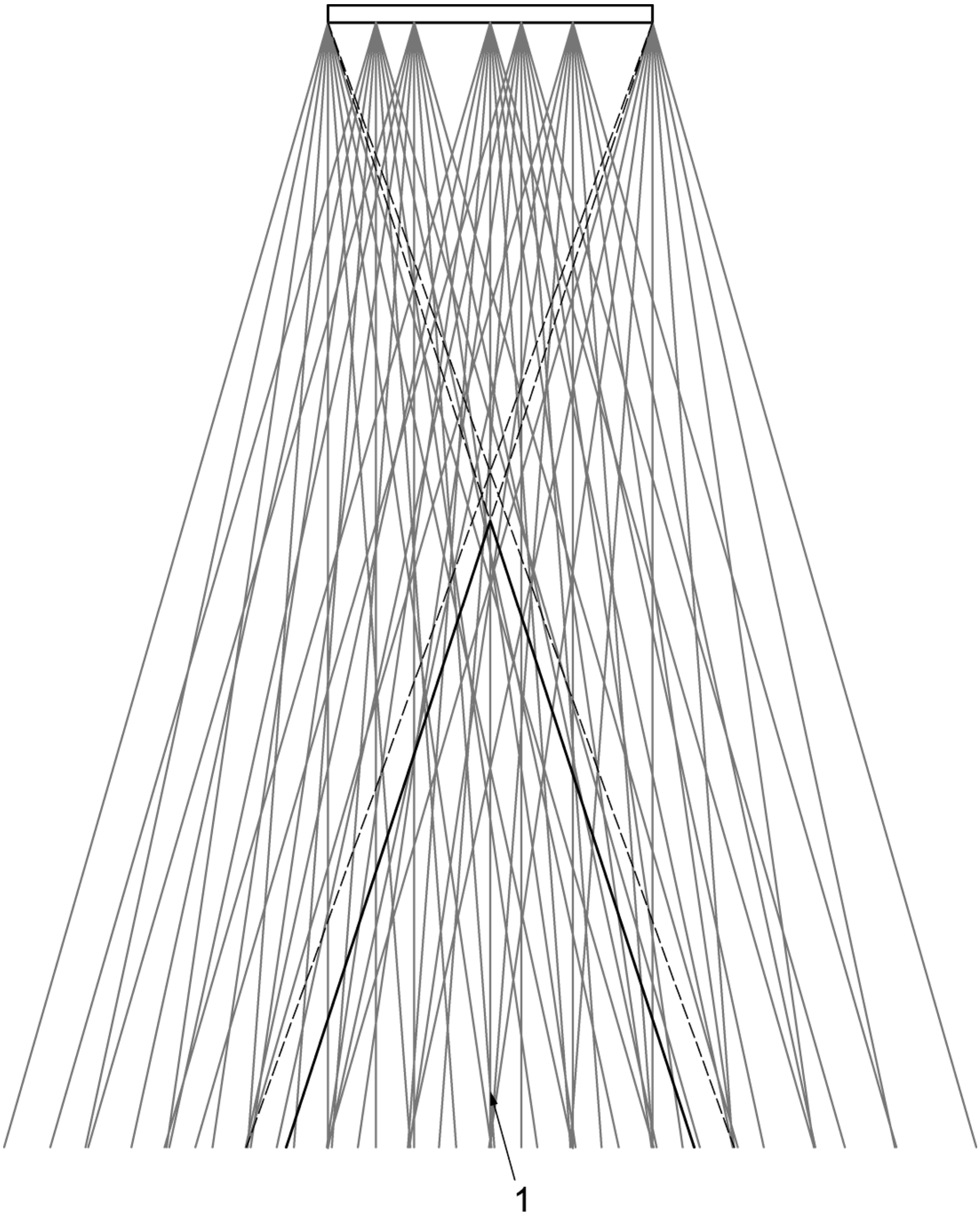


Key

1	Elemental image	2	High-resolution FPD device	3	Fly-eye lens

Figure 22 — Typical structure of the integral display

The design of an integral display is not based on the premise that there should be a point, that many rays pass through. For example, as shown in Figure 23, light sampling based on the orthographic projection has been proposed. Therefore, observers see the reproduced object stereoscopically and they perceive smoother simulated motion parallax as the number of rays increases. Due to the loose constraint of light path control, parallel projection is also applicable to the integral display.

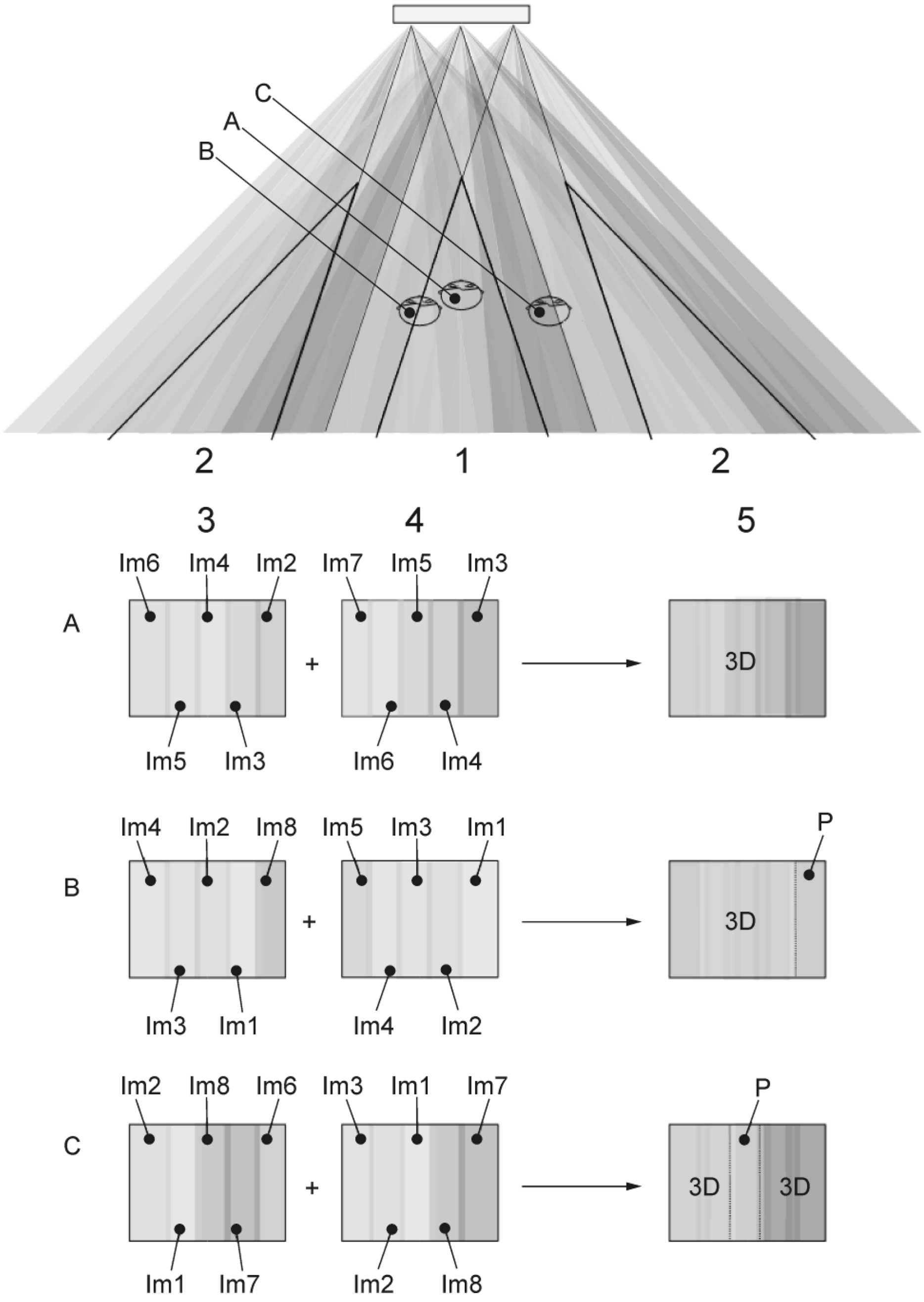


Key

1 main lobe

Figure 23 — Ray distribution of integral display (example of orthographic projection)

In the orthographic projection type of integral display, as shown in Figure 24, one of the stereoscopic images can not be seen on the whole screen (see the position (A)). In addition, at the positions (B) or (C) no pseudoscopy can be seen on the whole screen. This is sometimes called "image breaking", not "pseudoscopy".



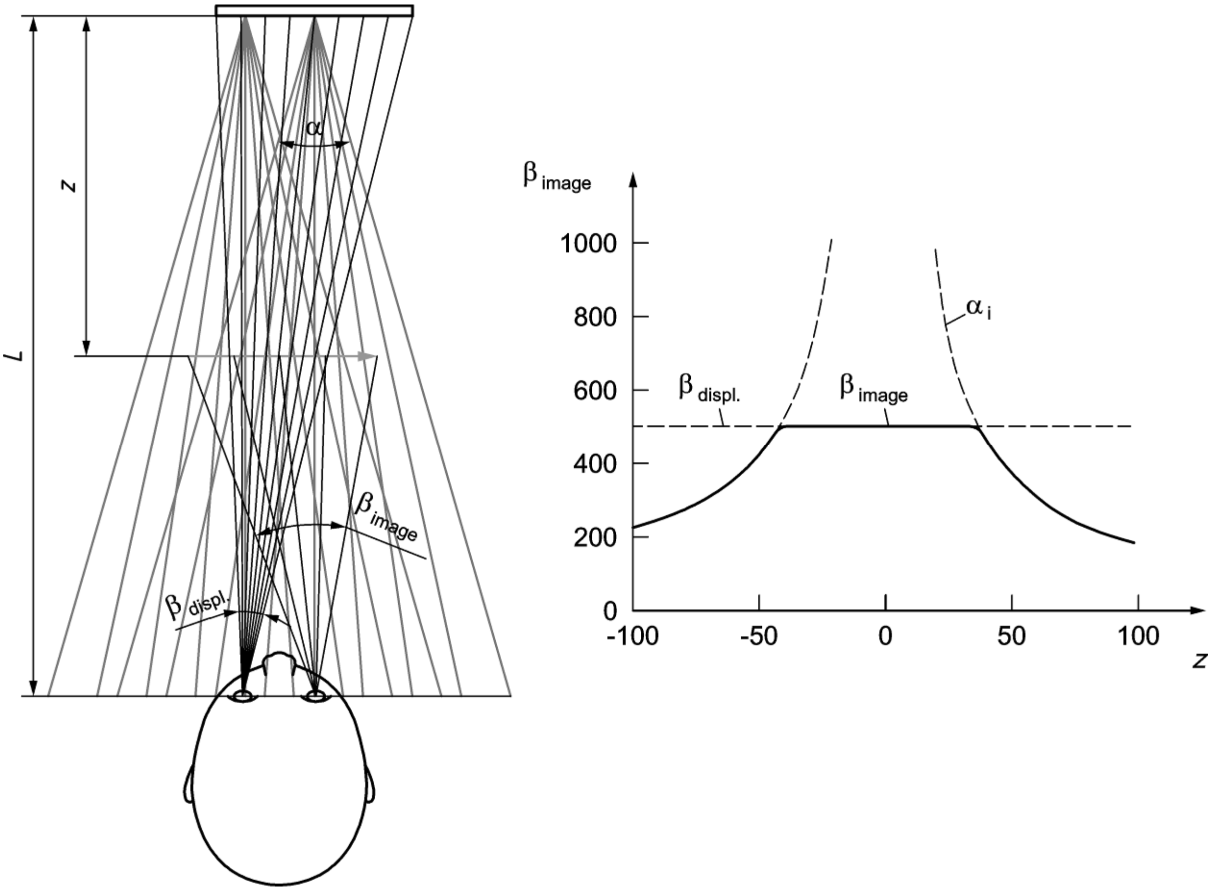
Key

1	main lobe	Im1	image 1	Im6	image 6
2	side lobe	Im2	image 2	Im7	image 7
3	left-eye view	Im3	image 3	Im8	image 8
4	right-eye view	Im4	image 4	3D	stereopsis
5	superimposed images of left and right eyes	Im5	image 5	P	pseudoscopy

Figure 24 — Relation between observer’s position and view

The fidelity of spatial image reproduction depends on three factors, the number of rays projected through a lenslet, the pitch of lenslets, and the distance between the screen and reproduced object. Since ray interval is determined by this distance, its increase causes a decrease of ray density, the limit of which is calculated by how many pixels of the FPD are covered by a lenslet. Taking into account the resolution limit of the reproduced object, which is estimated by the pitch of lenslets and the distance between the screen and the observer, the smaller value of those two limits is adequate to express the limit of display resolution.

According to sampling theory, a double image is interpreted as aliasing. It occurs when texture with higher resolution than the limit of spatial frequency at a depth is reproduced. A blurred image can be shown depending on modulation transfer function (MTF), which is connected to the beam profile and overlap of rays. The theoretical display resolution limit is illustrated in Figure 25.



Key

L	Viewing distance [mm]	α_i	$\alpha(L-z)/\lvert z\rvert$	[cpr]	cycles per radian
Z	Depth of image [mm][a]	β_{image}	Maximum spatial freq. of the image [cpr]		
α	Sampling spatial freq. [cpr]	$\beta_{disp.}$	Display resolution determined by lens pitch and viewing distance [cpr]		

[a] Positive value stands for depth of image is in front.

Figure 25 — Theoretical display resolution limit of the image in an integral display

In Figure 25, *L* is the viewing distance indicating how far the observer's eye position is from the display screen, and *z* is the displayed image depth indicating how far the image is from the display screen. *z*, one of the basic parameters of the display, can be calculated from the amount of parallax of the image. It can also be measured from the amount of lateral motion parallax compared to the display screen. The depth and the viewing distance are measured beginning from the display screen. Positive *L* and positive *z* denotes a distance in front of, and negative *z* denotes a depth behind the display screen. The parameters, α and β are spatial frequencies measured in the unit cycles per radian. The parameter α denotes an angle density between two rays from a point on the display screen. α is derived from the number of pixels assigned as an elemental image, which is equal to the number of rays distributed into the viewing space with an angular range. The parameter β stands for spatial resolution of the displayed image or spatial resolution of the display screen at the viewing distance *L*. Therefore, β is a variable of the viewing distance *L* and becomes larger if the observer steps back. The parameter $\beta_{disp.}$ is the spatial frequency of the display screen. It theoretically has a maximum value because it is equivalent to the display resolution. The parameter β_{image} is calculated as a smaller value of both $\beta_{disp.}$ and α transformed into a value in β_{space}, as follows;[44]:

$$\beta_{image} = \min\left(\alpha_i,\ \beta_{disp.}\right) \tag{1}$$

$$\alpha_i = \alpha \frac{L - z}{|z|} \tag{2}$$

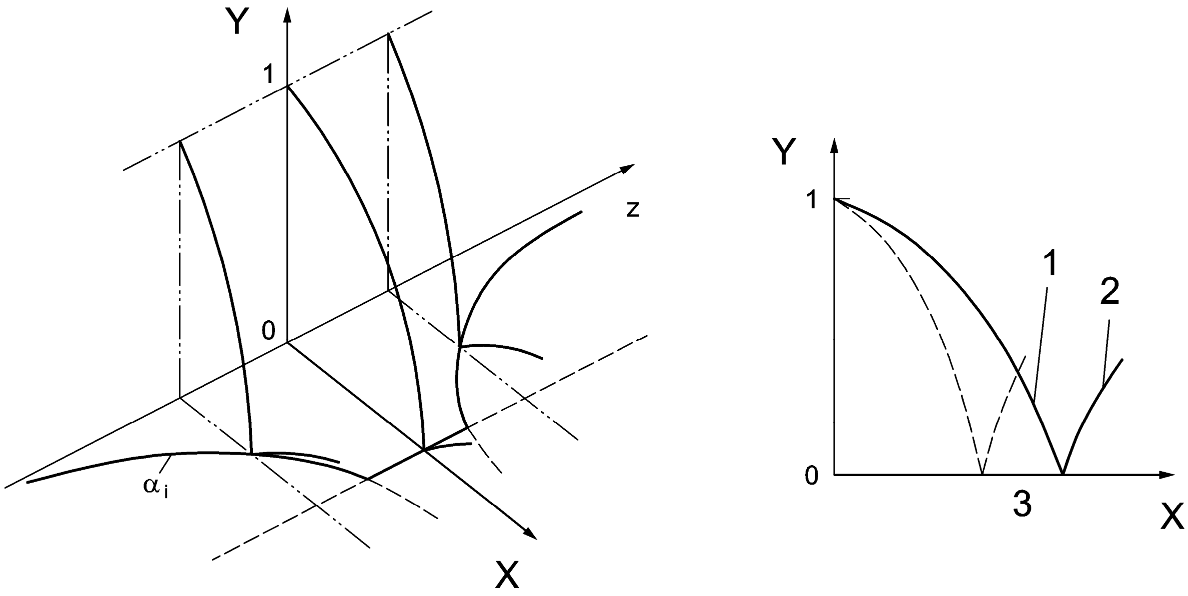
3.6.3 Features

Integral displays originate from integral photography proposed by Lippmann in 1908, whose feature is the use of photographs. The word "photography" has been replaced with "imaging" in the course of the progress of digital imaging technologies and therefore, "'integral photography" is often called "integral imaging". Other terms such as "integral videography", "integral TV" and so on are also used. Strictly, "display with integral imaging method" seems to be the most appropriate term. In this part of ISO 9241, however, "integral display" is used for the sake of simplicity. The basic concept of Lippmann is spatial image reproduction by means of many integrated images via lenslets. The integrated images can be generated by computer graphics or other digital imaging processing instead of optical photographs using lenslets and being projected as an image with high resolution synthesized on a matrix display device. Image integration using many rays in the object space can be discussed as an issue of ray sampling in space. Due to ample discussions of light field, mainly in the field of computer graphics, the concept of ray sampling has been advanced in recent years.

One of the features of integral displays is homogeneous image quality inside the lobes. The integral display distributes many rays, which are not concentrated towards observer's eyes but dispersed in the viewing space, keeping the relation between the object and image. As a result, the lobe(s) is/are formed with homogeneous image quality, i.e. image clearness and smooth simulated motion parallax along with observer's movement.

Lippmann proposed to use a so-called fly-eye lens, therefore the integrated and assigned elemental image is two-dimensional and full parallax is realized. However, the two dimensional elemental image requires many pixels of display device resulting in low display resolution. In order to maintain acceptable display resolution in practice and simplify the image processing to reduce calculating time or to cut the costs of taking photographic images, lenticular or barrier structure sometimes including slanted arrangement is offered. These structures provide only horizontal parallax similar to multi-view displays.

Integral displays follow the ray sampling theory. Therefore, the resolution limit of displayed image with depth is determined from spatial frequencies based on Figure 25. Moreover, degradation of image clearness such as image blurring and a double image can be explained using modulation transfer function (MTF) theory. Figure 26 shows the relation between the resolution limit with depth shown in Figure 25 and typical MTF profiles with depth. Coefficients of high spatial frequency near the resolution limit in the image cause image blurring. A double image occurs if the included spatial frequency in the image is larger than the resolution limit at the displayed depth. And if depth of image is increased, the resolution limit is decreased and MTF profile is changed. Therefore, image blurring becomes gradually visible with depth increasing and finally a double image occurs resulting in image collapsing.



Key

W	$\beta_{disp.}$	Z	Depth of image [mm]	2	Double image (Aliasing)
X	β_{image}	α_i	$\alpha(L-z)/\lvert z\rvert$	3	Increasing absolute depth |z|
Y	MTF	1	Image blurring (low MTF)		

Figure 26 — Relation between MTF and image depth

3.7 Discussion

3.7.1 Continuous/Discrete multi-view displays

For multi-view displays, two different aspects are discussed: continuous and discrete. This discussion is implicitly based on the smoothness of the simulated motion parallax in multi-view displays. If number of views of multi-view displays is too small to simulate motion parallax efficiently, then jaggy motion parallax, or image flipping, which is "noticeable jumps of the image from one perspective view to the next" [Pastoor, 1995], is obtained. To reduce the image flipping, increasing temporal resolution of relative image motion, which becomes motion parallax during head movements, is one possible solution [Ujike&Saida, 1998]. This, however, can be "image-consuming," and unrealistic for technical reasons [Pastoor, 1993]. Therefore, how to achieve smoothness of motion parallax is one of the ergonomic issues of multi-view displays.

Primary factors of motion parallax smoothness with a multi-view display can be:

a) the number of views per interpupillary distance (IPD);

b) overlaps of neighbouring images (and the resulting image blur); and

c) the extent of parallactic depth.

3.7.1.1 Number of views per IPD

The literature [14] reported that smoothness of motion parallax is limited by the number of views per a certain period appeared on an observer's retina, rather than by the number of views per a certain distance of an observer's head movement. In this part of ISO 9241, however, for the sake of simplicity, the "number of views per IPD" is adopted as one of the factors.

3.7.1.2 Overlaps of images

In multi-view displays, light rays of neighbouring views usually overlap each other. Pastoor (1995) [13] reported that overlapping images softened the flipping within a limited range of number of views per IPD. It also needs to be considered that overlapping images can reduce the resolution of images, thus blur 3D images.

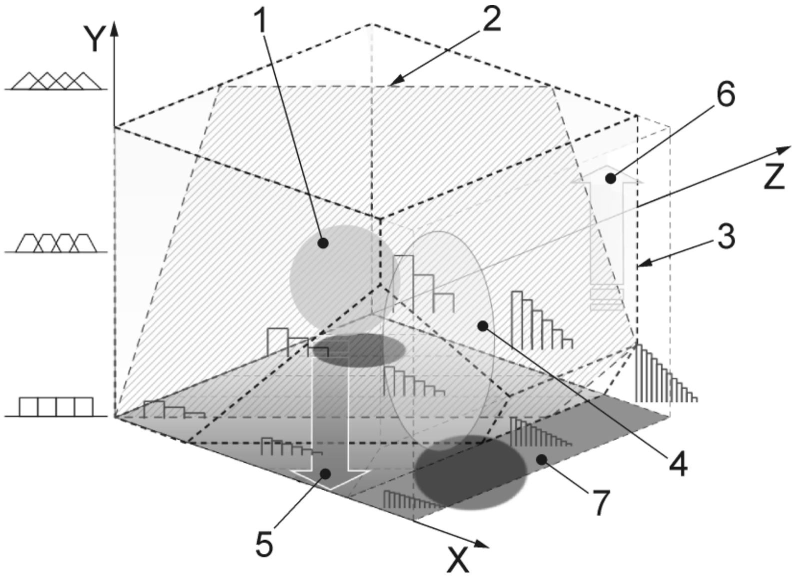
3.7.1.3 Extent of simulated parallactic depth

Another factor is the extent of simulated parallactic depth. Even if the number of views per IPD is small enough and image overlaps are small, small extent of simulated depth cannot induce image flipping. Ultimately, no depth produces no image flipping.

3.7.1.4 Combination effects of factors

Increasing both, the number of views per IPD and the degrees of overlapping images, increases the extent of motion parallax smoothness. An increase of simulated parallactic depth per se increases motion disparity per view; then, smoothness of motion parallax can be degraded. Because of these, the three dimensional space for motion parallax smoothness and image blur in multi-view displays can be drawn, which is illustrated in Figure 27. The smoothness and image blur can be affected by, at least, the three factors, each of which is represented in each of three axes. The nine series of rectangles shown near the bottom face of the cubic space schematically represent motion disparity gradient produced with views and also width of those views. Surface of equal smoothness of motion parallax can be drawn as enclosed with the dashed line named 2. The smoothness increases to the near side in the figure, while degree of image blurs increases upwards.

Multi-view ASDs are sometimes further classified as displays with continuous and discrete types [19]. These continuous and discrete types can correspond to the space enclosed in the ellipsoidal body in front and that behind, respectively, in the 3D space in Figure 27. As it shows, these two types are partially determined by extent of parallactic depth, which is a factor of visual content but not of display device. Therefore, the classification of continuous/discrete types, as a classification of display devices, does not seem appropriate. Moreover, the border of those two different types is not clear.



Key

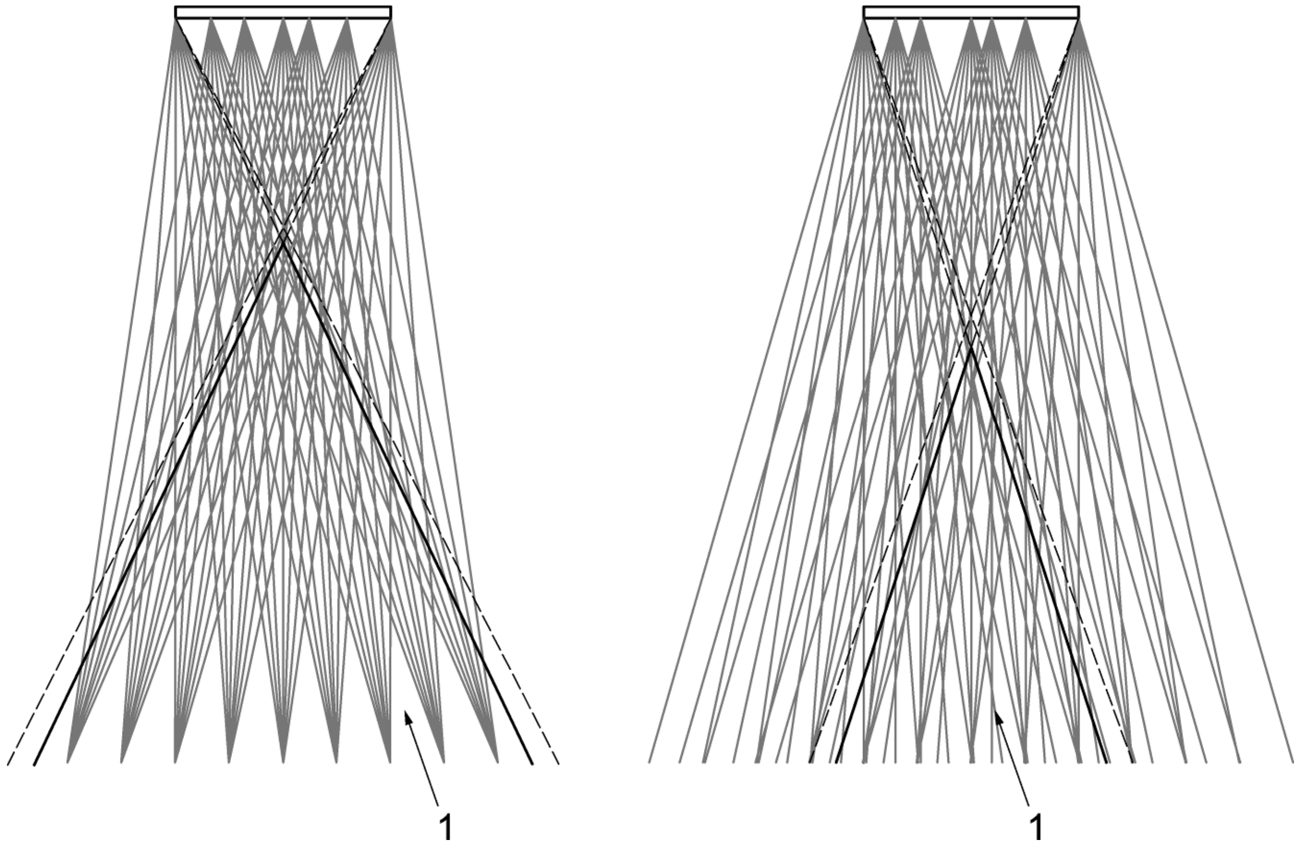
1	space corresponding to discrete views
2	surface of equal smoothness of motion parallax
3	space within blur image can be perceived (space enclosed by blue dashed line)
4	space corresponding to continuous views
5	direction to which smoothness increases
6	direction to which blur increases
7	smoothness increasing as represented as saturation of blue
X	number of views per IOD
Y	degree of image overlaps
Z	extent of simulated depth

Figure 27 — Smoothness of motion parallax and image blur in ASDs

3.7.2 Multi-view/Integral displays

In order to classify autostereoscopic displays appropriately, it is important to discuss the difference between a multi-view display and an integral display. In this section, the difference will be discussed based on the ray sampling approach, stereoscopic views and resolution analysis.

Figure 28 shows a comparison of ray distribution between a multi-view and integral displays. As shown in Figure 28 (a), the multi-view display has a condensing point of light rays from all locations on the screen, that is often called a “viewpoint”. At the “viewpoint”, clear stereoscopic images can be viewed but at the other positions, image quality tends to be degraded. On the other hand, as shown in Figure 28 (b), the integral display does not have a “viewpoint”. This means that the light rays from the screen are not condensed into a point, and that the directional non-uniformity can be decreased. Image quality is usually lower than that at the “viewpoint” in the multi-view display, but higher than that at the other positions.

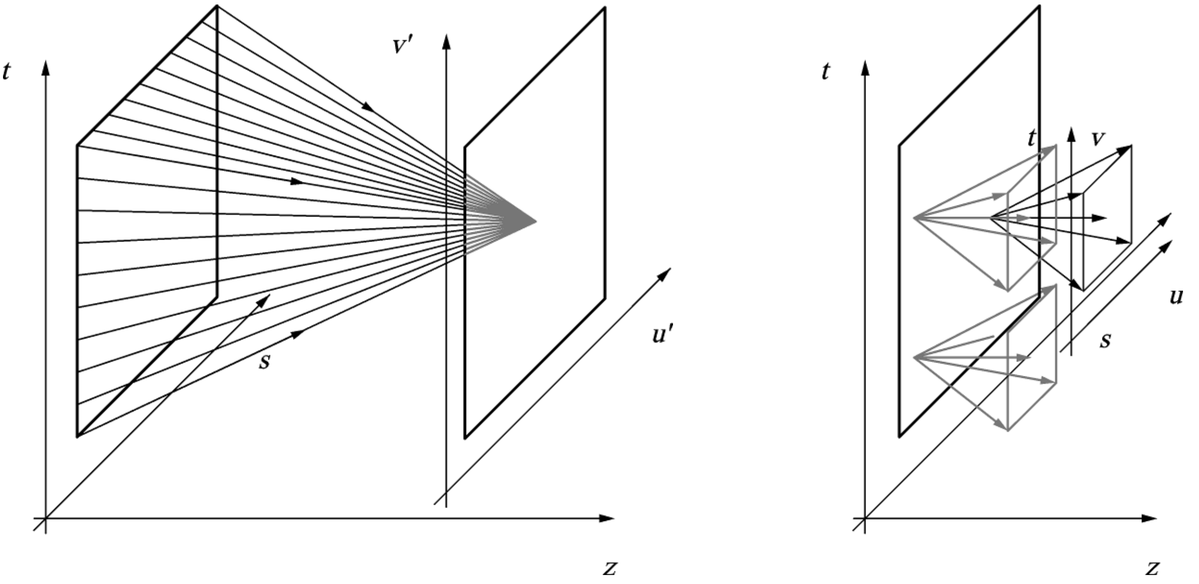


Key

1 main lobe

Figure 28 — Comparison of ray distributions between multi-view and integral displays

In order to analyse the difference in ray sampling approach, the image-based rendering by Levoy and Hanrahan is useful. In this method, four parameters are used to characterize light rays. Conventionally, five parameters to express positions (three parameters) and directions (two parameters) should be used. However, if a light ray goes straight, the *z* parameter can be omitted. This assumption is reasonable in geometric optics. The notations (*s*, *t*, *u*, *v*) and (*s*, *t*, *u*′ ,*v*′) are used in order to describe ray space. Figure 29 shows two parameterizations to describe ray space. Figure 29 (a) shows two-plane parameterization (2PP). In the parameterization, two parallel planes define ray space. The (*s*, *t*)-plane is a display surface and the (*u*′, *v*′)-plane is a surface by a group of “viewpoints”. 2PP corresponds to conventional multi-view displays. Figure 29 (b) shows another parameterization, which is called plane and direction parameterization (PDP). The (*s*, *t*)-plane is the same as that of the 2PP plane, but the (*u*, *v*)-plane is defined in each (*s*, *t*)-parameter, as shown in the figure. Thus, rays with the same direction have the same (*u*, *v*) values. The length between the (*s*, *t*)-plane and (*u*, *v*)-plane is the focal length (*f*) of the lens. PDP corresponds to conventional integral displays.



a) Two-plane parameterization (2PP) b) Plane and direction parameterization (PDP)

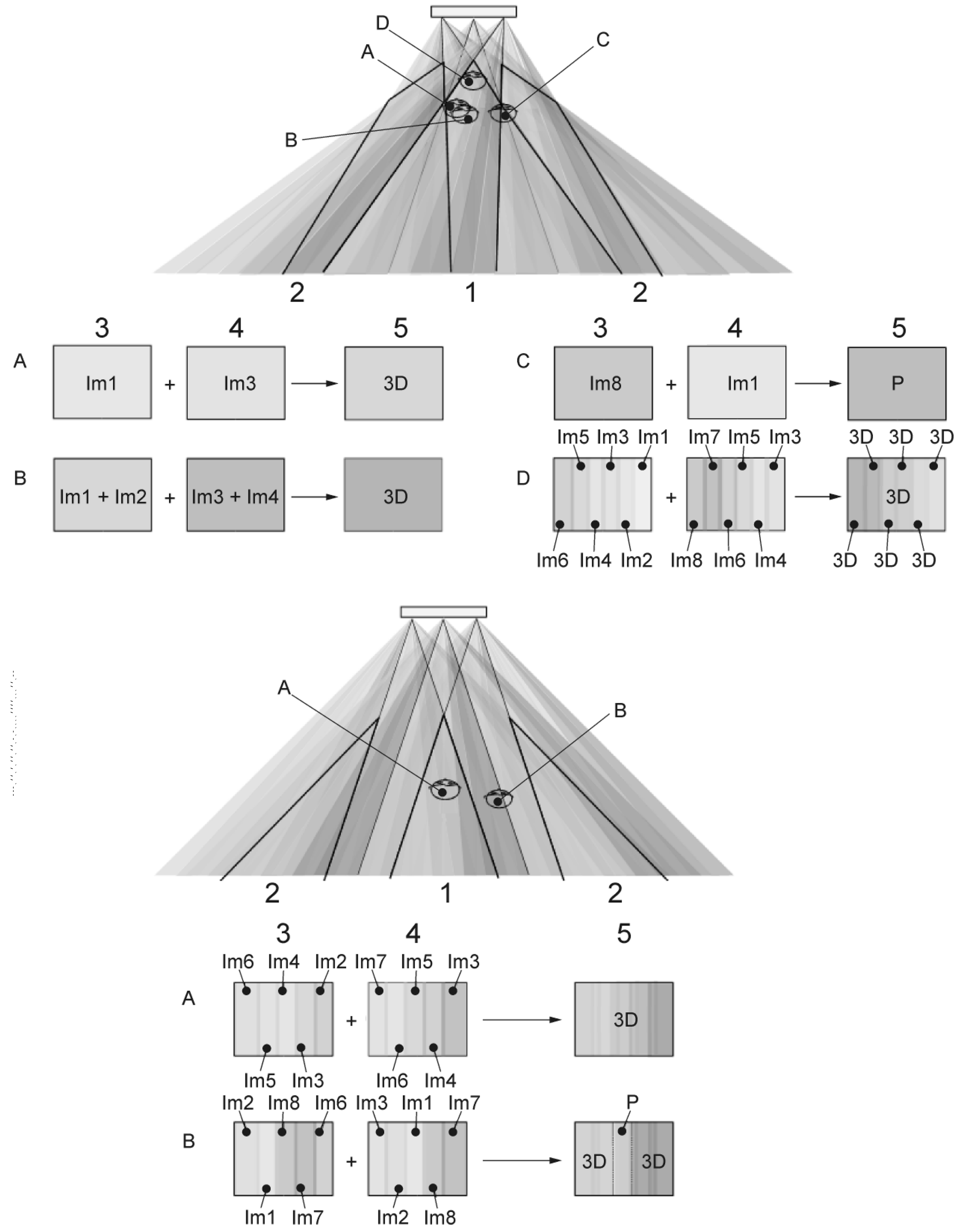
Figure 29 — Comparison in ray spaces between multi-view display and integral display

Next, the differences in stereoscopic views are described. Figure 30 shows a comparison of stereoscopic views between a multi-view and an integral displays (with orthographic projection).

As shown in the upper part of Figure 30, in the multi-view display, there are some viewing positions at which each of the stereoscopic images is viewed all over the screen (position (A)). This viewing position is exactly the “viewpoint”. When a viewer moves from the “viewpoint”, the viewer will see more stereoscopic images at the same time, that will degrade image quality (position (B)). As shown in lower part of Figure 30, the integral display does not have a “viewpoint”, and therefore the stereoscopic views consist of many stereoscopic images. This suggests that the image quality in the integral display can be averaged between the quality at the "viewpoint" and that at the other positions of the multi-view display.

In addition, as described in 3.5, the multi-view display provides a viewing position where pseudoscopic images are viewed all over the screen (position (C)), while not viewed in the integral display. This suggests that in the lobe formation, the integral display does not intend extremely good or bad conditions.

In the multi-view display, when the viewing distance is changed from the distance between the “viewpoint” and the display, it looks like the integral display (position (D)).



Key

1 main lobe
2 side lobe
3 left-eye view
4 right-eye view
5 superimposed images of left and right eyes

Im1 image 1
Im2 image 2
Im3 image 3
Im4 image 4
Im5 image 5

Im6 image 6
Im7 image 7
Im8 image 8
3D stereopsis
P pseudoscopy

Figure 30 — Comparison in stereoscopic views between multi-view display and integral display

As described above, it can be said that the different points between the multi-view and the integral displays prove the existence of the “viewpoint” and the lobe formation. Regarding with the “viewpoint”, the enhanced type of multi-view displays should be considered. For example, as shown in Figure 31, if a multi-view display has much larger number of views per IPD, it cannot be assured that the existence of the “viewpoint” is still that important for multi-view displays.

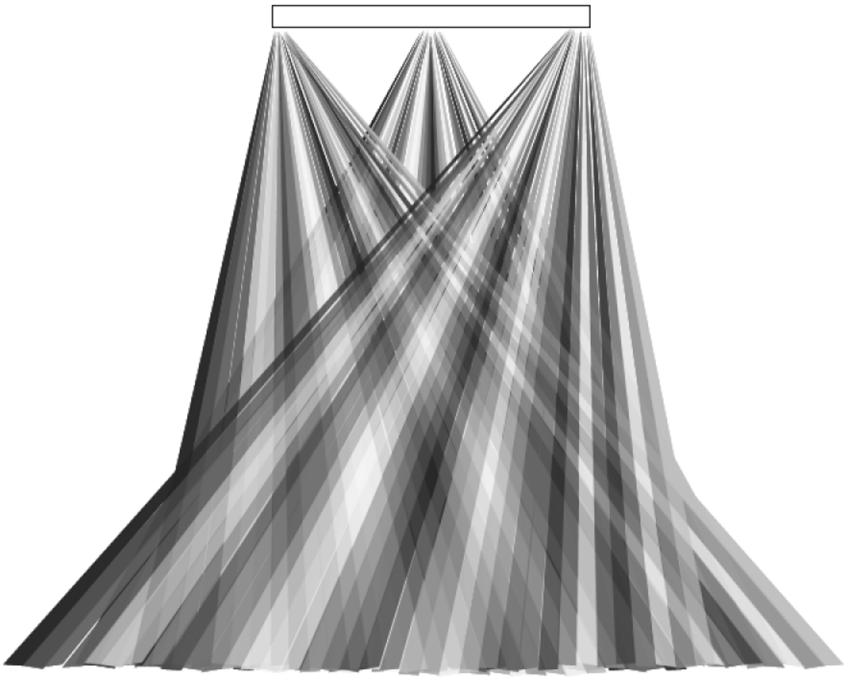


Figure 31 — Enhanced type of multi-view display

As a typical example for an integral display, the orthographic projection type is explained. However, other types such as a fractional type and an enhanced type of multi-view display using overlaid multiple projectors also exist. For the fractional type, the parallax barrier or lenticular sheet does not have to be aligned with the pixels on the display panel. One slit or semi-cylindrical lens does not correspond to each pixel group. Then the display is called “fractional”. As a result, the light rays proceed to various directions, and the images shown on the fractional display are adjusted in accordance with the direction of light rays.

For the enhanced type of multi-view display using overlaid multiple projectors, the number of rays depends on the location on the screen. These types of multi-view displays should also be considered.

Behaviour of resolution dependence with depth variation also seems to be important. Because the integral display follows the spatial sampling theory, MTF measurement and analysis of the displayed image with depth is frequently applied in order to evaluate optical characteristics of the integral display. Understanding of image degradation such as image blurring or double image occurring based on the MTF and the spatial sampling theory is quite different from the well-known understanding based on the image separation qualified by such as interocular crosstalk.

If a stereoscopic display follows the spatial sampling theory, maximum resolution of the display is inevitably restricted by the depth condition as shown in Figure 25. On the other hand, in case of stereoscopic displays using glasses, two-view and discrete multi-view with interocular crosstalk is ideally excluded. In that case the resolution of the displayed image is always equal to the display resolution of the screen independently of depth condition. The depth limitation of these displays is understood as the imperfection of the image separation, which causes image blurring or double images in large depth conditions. This reason for that condition is the lowering of the similarity of both images and the standing out of high-contrast edges in the displayed contents.

The differences of both resolution characteristics seem to be originated in the sampling theory. This issue is remarkable for qualifying resolution characteristics and considering assessment of crosstalk. Further investigation and discussion are required for understanding this issue and clarifying the applicable range of measurement and analysis based on the MTF approach.

3.8 Future work

In order to promote this part of ISO 9241 to become an International Standard in the future, more discussion and experimental verifications on multi-view and integral displays is needed. For example, the difference or similarity between multi-view and integral displays should be discussed. In addition, it should be clear whether images presented by autostereoscopic displays are regarded to be continuous or discrete for both eyes when they move.

In order to develop an extensive International Standard on 3D displays, stereoscopic displays other than the ones described in the scope of this part of ISO 9241, such as temporally interlaced and vertical parallax display types, should be discussed. Head tracking technologies and dynamically adjusted systems should also be considered.

4 Performance characteristics

4.1 General

In order to provide guidelines for autostereoscopic displays in standards, visual fatigue caused by watching stereoscopic images needs to be considered carefully. Therefore, in such guidelines, the specified items and their numerical criteria should be based on scientific data that is obtained by investigating and examining factors of visual fatigue from stereoscopic images.

In general, visual fatigue arises after visual stress for any of the functions of the eye. Thus, the autostereoscopic display condition that induces stress for the visual function should be extracted. Therefore, the functions of visual perception with two eyes as well as the functions of eye movements should be considered.

For visual perception with autostereoscopic displays, it should be considered that the two eyes usually obtain two different images with binocular parallax. Although the parallax produces binocular disparity between the retinal images resulting in depth perception, excessive amount of binocular disparity can be stressful for the visual function. Moreover, differences in retinal images between the two eyes, such as luminance difference, are the reasons for binocular rivalry. They can also induce visual stress. Furthermore, depth perception is usually produced not only by binocular disparity but also by many other cues. Therefore, the conflict of information among those different depth cues is also one source of stress for the visual function.

For eye movements, conditions inducing excessive amount of eye movement and also conditions disturbing the consistent coordination between convergence and accommodation can stress the visual function.

The factors possibly inducing stress for the visual function can be categorized in terms of their primary origin, such as display devices and visual contents. While for reducing visual fatigue, all the issues shown in Figure 32 are important, this part of ISO 9241 focuses on the issues closely related to optical characteristics of autostereoscopic displays. In autostereoscopic displays, on which this part of ISO 9241 focuses on, the observer can perceive depth in the contents presented on the display without any viewing aids. As a result, the space where the observer can be positioned to perceive the stereoscopic image is often limited. Therefore, it is very important to consider that this space is determined by each of the optical characteristics.

Performance characteristics can be summarized schematically as presented in Figure 33, which presents a link from physical values to human perception along the I/O arrows. Signals originated from contents (lower left corner) are converted every time they pass through an intermediate stage and are finally transferred to a human body (upper right corner). The factors described in boxes are results of the signal conversion, which can be affected by other factors referred to by the concept arrows. Almost all factors are mutually related. Therefore, the identification of their values by measurement would require devised methods to reduce the effects of the related factors as much as possible.

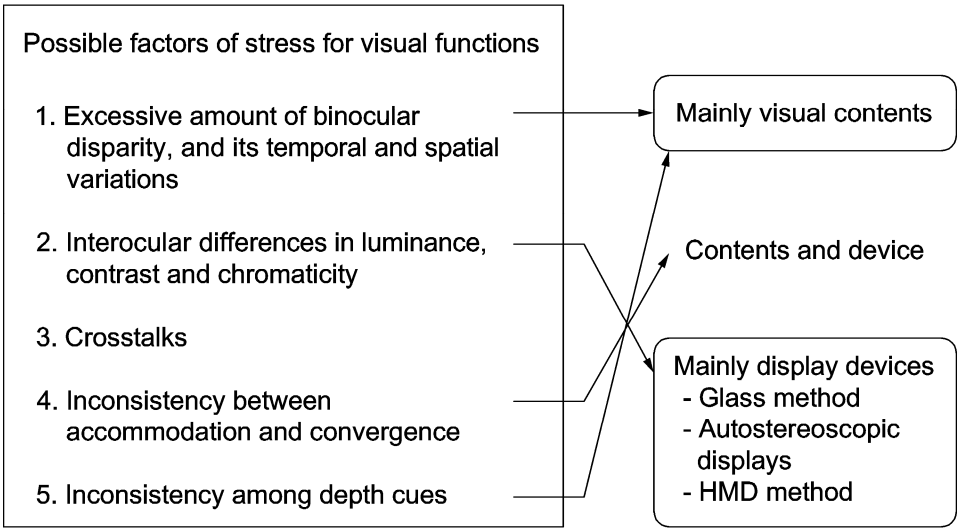


Figure 32 — Possible factors of stress for visual functions

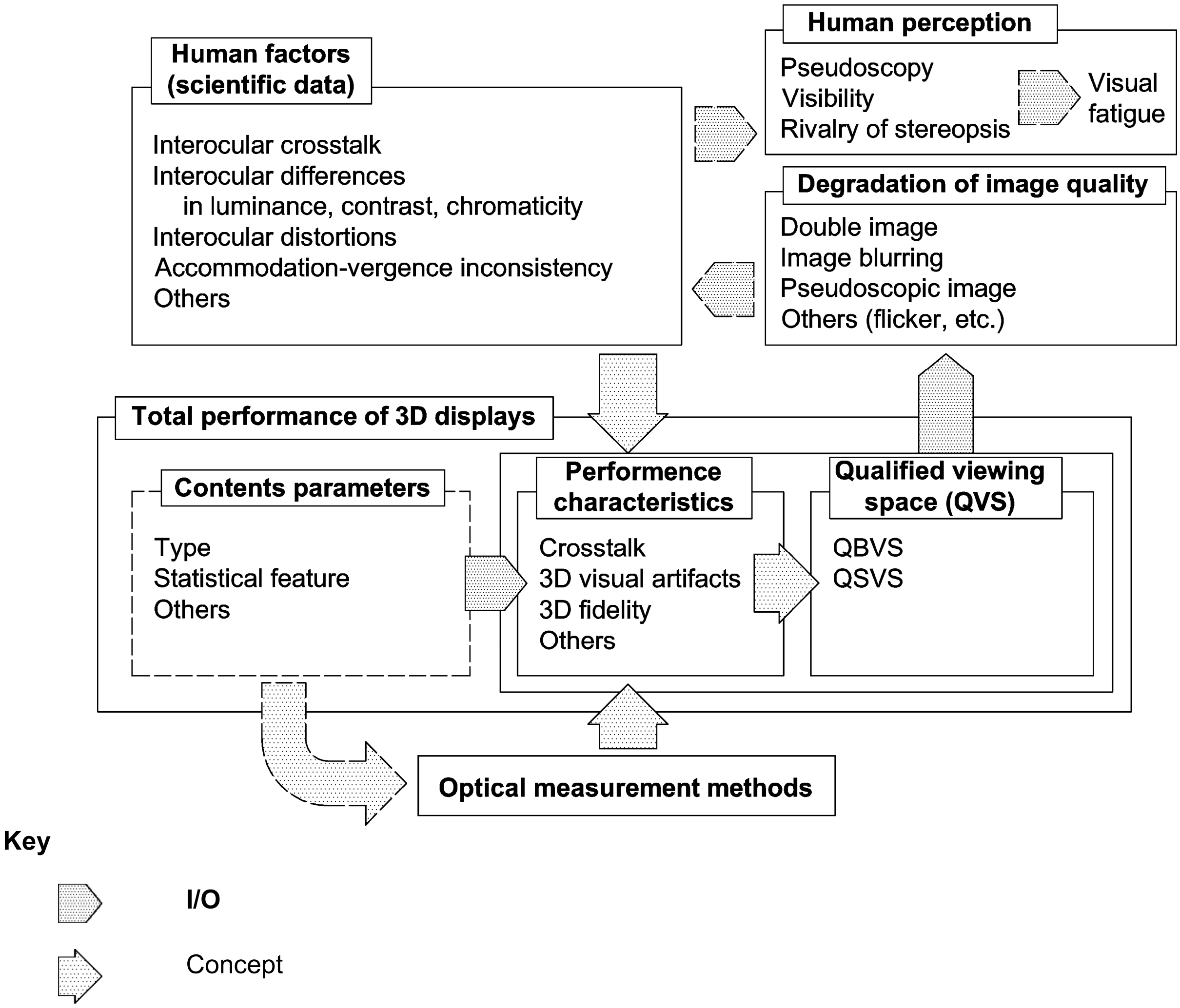


Figure 33 — Information flow from contents to visual perception

The performance characteristics focused on in this part of ISO 9241 are listed in Table 2.

Table 2 — Items of performance characteristics

Crosstalk	3D crosstalk
	Interocular crosstalk
	Interocular 3D contrast
3D visual artefacts	Interocular differences in luminance, contrast, colour
	Pseudostereoscopic images
	3D moiré
3D fidelity	Resolution
Others	…

Some characteristics that are important for autostereoscopic displays but are not discussed in this part of ISO 9241 are listed in Table 3.

Table 3 — Examples of characteristics that are not discussed in this part of ISO 9241

glare
dirt
pixel errors
accommodation-convergence-conflict
excessive amounts of binocular disparity
temporal variations of binocular disparity
not fitting geometry of images (trapezoid, vertical run out)
divergence
blurring
window effect
lost of texture/missed correspondences
inconsistency among depth cues

4.2 Crosstalk

4.2.1 Historical background of crosstalk

Crosstalk on stereoscopic displays is closely related to visual fatigue. This subclause focuses on crosstalk and related matters. Principally, crosstalk is intended to quantify the interference with different signals.

Figure 34 shows various types of crosstalk. The numbers (1) to (4) correspond to those in the following description.

In the past, crosstalk was studied from the viewpoint of how to evaluate the quality of stereoscopic displays with shutter glasses. Traditional crosstalk was defined as leakage ratio of left eye's to right eye's luminance and vice versa and thus corresponded to the interocular crosstalk.

After that, traditional crosstalk was applied to two-view autostereoscopic displays (see Figure 34 (1)). The result was equivalent to the traditional crosstalk, but it was calculated as a profile of brightness window or an angular profile of luminance. Based on this crosstalk, three kinds of crosstalk such as system crosstalk, viewer crosstalk and stereo crosstalk were introduced.

Calculation of the angular profile of luminance was applied to multi-view displays so that several types of crosstalk including 3D crosstalk were introduced (see Figure 34 (2)). 3D crosstalk represents luminance profile overlapping, where interocular characteristics is not shown. Based on the 3D crosstalk, point crosstalk and spatial crosstalk, as well as 3D contrast, which is an inverse number of the 3D crosstalk and represents purity of images, were introduced.

Originating from the 3D contrast, interocular 3D purity (or interocular 3D contrast) was introduced (see Figure 34 (3)). It represents the average (geometric mean) of 3D contrast values at right and left eyes. The interocular 3D purity can be applied to two-view, multi-view and integral displays.

Based on the interocular crosstalk for two-view display, that for multi-view and integral displays was introduced (see Figure 34 (4)).

In a two-view display, the results of any types of crosstalk are theoretically the same. However, in multi-view and integral displays, that should be evaluated with experiments.

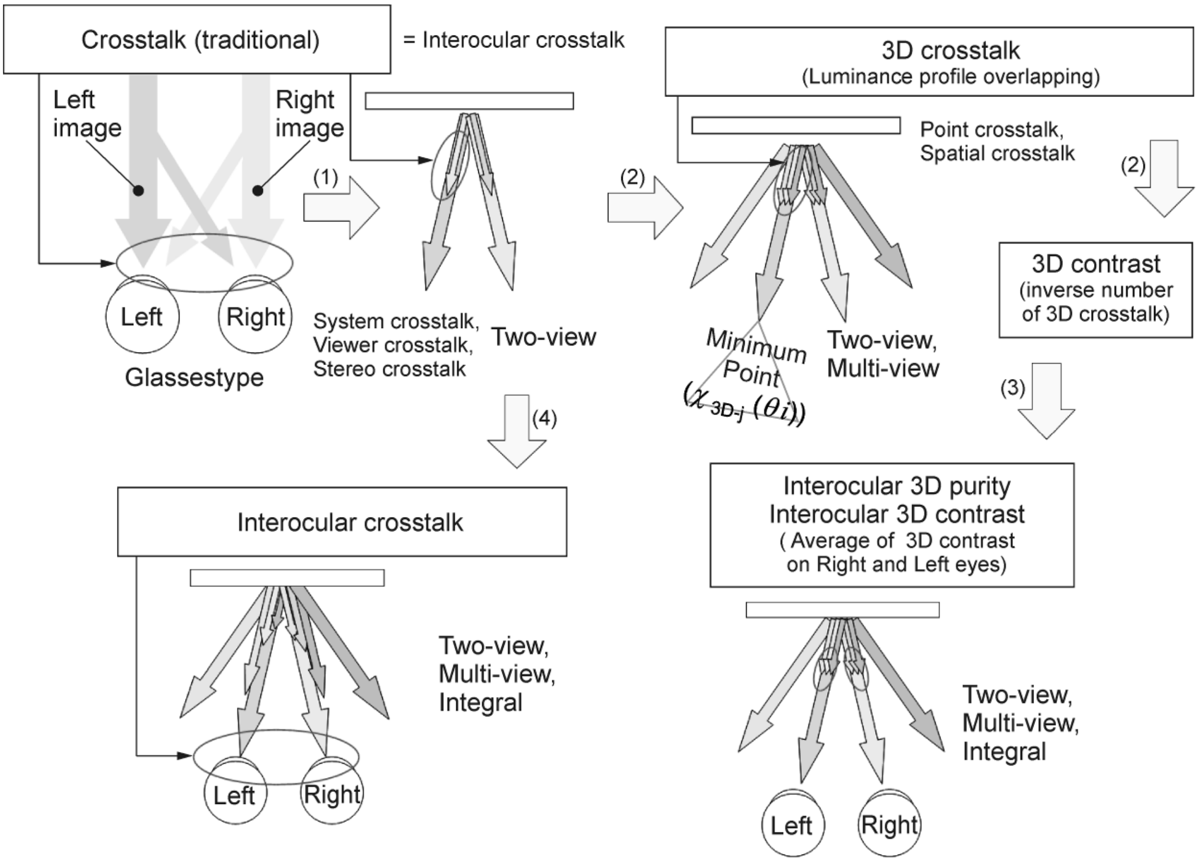


Figure 34 — Historically introduced derivatives of traditional crosstalk

4.2.2 3D crosstalk

- What it is:
- The basic characteristic of autostereoscopic 3D displays is the generation of the viewing spaces. Ideally, inside these viewing spaces, the left eye sees the left part of the stereoscopic image, and the right eye sees the right part of the stereoscopic image (in a two-view display). In practice, the left eye image leaks to the right eye and vice versa. This is a result of incomplete image separation in the display structures. Montgomery et al. [9] define 3D (interocular) crosstalk as the leakage of the left eye image data to the right eye and vice versa as a fraction of the window brightness. With multi-view displays, this definition can be extended so that 3D crosstalk is the leakage of unwanted image data.
- How it is related to visual fatigue:
  - On one hand, 3D crosstalk can be ergonomically undesirable when it is visible as blur or double images and it is a source of visual discomfort. On the other hand, in the context of some multi-view displays, decent amount of crosstalk can smoothen the transition from one view to another. [7], [8], [9], [10]
- The effect for different types of ASD:
  - For a two-view display, the crosstalk curves are calculated from the measured luminance profiles.
  - For multi-view displays with discrete views, the 3D crosstalk for one view (in %) can be determined based on the measured luminance profiles of each view and the full-screen black results [3].
  - In multi-view displays with continuous views, more than one view can contribute to one-eye image and there is more overlap in the luminance as well as the crosstalk profiles for each view. When such 3D displays are characterized, the views that are considered as wanted and the ones that are regarded as unwanted should be carefully chosen. In this part of ISO 9241 the views that the user is supposed to see as one monocular view are the basis for calculations. The results can be investigated together with the results from the subjective tests, and the connection to the perceived image quality can be maintained.
- Comments:
  - Different ways to deal with 3D crosstalk for continuous and discrete views should be examined in future.
  - The way to choose the views in multi-view displays with continuous views should be discussed in future.
  - 3D contrast is proposed as inverse of 3D crosstalk.
  - 3D crosstalk can be related to the following:
    - interocular crosstalk (in binocular sense);
    - double image or blur (in monocular sense);
    - motion parallax smoothness (in monocular sense);
    - performance of display resolution depending on depth *f* or multi-view or integral displays (in monocular sense).

- If 3D crosstalk is considered as an overlap of luminance profiles, the following questions arise:
    - how should the overlap be defined;
    - in case of a multi-view display of five views, is it good that the relation between the 1st and 3rd images is the same as that between the 1st and 2nd images;
    - does the luminance profile affect the performance;
    - the overlapping should have positive and negative effects – should they be considered separately?

4.2.3 Interocular crosstalk

- What it is:
    - Interocular crosstalk is the degree the extent to which one eye sees the image of the other eye, which can disturb stereopsis.
- How it is related to visual fatigue:
    - A large amount of interocular crosstalk disturbs stereopsis and then it causes visual fatigue.
- The effect for different types of ASD:
    - In two-view display, interocular crosstalk can be equivalent to 3D crosstalk.
    - In addition to the two-view case, some modifications are necessary for multi-view and integral displays.
- Comments:
    - The disturbance in multi-view or integral displays is not clear.
    - The interocular crosstalk has minimum factors that show correlation of both eyes. Therefore, appropriate enhancement, such as the treatment of more than two images, can be required.
    - When the result for the right eye is different from that of the left eye, it should be discussed how to deal with the results (i.e., linear average, logarithmic average, individual values, …). This issue should be discussed based on visual ergonomics, for which further experiments are necessary.

4.2.4 Interocular 3D purity (Interocular 3D contrast)

- What it is:
    - If a high quality 3D image on an ASD should be perceived, it is important to display stereoscopic images with minimum impurity. The impurity of the image occurs due to unwanted images that are mixed to some extent with the image that should be seen. The degree of purity is defined as the ratio of the luminance that comes from the wanted image to the luminances that leak from the unwanted images. The defined 3D purity is an average of the degree of purity for each eye. Interocular 3D purity is calculated from the 3D purity for all possible combinations of stereopsis in all viewing positions.
    - Interocular 3D purity is the average of both eyes' degree of how much the image is free from unwanted light. The content an eye sees on an ASD is composed of element images. Each of them is formed by rays of light supposed to form the element. The ratio of the former illuminance to the latter is regarded to signify how clearly the image is represented, i.e. purity of the image. Interocular 3D purity is averaged with a pair of ratios of measured values, which are obtained at right and left eye positions.

- How it is related to visual fatigue:
  - In the case of a small value of interocular 3D purity, double images or blurred images are seen. These images disturb stereopsis and cause visual fatigue.
  - Visual fatigue can be caused, when the luminance contrasts of right and left eyes decrease. Thus binocular vision suffers, when the ratio of the unwanted light to the wanted light increases. Moreover, there is a possibility that it also causes visual fatigue when there is a large difference between the right and the left luminance contrast.
- The effect for different types of ASD:
  - This is relevant for all types of autostereoscopic displays.
- Comments:
  - The following two cases can not be distinguished:

a) left and right eye’s contrasts are both high values, and

b) only one eye’s contrasts is very high.

  - The contrast should be the same level. It might be related to the “interocular difference".

4.3 Visual artefacts

4.3.1 Interocular differences in luminance, contrast and chromaticity

- What it is:
  - Difference in luminance (contrast, chromaticity) between left and right views (at designed viewing distance).
- How it is related to visual fatigue:
  - If the interocular difference is large, even if the quality of each view is high enough, it is possible that the visual processing can be negatively affected, or stressed, by the difference and becomes the factor of visual fatigue caused by stereoscopic images.
  - Excessive interocular luminance difference between both eyes is considered to be undesirable. Interocular differences in retinal illuminance can introduce illusory depth and have disturbing effects on visual function. With moderate interocular luminance difference, robust depth perception can be maintained.
- The effect for different types of ASD:
  - Autostereoscopic displays emit two or more different images in different directions in the space, so that a series of those different images can be seen. With these spatially-sequential images, a single eye’s view tends to fluctuate in its luminance, contrast and colour. Therefore, the interocular differences in those attributes of images can be large enough to induce visual fatigue.
- Comments:
  - The effects of luminance difference should be investigated both globally and locally in the future. The global luminance difference indicates the difference in average luminance of the whole display area, while the local luminance difference indicates the difference in luminance of each part of the image. The effects on visual fatigue can originate from both of these or either of them.

4.3.2 Pseudo(stereo)scopic images

- What it is:
  - A set of images with inverted parallax is shown on a stereoscopic display.

    EXAMPLE In the case of two-view display, visual images to be presented to the right and left eyes for stereopsis are presented to the left and right eyes, respectively.

  - Pseudostereoscopy is the state in which unintended direction of depth occurs and which is produced by pseudostereoscopic images.
  - If the stereoscopic images include other depth cues, such as pictorial depth cues, perceived depth can be reversed intermittently or in a partial display area, or can not be reversed.
- How it is related to visual fatigue:
  - It is not proven whether pseudostereoscopy induces visual fatigue, although pseudostereoscopy can be ergonomically undesirable in the light of the following:
    - when other depth cues included in the stereoscopic images are in conflict with stereoscopic depth cues, this condition can be a stress on visual function;
    - excessive amount of depth can be induced, or vergence response can be deviated from the allowable range (need to be checked).
- The effect for different types of ASD:
  - For most of autostereoscopic displays, pseudoscopy can be induced on the entire screen, or in part of it (“image breaking”).
- Comments:
  - The literature reporting the relation between pseudostereoscopy and visual fatigue should be reviewed again, especially the relation between the ratio of the image area inducing pseudostereoscopy to whole image area when an pseudostereoscopic image is partially included in an image.
  - It seems difficult to distinguish crosstalk from pseudostereoscopic images as the cause of visual fatigue.

4.3.3 3D moiré (moiré)

- What it is:
  - 3D moiré is defined as periodical irregularity of luminance or chromaticity in space or angular directions on a 3D display. 3D moiré is a moiré phenomenon appearing on a 3D display. The periodical irregularity is generated by an interference of optics with light absorption, reflection, refraction and so on.
  - Since a 3D display uses additional optical components, such as a lenticular sheet or parallax barrier, 3D moiré tends to appear. In autostereoscopic displays, 3D moiré is caused by the optics of the lenticular sheet or parallax barrier and by the structure of the pixel array or backlight system. Regarding the influence of the pixel structure, it seems to be essential that there is a part where light is not emitted, since light absorption by the black matrix that masks the borders between the pixels is a well-known reason for 3D moiré. In fact, in addition to the black matrix between the pixels, in multi-domain vertical alignment liquid crystal mode, the borders between the domains, which absorb light, cause 3D moiré.

  - In 3D moiré, two types are observed. One is like moiré on ordinary 2D displays observed as a pattern of intensity variations superimposed on the screen image. ISO 9241-303 defines that moiré is a regular image superimposed on the intended image and that it can appear as ripples, waves and intensity variations on the screen image. This type of moiré occurs when its spatial frequency is high, e.g. in case of displays with slant lenticulars.
  - The other type of moiré appears when its spatial frequency is low and it is observed as a different pattern from those of ordinary 2D displays. When luminance angular fluctuation increases in this type, uniformity on the screen is degraded and what is called, a black band or banding can be seen.
  - The two types of moiré described above are not clearly classified because there is a marginal type of moiré.
  - Not only in luminance but also in chromaticity 3D moiré can be caused due to display panels, which have a colour filter.
- How it is related to visual fatigue:
  - The lateral non-uniformity in luminance affects interocular luminance difference. In addition, non-uniformity can be different between left and right eyes. When each eye sees different ripples, it can affect binocular fusion.
- The effect for different types of ASD:
  - 3D moiré occurs in any type of autostereoscopic displays due to their complex optical structures. Since multi-view and integral displays show many images with parallax, high spatial frequency 3D moiré tends to appear. In two-view displays, when the influence of the black matrix is great, low spatial frequency 3D moiré tends to be noticeable.
- Comments:
  - 3D moiré is also considered as the directional and lateral non-uniformity in luminance and chromaticity.

4.3.4 Non-uniformity

- What it is:
  - As shown in Figure 35, this characteristic can be classified into two aspects: lateral non-uniformity and directional non-uniformity (deviation). The lateral non-uniformity represents the non-uniformity on the screen when the display is seen at a position. On the other hand, the directional non-uniformity represents angular characteristics, such as luminance angular fluctuation. These two aspects should be considered together. For compliance, it is more practical to treat them separately in order to simplify the analysis. These can be applied to the other characteristics mentioned above.
- How it is related to visual fatigue:
  - It depends on each characteristic.
- The effect for different types of ASD:
  - This applies to all autostereoscopic displays.
- Comments:
  - none.

a) Lateral non-uniformity

b) Directional non-uniformity

Figure 35 — Non-uniformity

4.4 3D fidelity

4.4.1 Resolution

- What it is:
  - In general, resolution of a 2D display describes both the pixel density and the total pixel number of screen. It is unknown how much the total pixel number affects visual fatigue, therefore resolution of the 3D display is assumed to be quantified in this part of ISO 9241.
  - Resolution of a 3D display is expressed by horizontal and vertical resolutions, which are used in the 2D display, as well as by depth resolution. To include depth resolution, it is necessary that the 3D display is able to present the images with two different depths, for instance, flat planes placed near and far, or enables an observer to discern the difference. Horizontal and vertical resolutions are right-left and up-down resolutions of the 3D image at a constant depth.
  - It is desirable that 3D displays deliver clear 3D images to people with comfort, but since 3D images slightly show a blur as explained in the bullet point below, MTF of the 3D display is required to be measured for its quantitative assessment. From an ergonomics point of view, it is practical and affordable to ensure that horizontal and vertical stripes presented on the screen are discernable to people.
  - In a multi-view display with slant lenticulars, the pixel shape is not often square so that horizontal and vertical resolution evaluation applied to conventional 2D displays can not be correct. Since apparent resolution changes depending on viewing distance, CPR (Cycle per Radian) can be a universal unit of resolution and it is preferable to PPI (Pixels per Inches). However, even CPR changes depending on the depth of the image and therefore, CPR should be evaluated at any depth for the sake of exact assessment of the 3D display.
- How it is related to visual fatigue:
  - 3D images, dependent to the principle of the 3D display, generally accompany a small amount of blur due to the performance of the optical system such as a lens. In particular, a raised part of the 3D image, the blur is not usually ignorable. A long period of time of watching blurred images can affect the focusing function of the eyes. Since blurs cause diffuse edges of the 3D image, stereopsis is disturbed and depth perception itself can be lost.
- The effect for different types of ASD:
  - For a two-view display, the definition of resolution is almost the same as for conventional 2D displays. For multi-view and integral displays, it is related to depth resolution and two-dimensional resolution at any depth.

4.5 Future work

The following points should be discussed before establishing future International Standards:

a) relation between depth perception and visual fatigue in stereoscopy;

b) subjective testing on the relation between depth perception and visual fatigue in stereoscopy;

c) consistent definition of crosstalk;

d) treatment of display contents in order to affect depth perception.

5 Optical measurement methods

5.1 General

5.1.1 Measurements — Basic measurements and derived procedures

The collection of optical measurements in this clause necessary for the viewing space analysis are divided into basic measurements — identified by M and a measurement number — and measurement procedures — identified by P and a procedure number (and letter in the case of supplementary procedures) — as briefly described below.

5.1.2 Basic measurements (or evaluation) — Method M

Basic measurements should describe a fundamental method as simple as possible. Most of the essential measurement parameters (such as screen location, viewing direction, test pattern) are not specified. The specified result is a physical quantity or some other directly measured property, and does not involve any processing of the collected data. These results are usually not directly used in a procedure as specified in the next subclause. Rather, in a compound measurement procedure (see 5.1.3), a basic measurement will be used to achieve sets or collections of data. These basic measurements define the types of meters acceptable for use, meter parameters, and any default parameters ("fixed measurement conditions"), and list the parameters that are to be varied by the compound measurement procedure ("configurable measurement conditions"). These latter parameters are often defined by the compliance procedure (see the next clause).

5.1.3 Compound measurement procedures — Procedure P

Compound measurement procedures are methods that collect and evaluate physical quantities that were measured using a basic method (see 5.1.2). These procedures reference basic measurements, and can specify the specific requirements for the "configurable measurement conditions". They also include any special preparation procedures. The result of a procedure is a collection of basic quantities (e.g. area or angular distribution of luminance), or derived quantities (e.g. crosstalk, interocular difference). In many cases, the measurement procedures could have some of the configurable measurement conditions defined by the procedure of viewing space analysis (see the next clause).

5.1.4 Structure

The measurement methods given in this clause are structured as follows:

a) objective – describes the purpose and quantities measured;

b) applicability – describes the type of displays/applications in which the particular measurement is relevant;

c) preparation and set-up – describes fixed and configurable measurement conditions, optional accessory equipment and any special preliminary requirements;

d) procedure – describes the measurement or references basic measurement method;

e) analysis – describes any analysis of the measured data;

f) reporting – describes the form of reporting, including the number of significant digits, where appropriate;

g) comments – describes any special concerns or relevant information not contained elsewhere.

5.2 Measurement conditions

5.2.1 Preparations and procedures

5.2.1.1 Display warm-up

Allow sufficient time for the display luminance to stabilize, with a minimum of 20 min. When indicated by the manufacturer, the display should be warmed up for the specified time (not to exceed 1 h).

5.2.1.2 Technology dependent parameters

Testing should be conducted under normal user conditions for power supply. The bias settings (if any) of the display should be set to those expected under typical use.

5.2.1.3 Cleaning

Ensure that the display is clean.

5.2.1.4 Alignment

The display screen should be aligned such that a plane tangential to the screen centre is parallel to the axes of the measurement system(s).

5.2.1.5 Brightness and contrast control settings

The display should be adjusted to its default or preset brightness and contrast. The controls should remain at these settings for all measurements.

5.2.1.6 Image size

Use the factory setting or the default, if available. Otherwise, adjust to a specified size.

5.2.1.7 Video drive levels

A digital interface is applied. If the display only uses an analogue interface, then the drive level(s) should be specified for video signal lines. The value used should be specified.

5.2.2 Test accessories

5.2.2.1 Mirror standard

Mirror standards are mainly used for checking the geometrical alignment and for redirecting light from a source into a light-measuring device (LMD).

5.2.2.2 Data acquisition

LMD samples as a function of time are typically collected, stored, processed and displayed by a storage device such as a computer or storage oscilloscope.

5.2.2.3 Ruler

A steel ruler (mm resolution) or equivalent linear or digital micrometer can be used for small measurements. For large measurements, a steel tape measure (with mm resolution) can be used for determining large area dimensions, such as the size of a projected image.

5.2.2.4 Graduated scales

Linear and rotational scales are recommended for achieving accurate alignment.

5.2.3 Test patterns

The test patterns that are used by the measurement procedures are described below.

- All pixels are white (all white).
- All pixels are black (all black).
- One of stereoscopic images is white, the others are black.
- One of stereoscopic images is grey, the others are grey in a different shading.
- Colour test images (red, green, blue).
- Grey and colour levels will be expressed accordingly.

EXAMPLE 1 For RGB, red is R = 100 %, G = 0 %, B = 0 %.

EXAMPLE 2 50 % grey is R = 50 %, G = 50 %, B = 50 %.

NOTE 1 In some cases, grey patterns are used.

NOTE 2 For preparing test patterns, the supplier specifies which pixels are used for measurement. in other cases, the supplier can prepare test patterns. If the supplier does not prepare test patterns, other methods, such as user performance tests, are needed.

5.2.4 Alignment — Measurement location and meter position

5.2.4.1 Standard five locations

Five standard measurement locations are defined for making measurements of various types (see Figure 36).

The locations are the following:

a) at the centre (i.e. at the intersection of the two diagonals of the addressable area);

b) at the locations on the diagonals that are 10 % of the diagonal length in from the corners of the addressable area of the display.

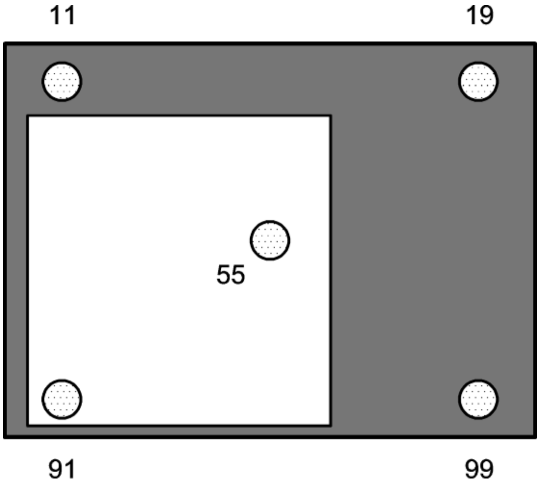


Figure 36 — Standard five locations

NOTE In an autostereoscopic display, it can be discussed whether the 10 % inside is appropriate or not.

5.2.4.2 Standard nine-point locations

Standard nine-point locations are defined in ISO 9241-305 as an alternative set of nine standard measurement locations (see Figure 37).

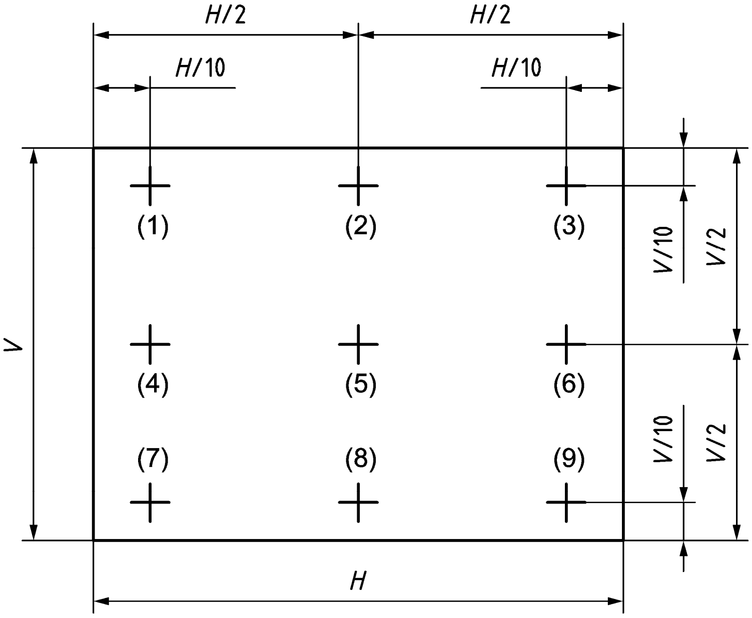


Figure 37 — Alternative nine-point locations (VESA)

NOTE In an autostereoscopic display, it can be discussed whether the 10 % inside is appropriate or not.

5.2.5 Light measuring device (LMD)

5.2.5.1 Spot meter

The spot meter creates an image of the object on a photodetector using a lens, the sample part of that image to produce the measurement. Many of these LMD have a viewing port or viewfinder (either optical or video) such that the lens focuses the image of the object to be measured onto the detection aperture. It is always important to properly focus the device so that the image lies in the plane of the measurement aperture.

Any instrument with a lens is sensitive to stray light and thus to methods taken to minimise any corruption. In autostereoscopic displays, since directional characteristics are not made to be uniform, aperture size (lens size) should be considered appropriately. If the size of the aperture is large, it will average angular luminance distribution in space. On the other hand, if the size of the aperture is small, the influence of noise will increase. Therefore, appropriate size should be considered and measurement accuracy should be verified.

5.2.5.2 Conoscopic light measuring device

Conoscopic LMD measure the directional distribution of light without goniometric directional scanning by the projection of a directions image on a two-dimensional detector array (e.g. electronic camera). These devices can be used for the measurement of luminance and colour stimuli, which can then be further evaluated for luminance contrast, transmittance, reflectance, chromaticity, colour difference, and other quantities.

NOTE Any instrument with a lens is sensitive to stray light and thus to methods taken to minimise any corruption. When the separation of each image is not good, the result is almost the same as that of spot meter. However, the better the separation is, the more attention is necessary.

The influence of aperture size should be considered.

5.2.5.3 Array devices

In addition to the general requirements already outlined for all LMD above, there are complications particular in the use of array detectors such as charge-coupled devices (CCD). Several sources of errors are associated with array detector imaging systems.

NOTE The imaging system includes the lens.

A calibrated CCD can have exactly the same response for each array pixel. When it is put into a system with a lens, the entire imaging system likely no longer preserves that uniformity because of the performance of the lens, reflections, etc. Thus, there are several factors to consider when using an array photodetector including:

a) non-uniform response over the array;

b) non-uniform imaging from lens system;

c) glare, veiling glare and lens flare;

d) background subtraction;

e) flat-field corrections;

f) photopic response;

g) aliasing between the detector pixel and the display pixel; and

h) calibration in luminance.

For a further description of these complications, see VESA-2005-5, section A 111.

The aperture size should be considered. Other factors, such as geometric calibration, resolution of array device, moiré caused by display and array device should be considered.

5.2.6 Measurement field

For the measurement of conventional 2D display, a minimum of 500 pixels should be measured. If fewer pixels were used, it should be proven that any spatial non-uniformity is insignificant. With autostereoscopic displays however, since the lateral characteristic is not made to be spatially uniform, the measurement field should be considered appropriately. If the measurement field is large, the different results can be unintentionally averaged. A smaller measurement field will be needed. In this condition, measurement accuracy should be verified.

5.2.7 Angular aperture

For the measurement of conventional 2D display, the angular aperture of the measurement instrument should be 5 ° or less. For certain measurements the angular aperture can be 2 ° or less, unless it can be demonstrated that it is equivalent to measurements made at 2 ° or less. In autostereoscopic displays, the aperture size is desired to be smaller than the pupil size (2 – 8 mm) at the measuring distance. In angular units, some literature sources request 0,5 ° or less. However, measurement accuracy should also be considered at the same time.

If the detector head is used for illuminance measurements, it should be fitted with a cosine-correcting accessory.

5.2.8 Meter time response

The measurement time interval should be long enough so that the standard deviation of 10 or more luminance measurements is no greater than 1 %. The instrument can be time-synchronised to trigger a measurement with the refresh rate of the display. Measurement interval should be a multiple (n W 1) of the refresh rate.

5.2.9 Test illumination

5.2.9.1 Parameters and tolerances

The various parameters referenced in this section are listed in Table 1 for reference. The size of the tolerances will depend upon the characteristics of the display. The tolerances should be adequately set to provide a ± 5 % reproducibility of the particular measurement.

5.2.9.2 Darkroom

Ensure not only that all room lights are turned off, but that light from equipment in the room, and reflections from surrounding objects back to the screen are controlled such as they are at a negligible level. Illuminance, E, on the screen should be 1 lx or less (E u 1 lx). This is equivalent to stating that the luminance of a diffuse white surface at the position of the screen should have a luminance of less than 0,32 cd/m^2. However, there are cases where this specification is insufficient. In general, the goal is to avoid corruption of measured dark colours due to ambient light or reflections. Avoid measuring as screen luminance reflections off the screen from clothing and equipment lights. Ambient lighting — direct (instrumentation, room lighting, windows and other sources) and indirect (walls, tables, equipment, lab personnel clothing and other surfaces) — should be controlled to avoid errors caused by reflections from the display screen. Additional errors can be contributed by lens flare or veiling glare from the rest of the screen. For screens that exhibit strong viewing-angle dependence, the glare contributions can be particularly significant. For luminance measurements less than 3 cd/m^2, a diffuse white standard placed at the position of the screen should have a reflected luminance of < 1/10 of the lowest luminance reading to be measured. This is equivalent to an illuminance of $E < 0{,}1\ \pi L$ for luminance values $L < 3$ cd/m^2. “Best conditions” assume a room that is completely dark and filled only with dark objects. Reflections from light-emitting devices or from bright or reflective surfaces could reflect off the surface of the EUT, corrupting the measurement. This includes white clothing, lightly coloured objects in the room, lights on instruments, computer displays, bright spots or light leaks in distant areas, etc.

5.2.10 Other ambient test conditions

Normal lab conditions assume an environment similar to normal office conditions. If the EUT should be operated beyond the conditions described, use the conditions recommended by the manufacturer and agreed upon by all interested parties. Report compliance with conditions. Any deviation from these limits should be reported:

- Temperature: 20 °C ± 5 °C.
- Humidity: 25 % to 85 % relative humidity, non-condensing.
- Barometric pressure: 86 kPa to 106 kPa (approx. sea level to 1400 m).

5.3 Measurement methods

5.3.1 Basic light measurements

5.3.1.1 M 31.1 — Basic spot measurement

a) Objective: Measure the photometric and/or spectral properties of the display at the specified parameters.

b) Applicability: all autostereoscopic displays

c) Preparation and set-up:

- fixed measurement conditions;
- measurement field: many pixels, see 5.2.6;
- meter angular aperture: 5.2.7 Angular aperture ;
- meter response time: time-averaging meter, see 5.2.8;
- configurable measurement conditions;
- test patterns;
- measurement locations;
- meter direction;
- test illumination;
- spectral characteristics;

d) Procedure:

1) generate specified pattern on the EUT screen;
2) measure the luminance and/or the chromaticity coordinates and/or spectral power distribution for each of the specified measurement location(s) at the specified direction(s);
3) repeat for additional patterns if specified.

e) Analysis:

- none.

f) Reporting:

- report luminance in cd/m², chromaticity spectral power distribution in W/(sr nm m²)

g) Comments:

- The measurement of the black luminance is particularly susceptible to errors caused by the room ambient lighting conditions. See 5.2.9.2 "Darkroom" for more details.

5.3.1.2 M 32.1 — Site screening — Standard measurement locations

a) Objective: To measure the full screen luminance at predefined positions based on screen size, and report the minimum, maximum, and centre screen luminances. This procedure is based on 5.3.1.1 M 31.1 – Basic spot measurement.

b) Applicability: all autostereoscopic displays

c) Preparation and Set-up:

- fixed measurement conditions;
- measurement field: many pixels, see 5.2.6;
- meter angular aperture: 5.2.7 Angular aperture ;
- meter response time: time-averaging meter, see 5.2.8;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: 5.2.3 Full screen 100 % white;
- measurement location: 5.2.4.2 Standard nine-point locations;
- meter direction;
- test illumination: 5.2.9.2 Darkroom ;
- spectral characteristics: luminance.

d) Procedure:

- Perform luminance measurement at each specified location. See 5.3.1.1 M 31.1 – Basic spot measurement.

e) Analysis:

- none.

f) Reporting:

- Report the maximum, minimum, and centre screen luminances along with their respective screen positions.

g) Comments:

- See 5.3.1.1 M 31.1 – Basic spot measurement.

5.3.2 Directional light measurement — P 33.1 — Luminance angular distribution

a) Objective: To make full screen luminance measurements made at the locations of the screen to determine luminance characteristics for a set number of viewing directions.

b) Applicability: all autostereoscopic displays

c) Preparation and set-up:

  - fixed measurement conditions;
  - measurement field: many pixels, see 5.2.6;
  - meter angular aperture: 5.2.7 Angular aperture;
  - meter response time: time-averaging meter, see 5.2.8;
  - configurable measurement conditions (use parameters as described unless otherwise specified);
  - test pattern: 5.2.3 Full screen: at specified colours;
  - measurement location;
  - meter direction: Normal to display screen – at specified values of θ and ϕ
  - test illumination: 5.2.9.2 Darkroom;
  - spectral characteristics: spectral distribution, luminance.

d) Procedure:

  - Make the required goniometric measurements of luminance $L\theta$, ϕ and chromaticity co-ordinates of the required patterns with the meter positioned at each of the appropriate viewing angles. See 5.3.1.1 M 31.1 – Basic spot measurement. The conoscopic measuring device can also be applied.

e) Analysis:

  - none.

f) Reporting:

  - Data should be presented in tabular or graphic form showing no more than three significant figures.

g) Comments:

  - See 5.3.1.1 M 31.1 – Basic spot measurement.

5.3.3 Full screen measurement — P 34.1 — Array device measurement

a) Objective: Full screen luminance measurements are made to determine luminance characteristics for a set number of viewing directions.

b) Applicability: all autostereoscopic displays

c) Preparation and set-up:

- fixed measurement conditions;
- measurement field: Full screen;
- meter angular aperture: 5.2.7 Angular aperture;
- meter response time: time-averaging meter, see 5.2.8;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: 5.2.3 Full screen: at specified colours;
- measurement location;
- meter direction: Normal to display screen – at specified values of θ and ϕ;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: spectral distribution, luminance.

d) Procedure:

- Make the goniometric measurements of luminance $L(\theta, \phi)$ and chromaticity co-ordinates of the test patterns with the meter positioned at each of the appropriate viewing angles.

e) Analysis:

- none.

f) Reporting:

- Data should be presented in tabular or graphic form showing no more than three significant figures.

5.3.4 Crosstalk analysis

5.3.4.1 P 35.1 — 3D crosstalk 1

a) Objective: In a two-view display, the 3D crosstalk shows the leakage of the left eye image data to the right eye and vice versa. In a multi-view display, the definition can be extended so that the 3D crosstalk is the leakage of the unwanted image data.

b) Applicability: two-view, multi-view display (discrete)

c) Preparation and set-up:

- fixed measurement conditions See P 33.1. – Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3;
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: only luminance required;

d) Procedure:

- See P 33.1 – Luminance angular distribution.

e) Analysis:

3D crosstalk curves χ_{3Di}, *i* = 1, 2, …, # *of views* for each view are first calculated:

$$\chi_{3Di}(\theta,\ \phi) = \frac{\sum_{j=1}^{\#\,of\ views} \left(L_{3Dj}(\theta\ ,\phi) - L_{3DK}(\theta,\ \phi)\right) - \left(L_{3Di}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)\right)}{L_{3Di}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)} \tag{3}$$

where

$\chi_{3Di}(\theta,\ \phi)$ is the calculated 3D crosstalk curve for each view;

$L_{3Dj}(\theta,\ \phi)$ is the measured luminance curve for the view *j* when the view is white;

$L_{3Di}(\theta,\ \phi)$ is the measured luminance curve for the view *i*, that is the view for which the 3D crosstalk is determined, when the view is white;

$L_{3DK}(\theta,\ \phi)$ is the measured luminance curve when all display pixels are black (all black).

f) Reporting:

- Report the 3D crosstalk at each angle for each view.

5.3.4.2 P 35.2 — 3D crosstalk 2

a) Objective: In a multi-view display, the 3D crosstalk is defined as the leakage of the unwanted image data.

b) Applicability: multi-view display (continuous, odd *n*)

c) Preparation and set-up:

- fixed measurement conditions See P 33.1 – Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3;
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance.

d) Procedure:

- See P 33.1 – Luminance angular distribution.

e) Analysis:

— 3D crosstalk curves χ_{3Di}, *i* = 1, 2, …, # *of views* for each view are first calculated:

$$\chi_{3Di}(\theta,\ \phi) = \frac{\sum_{j=1}^{\#\,of\ views} \left(L_{3Dj}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)\right) - A(\theta,\ \phi)}{A(\theta,\ \phi)} \tag{4}$$

where

$\chi_{3Di}(\theta,\ \phi)$ is the 3D crosstalk curve for each view;

$A(\theta,\ \phi)$ is sum of the measured luminance curves for the sub-views contributing to the one view, that is the view for which the 3D crosstalk is determined;

$L_{3Dj}(\theta,\ \phi)$ is the measured luminance curve for the sub-view *j* when the sub-view is white;

$L_{3DK}(\theta,\ \phi)$ is the measured luminance curve when all display pixels are black (all black).

when *i* ≤ (*n* – 1)/2,

$$A(\theta,\ \phi) = \sum_{a=\#\,of\ views+i-\frac{n-1}{2}}^{\#\,of\ views} \left(L_{3Da}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)\right) + \sum_{a=1}^{i+\frac{n-1}{2}} \left(L_{3Da}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)\right) \tag{5}$$

where

$A(\theta,\ \phi)$ is the sum of the measured luminance curves for the sub-views contributing to the one view, that is the view for which the 3D crosstalk is determined;

$L_{3Da}(\theta,\ \phi)$ is the measured luminance curve for the sub-view *a* when the sub-view is white;

$L_{3DK}(\theta,\ \phi)$ is the measured luminance curve when all display pixels are black (all black).

when (*n* + 1)/2 ≤ *i* ≤ # *of views* – (*n* – 1)/2,

$$A(\theta,\ \phi) = \sum_{a=i-\frac{n-1}{2}}^{i+\frac{n-1}{2}} \left(L_{3Da}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)\right) \tag{6}$$

where

$A(\theta,\ \phi)$ is the sum of the measured luminance curves for the sub-views contributing to the one view, that is the view for which the 3D crosstalk is determined;

$L_{3Da}(\theta,\ \phi)$ is the measured luminance curve for the sub-view *a* when the sub-view is white;

$L_{3DK}(\theta,\ \phi)$ is the measured luminance curve when all display pixels are black (all black).

when # *of views* – (*n* – 1)/2 < *i* ≤ # *of views*,

$$A(\theta,\ \phi) = \sum_{a=i-\frac{n-1}{2}}^{\#\,of\ views} \left(L_{3Da}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)\right) + \sum_{a=1}^{\frac{n-1}{2}} \left(L_{3Da}(\theta,\ \phi) - L_{3DK}(\theta,\ \phi)\right) \tag{7}$$

where

$A(\theta,\ \phi)$	is the sum of the measured luminance curves for the sub-views contributing to the one view, that is the view for which the 3D crosstalk is determined;
$L_{3Da}(\theta,\ \phi)$	is the measured luminance curve for the sub-view *a* when the sub-view is white;
$L_{3DK}(\theta,\ \phi)$	is the measured luminance curve when all display pixels are black (all black).

f) Reporting:

— Report the 3D crosstalk at each angle.

g) Comments:

— The measurement method in even n case should be developed.

5.3.4.3 P 35.3 — 3D crosstalk 3

a) Objective: In a two-view display, 3D crosstalk is considered to be impact parameter that shows the leakage of left-eye image data to the right eye and vice versa.

b) Applicability: two-view display

c) Preparation and set-up:

- fixed measurement conditions See P33.1 Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3;
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance;

d) Procedure

— See P 33.1 – Luminance angular distribution.

e) Analysis:

— Calculate 3D crosstalk:

$$C_R(\theta,\phi) = 100 \cdot \frac{\left(L_L(\theta,\phi) - L_K(\theta,\phi)\right)}{\left(L_R(\theta,\phi) - L_K(\theta,\phi)\right)} \tag{8}$$

where

$C_R(\theta,\phi)$	is the 3D crosstalk for right;
$L_L(\theta,\phi)$	is the luminance for right black and left white;
$L_K(\theta,\phi)$	is the luminance for all black;
$L_R(\theta,\phi)$	is the luminance for right white and left black.

$$C_L(\theta,\phi) = 100 \cdot \frac{\left(L_R(\theta,\phi) - L_K(\theta,\phi)\right)}{\left(L_L(\theta,\phi) - L_K(\theta,\phi)\right)} \qquad (9)$$

where

$C_L(\theta,\phi)$	is the 3D crosstalk for left;
$L_L(\theta,\phi)$	is the luminance for right black and left white;
$L_K(\theta,\phi)$	is the luminance for all black;
$L_R(\theta,\phi)$	is the luminance for right white and left black.

f) Reporting:

- Report the 3D crosstalk at each angle.

5.3.4.4 P 35.4 — Interocular crosstalk

a) Objective: In autostereoscopic displays, interocular crosstalk is considered to be impact parameter that shows the leakage of left-eye image data to the right eye and vice versa.

b) Applicability: all autostereoscopic displays

c) Preparation and set-up:

- fixed measurement conditions: see P 33.1 – Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3;
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance;

d) Procedure:

- See P 33.1 – Luminance angular distribution.

e) Analysis:

- Calculate the luminance ratios of each view. If there is a sufficient difference over the threshold between both eyes, the higher value is assigned to the wanted view, while the lower value to the unwanted view. If there is no sufficient difference, both are assigned to the unwanted view, because these do not contribute to stereoscopy. This is also applied to other views. The ratios of the luminance between the wanted and the unwanted view are calculated for all views. That is the interocular crosstalk.

f) Reporting:

- Report the interocular crosstalk at each angle.

5.3.4.5 P 35.5 — 3D contrast 1

a) Objective: 3D contrast is the inverse number of 3D crosstalk, which is considered to be impact parameter that shows the leakage of left-eye image data to the right eye and vice versa.

b) Applicability: Two-view display

c) Preparation and set-up

- fixed measurement conditions: see P 33.1 – Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3;
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance;

d) Procedure:

- See P 33.1 – Luminance angular distribution.

e) Analysis:

- Calculate 3D contrast

$$C_R(\theta,\phi) = \frac{L_R(\theta,\phi) - L_K(\theta,\phi)}{L_L(\theta,\phi) - L_K(\theta,\phi)} = \frac{1}{\chi_R} \tag{10}$$

where

$C_R(\theta,\phi)$ is the 3D contrast for right;

$L_R(\theta,\phi)$ is the is the luminance for right white and left black;

$L_K(\theta,\phi)$ is the is the luminance for all black;

$L_L(\theta,\phi)$ is the is the luminance for right black and left white;

$$C_L(\theta,\phi) = \frac{L_L(\theta,\phi) - L_K(\theta,\phi)}{L_R(\theta,\phi) - L_K(\theta,\phi)} = \frac{1}{\chi_L} \tag{11}$$

where

$C_L(\theta,\phi)$ is the 3D contrast for left;

$L_L(\theta,\phi)$ is the is the luminance for right black and left white;

$L_K(\theta,\phi)$ is the is the luminance for all black;

$L_R(\theta,\phi)$ is the is the luminance for right white and left black;

$$C^{3D}(\theta,\phi) = \sqrt{C_R(\theta_R,\phi_R) \cdot C_L(\theta_L,\phi_L)} \tag{12}$$

where

$C^{3D}(\theta,\phi)$ is the 3D contrast;

$C_R(\theta_R,\phi_R)$ is the 3D contrast for right;

$C_L(\theta_L,\phi_L)$ is the 3D contrast for left.

f) Reporting:

- Report the 3D contrast at each angle.

5.3.4.6 P 35.6 — 3D contrast 2

a) Objective: 3D contrast is the inverse number of 3D crosstalk, which is considered to be impact parameter that shows the leakage of left-eye image data to the right eye and vice versa.

b) Applicability: multi-view display

c) Preparation and set-up:

- fixed measurement conditions See P 33.1 – Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3;
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance;

d) Procedure

- See P 33.1 – Luminance angular distribution.

e) Analysis:

- Calculate 3D contrast

$$C_i(\theta,\phi) = (N-1)\frac{L_i(\theta,\phi) - L_K(\theta,\phi)}{\sum_{j \neq i}\left(L_j(\theta,\phi) - L_K(\theta,\phi)\right)} \tag{13}$$

where

$C_i(\theta,\phi)$ is the 3D contrast;

$Y_i(\theta,\phi)$ is the luminance of view i;

$Y_K(\theta,\phi)$ is the luminance for all black;

$Y_j(\theta,\phi)$ is the luminance of other views but i.

f) Reporting:

- Report the 3D contrast at each angle.

5.3.4.7 P 35.7 — Interocular 3D purity (Interocular 3D contrast)

a) Objective: To estimate a quality of 3D display, analyse the ability to display the correct images in the observer's right and left eyes. The basic idea is similar to 3D contrast, a product of each eye's "contrast".

b) Applicability: all types of autostereoscopic display

c) Preparation and set-up;

- fixed measurement conditions: See P 33.1 – Luminance Angular Distribution;
- configurable measurement conditions;
- test patterns: see 5.2.3 one view is white and the others are all black:
- measurement location:
  - three locations in horizontal (at the centre, the right and the left on the screen);
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristic: luminance only;

d) procedure:

- See P 33.1 – Luminance Angular Distribution;
- luminance profiles of each view are measured at three locations (centre, R&L);
- emission pattern of each "view" is treated as a separate single image data set (2 array data):
  - convert measurement area (*D*[mm] × *W*[mm]);
  - into the image data *I*(*i*,*j*), *i* = 1...*pD*, *j* = 1...*pW*, *pW* * Δ*x* ＝ *W*、 *pD* * Δ*z* = *D*;
- the pixel values of the image data at a position (*i*,*j*) are represented as the luminance value at that position;

e) Analysis:

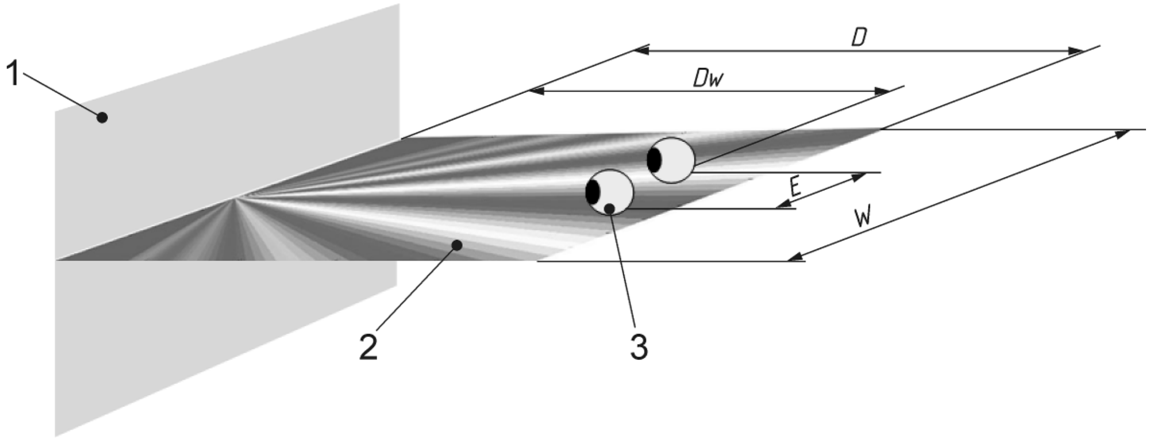
- if an interocular distance is e pixels, when the observer's right eye position is set to (*i*,*j*), the left eye always set to (*i* + *e*,*j*);
    - interocular contrast is calculated by a product of 2 positions of contrasts, i.e. *I*(*i*,*j*) and *I*(*i* + *e*,*j*);
- calculate interocular contrast (IC) in all positions of (*i*,*j*);

$$\mathrm{IC}\left(i+\frac{e}{2},j\right)=\sum_{step=1}^{N}\sum_{k=1}^{N-step}\sqrt{\frac{I_k(i,j)}{\sum\limits_{l\neq k} I_l(i,j)}\cdot\frac{I_{k+step}(i+e,j)}{\sum\limits_{l\neq k+step} I_l(i+e,j)}} \qquad (14)$$

where

IC	is the interocular contrast;
$\frac{e}{2}$	is the position of a cyclopean eye;
$\#k$	reaches the right eye;
$\#(k+step)$	reaches the left eye;
(i,j)	are the positions;
I	is the image.

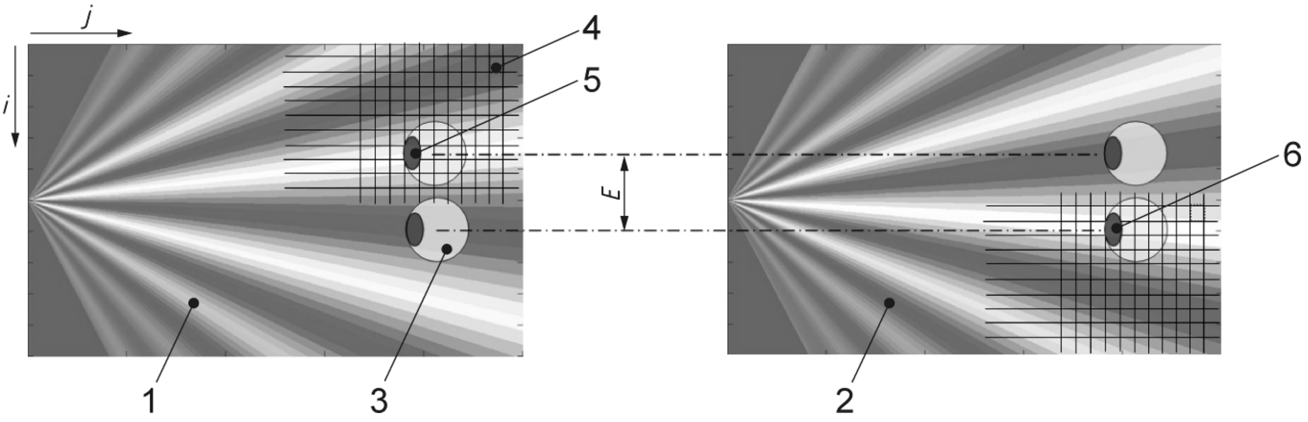
- where, *e*/2 indicates the position of a cyclopean eye;
- "view" #k reaches the right eye, "view" # (*k* + *step*) reaches the left eye;
    - "step" means interval step of views used for stereoscopy;
    - ex: in case of 2-view display, *step* = 1, *N* = 2;



Key

1	Display	E	Inter ocular distance	Dw	Viewing distance
2	Ray emission pattern on transversal plane	W	Width of ray emission pattern (i line)		
3	Eye	D	Depth of ray emission pattern (j column)		

Figure 38 — Emission patterns of a "view"



Key

1	Ray emission pattern of l_{right} (right eye is white left eye is black)	3	Eye	6	Left eye's position (i+e, j)
		4	Pixel		
2	Ray emission pattern of l_{left} (right eye is black left eye is white)	5	Right eye's position (i,j)	E	Interocular distance (E[mm] = e [pixel])

Figure 39 — Image data for left and right

f) Reporting:

- report the value of Interocular contrast of the whole calculated area.

g) Comments:

- more discussion about a consideration of an observer's gaze position is needed;
- this definition does not include the case that multiple "views" are entered in single eye simultaneously;
- equation 12 can not distinguish the two different cases: left and right eye's contrast is high, or either one is very high;
- the accuracy depends on the resolution of image data (number of pixels).

5.3.5 Interocular difference analysis

5.3.5.1 P 36.1 — Interocular luminance difference

a) Objective: Since excessive luminance difference between both eyes is considered to be undesirable for viewing, interocular luminance difference should be checked.

b) Applicability: all autostereoscopic displays

c) Preparation and set-up:

- fixed measurement conditions: See P 33.1 – Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3 all views white (to be added);
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance;

d) Procedure:

- See P 33.1 – Luminance angular distribution.

e) Analysis

- In the angular ranges of each lobe, calculate luminance difference between both eyes, considering that the angles between both eyes vary with the viewing distance and IPD, and that the positions of each eye vary with the user's position.
- Interocular luminance difference $\left[\%\right] = 100 \cdot L_{\text{min}} / L_{\text{max}}$;
  - where L_{max} and L_{min} are the higher and the lower in measured display luminance between both eyes, respectively.

f) Reporting:

- Report the interocular luminance difference.

5.3.5.2 P 36.2 — Interocular chromaticity difference

a) Objective: Since excessive chromaticity difference between both eyes is considered to be undesirable for viewing, interocular chromaticity difference should be checked.

b) Applicability: all autostereoscopic displays

c) Preparation and set-up:

- fixed measurement conditions See P33.1 Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3 all views white (to be added);
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance, chromaticity (or spectral);

d) Procedure:

- See P 33.1 – Luminance angular distribution.

e) Analysis:

- in the angular ranges of each lobe, calculate chromaticity difference between both eyes, considering that the angles;
- between both eyes vary with the viewing distance and IPD, and that the positions of each eye vary with the user's position;
- interocular chromaticity difference;

$$\Delta u'v' = \sqrt{(u'_R - u'_L)^2 + (v'_R - v'_L)^2} \tag{15}$$

where

$\Delta u'v'$ is the interocular chromaticity difference;

u'_R, v'_R are the colour coordinates for right eye;

u'_L, v'_L are the colour coordinates for left eye;

f) Reporting:

- Report the interocular chromaticity difference.

5.3.6 3D moiré analysis

5.3.6.1 P 38.1 — 3D luminance moiré

a) Objective:

- Since 3D moiré causes lateral non-uniformity, interocular differences, and so on, angular dependence of luminance fluctuation should be checked.

b) Applicability: all autostereoscopic displays

c) Preparation and set-up:

- fixed measurement conditions See P 33.1 – Luminance angular distribution;
- configurable measurement conditions (use parameters as described unless otherwise specified);
- test pattern: see 5.2.3 all views white (to be added);
- measurement location;
- meter direction;
- test illumination: 5.2.9.2 Darkroom;
- spectral characteristics: luminance;

d) Procedure:

- See P 33.1 – Luminance angular distribution.

e) Analysis

- In the angular ranges of each lobe, calculate inflection points, which are points where the curvature changes sign. Luminance contrast modulation and angular differences are calculated between two neighbouring inflection points. These results show the 3D moiré. The luminance contrast modulation is

$$C_m = \left|L_A - L_B\right| / \left(L_A + L_B\right) \tag{16}$$

where

C_m is the luminance contrast modulation;

L_A is the first luminance inflection point ;

L_B is the second luminance inflection point.

f) Reporting:

- Report the highest luminance contrast modulation value and the angular difference.

g) Comments:

- For conventional high-frequency moiré, such as that described in ISO 9241-303, the measurement and analysis methods described in ISO 9241-305 and ISO 9241-307 can be applied.

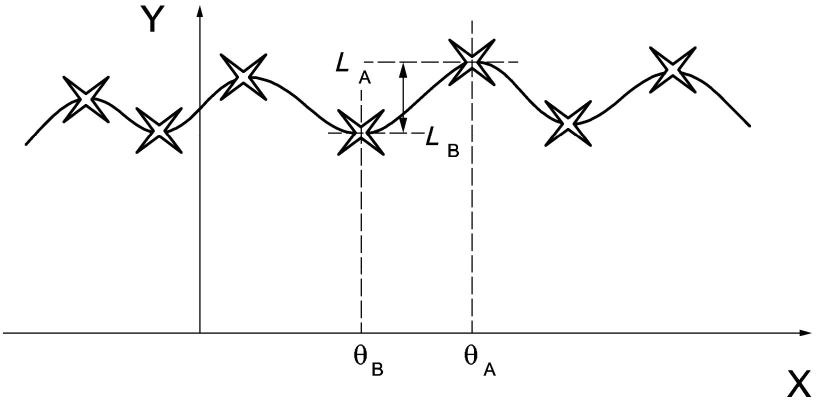


Figure 40 — 3D luminance moiré

5.4 Future work

The following points need discussions for establishing the future Standards:

a) establishment of the basis of measurement technology for autostereoscopic displays;

b) experiments on specification of measurement equipment;

c) verification of the measurement conditions; how to treat aperture and stray light;

d) ergonomic studies on how all the measurement items are related;.

6 Viewing spaces and their analysis

6.1 General

In this clause, analysis and report methods for viewing spaces are described. Most of the autostereoscopic displays are considered to have limited size of viewing space, and if well-designed measurements were made, the boundary of the viewing space could be clearly shown. As far as the viewing space is concerned, its characteristics described in Clause 4 and basic concepts of analysis explained in Clause 5 originate from the idea mentioned above. In the context of viewing spaces, it can also be relevant to consider viewing postures and postural requirements which are covered in ISO 9241-5.

Viewing space is a newly-devised concept appearing first in ISO 9241-307 for conventional 2D displays based on visual ergonomics. Some parts of this part of ISO 9241 contribute to the explanation on how to check if the characteristics of the viewing space, i.e. luminance and contrast, meet the requirements with reported values by the measurement methods where the values are measured according to display attributes, so that the viewing space can be certified.

In ISO 9241-302 and ISO 9241-305, Qualified Viewing Space (QVS) is also introduced for virtual-image displays. QVS is defined separately for each eye and means a space (volume, centre of volume) from where the image is perceived at an acceptable level. QVS for virtual-image displays is limited by the aberrations across the beam, e.g. chroma, coma, astigmatism, spherical aberration, focus point change, convergence point change, luminance, contrast, colour balance etc. It is notified that due to the complexity of the phenomenon, no single, easy, quantitative measurement can reliably be used as a criteria for the QVS in virtual-image displays.

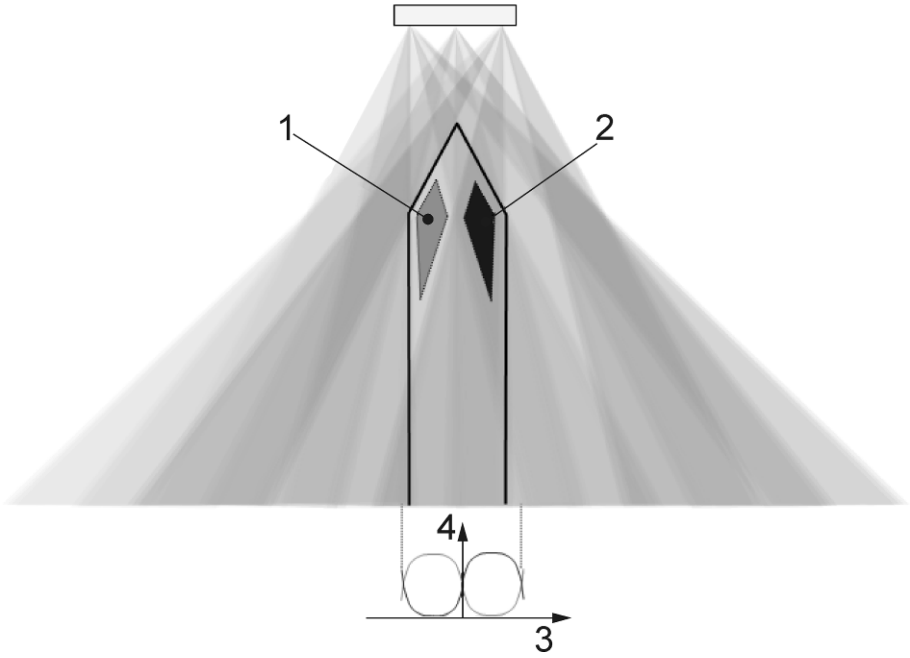
In autostereoscopic displays, the same procedure is considered to be applicable. However, and similar to QVS for virtual-image displays, there is such a disadvantage that the boundary of the viewing space is difficult to identify due to ambiguity of its expanse in the nature of autostereoscopic displays. It is also difficult to give a persuasive requirement to the size of viewing space since no substantial reasons are found yet. Even though the procedure mentioned above could not be applied in a straightforward way to autostereoscopic displays, some modification would make the procedure feasible. The size of viewing space and the quality ensured in the space for autostereoscopic displays depend on application (cf. handheld/desktop) and display size.

6.2 Qualified viewing spaces

6.2.1 Qualified viewing space

Qualified Viewing Space (QVS) is a space for the eye in which image(s) on a stereoscopic display is observed at an acceptable level of visual fatigue. QVS is comparable with the definition of QVS for virtual-image displays, though the characteristics defining the boundary of the space are not the same. QVS is a "monocular" viewing space and is insufficient for determining fully the characteristics of autostereoscopic displays that require "binocular" viewing.

In order for the observer to see the stereoscopic images correctly, viewing spaces for each eye shown in Figure 41 are needed. In each viewing space, the requirements for monocular viewing, such as the crosstalk, should be satisfied.

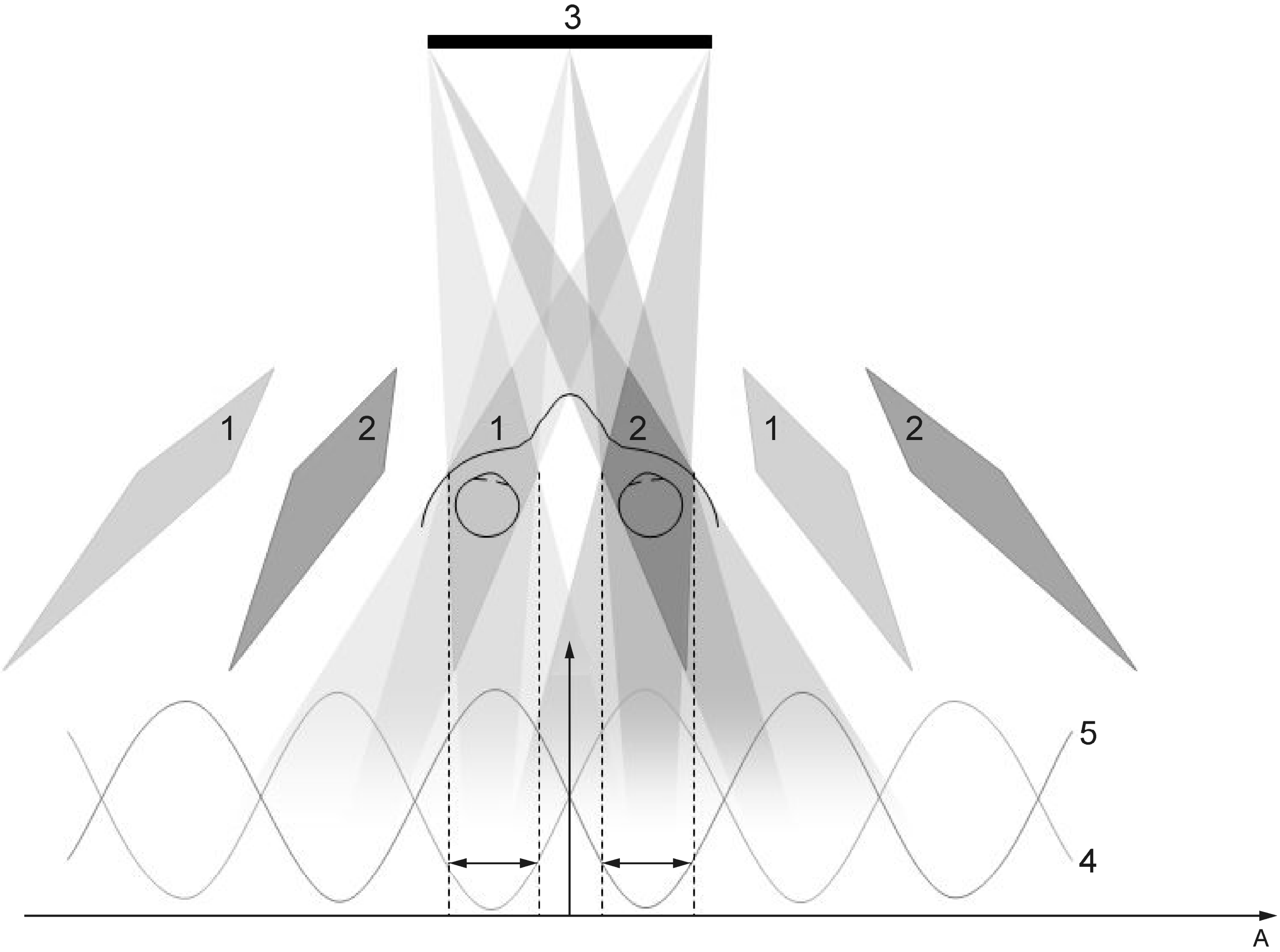


Key

1	viewing space for left eye	3	angle
2	viewing space for right eye	4	luminance

Figure 41 — Viewing spaces for right and left eyes

In a two-view display, the crosstalk is considered to be one of significant characteristics, and it represents the leakage of one-eye data to the other eye. The crosstalk can be calculated as the ratio of the luminance. The lower crosstalk value is considered to be preferable. Figure 42 shows the viewing space determined by the crosstalk analysis. In this case, the viewing space represents the space where the crosstalk is under a proper threshold level.



Key

1	viewing space for left eye	3	angle	5	X3D2
2	viewing space for right eye	4	X3D1	A	Angle

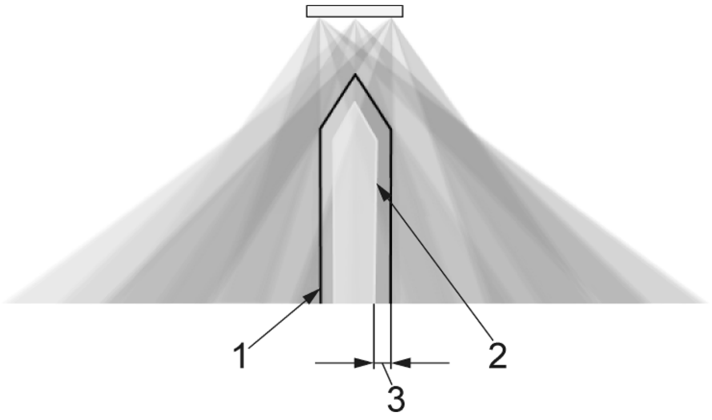
Figure 42 — Viewing spaces based on 3D crosstalk analysis

6.2.2 QBVS and QSVS

QBVS is a space for the mid-point of eyes in which images on a stereoscopic display are observed by both eyes at an acceptable level of visual fatigue. QSVS is a space in which images on a stereoscopic display induce stereopsis at an acceptable level of visual fatigue.

The lobe analysis is considered to be useful to determine how to eliminate pseudoscopy in QVS for viewing, which is related to QBVS (see Clause 2). Since QBVS is one of the binocular characteristics, QBVS should be represented as the space where the midpoint of the eyes can move within an acceptable level of visual fatigue. Strictly, the requirements for eliminating pseudoscopy should be established. However, these kinds of requirements are not discussed yet.

Simplified, as shown in Figure 43 for a two-view display, QBVS can be regarded as space where half width of an average IPD is excluded at each lobe boundary. Strictly saying, not only the characteristic for inducing pseudoscopy and its condition, but also other characteristics, such as interocular differences, should be verified. These performance characteristics have been introduced in Clause 4.



Key

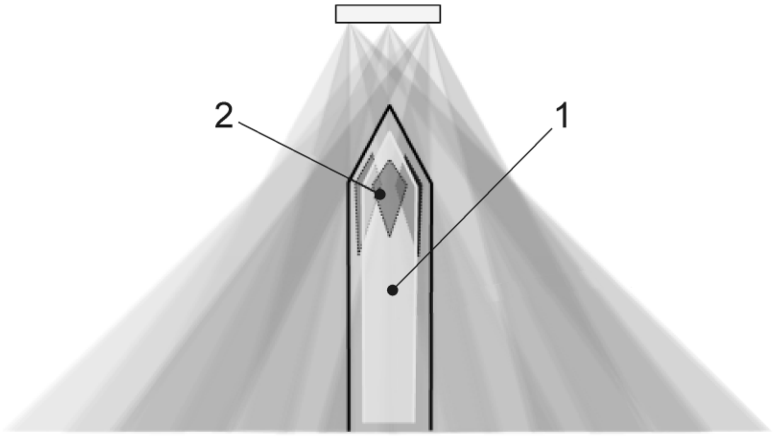
1 main lobe

2 QBVS

3 IPD/2

Figure 43 — QBVS in main lobe

In addition, since each eye needs to be positioned in each viewing space correctly, the stereoscopic viewing space, such as the QSVS, should be represented as the space where the midpoint of eyes can move, as shown in Figure 44.



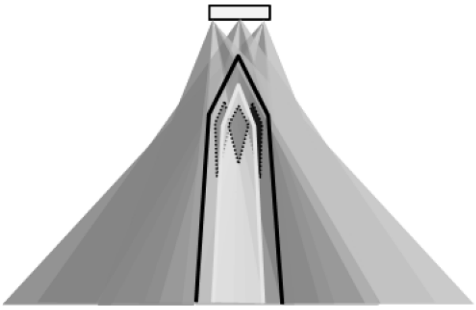
Key

1 QBVS

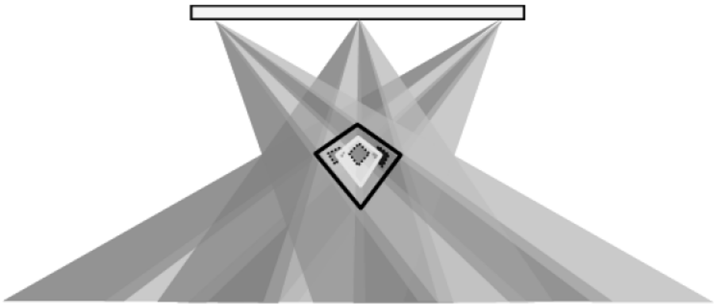
2 QSVS

Figure 44 — QBVS and QSVS

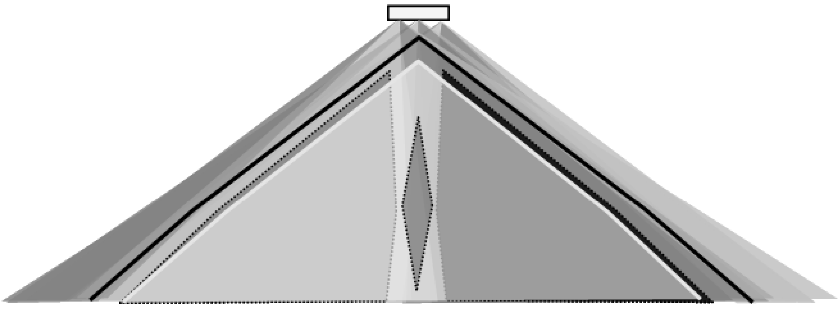
Figure 45 shows the influence of the screen size and the lobe angle. In a two-view display, the larger the screen size is, the smaller is the size of QBVS. On the other hand, the QSVS size does not change that much, because the pitch of viewing spaces for each eye is adjusted to the average IPD at a designed viewing distance traditionally, and because the QSVS size is limited by the IPD. However, larger lobe angle is also adopted in order to make pseudoscopy less noticeable. In this case, the QSVS size is not large.



a) Small size and regular angle



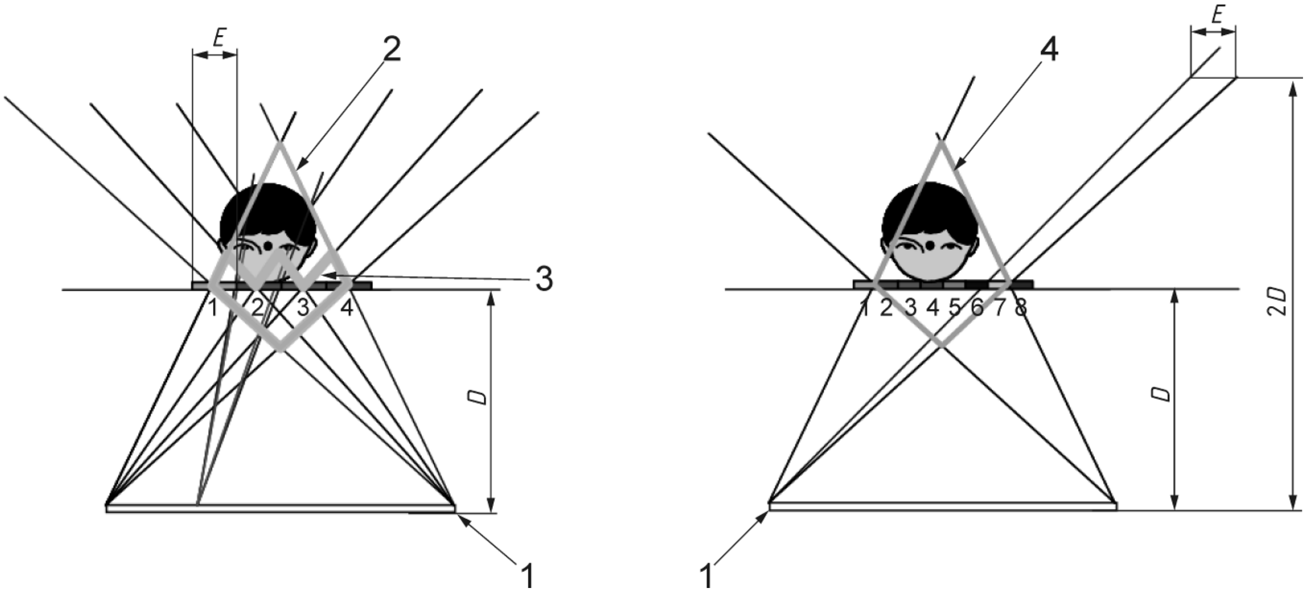
b) Large size and regular angle



c) Small size and larger angle

Figure 45 — Screen size and lobe angle

Figure 46 shows examples of QBVS and QSVS in a multi-view display. When a narrower view width (IPD/2) is used, the position in which the extension of the rays of one viewpoint image exceeds IPD becomes more distant. As shown in Figure 46 b), in the above case, QBVS = QSVS, because the position at which the requirement is met is further than the rear end of QBVS. When the display width is small and QBVS becomes long, QSVS is again narrower than QBVS.



a) view width IPD **b) view width IPD/2**

Key

1	3D display surface	3	QSVS	D	optimum viewing distance
2	QBVS	4	QBVS = QSVS	E	view width

Figure 46 — QBVS and QSVS

6.3 Related performance characteristics

According to the QBVS and QSVS definitions, if both eyes observe images shown by a stereoscopic display in QBVS or QSVS, people will suffer from visual fatigue just at an acceptable level, and in the latter case, they feel stereopsis.

The characteristics of QBVS and QSVS are determined by the performance characteristic items shown in Table 4, and each of them should meet the requirements. The items can be classified into two categories: binocular and monocular characteristics. As shown in Clause 4, binocular and monocular characteristics are significant from the viewpoint of stereopsis mechanism in human side and optical property in display side, respectively.

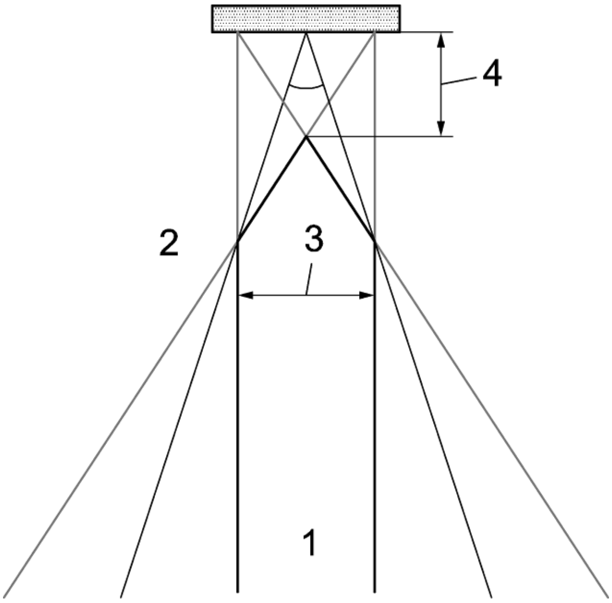
Table 4 — QBVS/QSVS and their performance characteristic items

		QBVS	QSVS
Binocular characteristics	Crosstalk		x
	Interocular differences in luminance, chromaticity,…	x	x
	Pseudoscopic images	x	
	3D moiré	x	x
Monocular characteristics	Resolution	x	x
	Luminance	x	x
	…		

As described in Clause 3, an autostereoscopic display has directional and lateral non-uniformity, in general. Without the condition of uniformity, the analysis of QBVS and QSVS incurs a great deal of measurement time. If there is lateral non-uniformity in the display, measurement should be carried out at a lot of points spread out on the entire screen. It is time-consuming and can not be afforded in a practical sense. It can be an issue that the measurement procedure should be simplified, for instance, by reduction of measuring points while the reliability of measurement results should be ensured.

To study the requirements for the size of QBVS and QSVS, display types (two- and multi-view, and integral), display use (handheld, stationary), environment, application, etc. should be considered. A multi-view or integral display can be for stationary use with enlarged size of QSVS. For handheld use like a mobile phone, large size of QBVS or QSVS can not be needed because users see the screen at an almost constant distance.

Reports of QBVS and QSVS should be given without the loss of three-dimensional information while its way of showing should be easy and simple. Attaching an illustration such as Figure 47 to the reports can be an effective way to help understand the results.



Key

1	QBVS/QSVS	3	QBVS/QSVS width
2	QBVS/QSVS angle	4	minimum distances

Figure 47 — Example of reporting methods for the QBVS/QSVS

6.4 Analysis methods

In this section, the analysis methods for QBVS/QSVS are described. These methods should be verified by experiments.

Table 5 — Interocular crosstalk analysis

Attribute	Analysis	Measuring methods	Reporting
Interocular crosstalk	(In future standards, the requirements are established, and the analysis results are checked to fulfil the requirements.)	5.3.1.1 M 31.1 – Spot measurement	Method 1: Measurement locations: 4 to 6 (Three locations in horizontal). Report the viewing space where the requirements are fulfilled.
		5.3.2 P 33.1 – Luminance angular distribution	Method 2: When the supplier indicates the viewing space, it can be measured from some positions (i.e., minimum, left, right, ...) in the indicated viewing space.
		5.3.1.2 M 32.1 Measurement locations	Method 3: Measurement locations: 1, 3, 5, 7 and 9 (five locations). Report the viewing space where the requirements are fulfilled.
		5.3.4.4 P 35.4 – Interocular crosstalk	Method 4: Measurement locations: 1 to 9 (Nine locations). Report the viewing space where the requirements are fulfilled.
NOTE 1 In case of a slanted lenticular or a slanted barrier, more measurement locations (i.e., nine locations) will be needed. NOTE2 In case that number of views on each screen location is not the same, more measurement locations needed.			

- Comments:
  - Horizontally three locations are essential, because autostereoscopic displays offer the different images into different angular direction in horizontal. The minimal and essential locations are on the right and left side on the screen. In addition, the centre location is also important, because the central area is most often viewed. In the Method 3 (see Table 5), five locations do not contain the left and right location (4 and 6).
  - Measurement locations for appropriate certification of viewing space should be discussed.

Table 6 — Interocular luminance difference analysis

Attribute	Analysis	Measuring methods	Reporting
Interocular luminance difference	(In future standards, the requirements are established, and the analysis results are checked to fulfil the requirements.)	5.3.1.1 M 31.1 – Spot measurement	Method 1: Measurement locations: 4 to 6 (Three locations in horizontal). Report the viewing space where the requirements are fulfilled.
		5.3.2 P 33.1 – Luminance angular distribution	Method 2: When the supplier indicates the viewing space, it can be measured from some positions (i.e., minimum, left, right, ...) in the indicated viewing space.
		5.3.1.2 M 32.1 – Measurement locations	Method 3: Measurement locations: 1, 3, 5, 7 and 9 (five locations). Report the viewing space where the requirements are fulfilled.
		5.3.5.1 P 36.1 – Interocular luminance difference	Method 4: Measurement locations: 1 to 9 (Nine locations). Report the viewing space where the requirements are fulfilled.

- Comments:
  - Because the interocular luminance difference is defined as a difference in luminance between stereoscopic views, and because the stereoscopic views are defined as a pair of sights producing retical disparity provided by the stereoscopic display, the measurements and analysis should be basically carried out on all locations on the screen. However, it is not so easy. The array device measurement can be a good solution, but it has some difficulties now (see 5.2.5.3.). If the spot measurement is applied, more locations can be necessary (see Table 6).

Table 7 — Pseudoscopic images analysis

Attribute	Analysis	Measuring methods	Reporting
Pseudoscopic images	(In future standards, the requirements are established, and the analysis results are checked to fulfil the requirements.)	5.3.1.1 M 31.1 – Spot measurement	Method 1: Measurement locations: 4 to 6 (Three locations in horizontal). Report the viewing space where the requirements are fulfilled.
		5.3.2 P 33.1 – Luminance angular distribution	
		5.3.1.2 M 32.1 – Measurement locations	
		5.3.4.4 P 35.4 – Interocular crosstalk	

- Comments:
  - In order to establish the analysis, the condition of pseudoscopic images should be clear.
  - In a two-view display, the number of measurement locations can be reduced, because QSVS is considered to be more important than QBVS.

Table 8 — Pseudoscopic images analysis (alternative)

Attribute	Analysis	Measuring methods	Reporting
Pseudoscopic images	(In future standards, the requirements are established, and the analysis results are checked to fulfil the requirements.)	5.3.1.1 M 31.1 – Spot measurement	Method 1: Measurement locations: 4 to 6 (Three locations in horizontal). Report the viewing space where the requirements are fulfilled.
		5.3.2 P 33.1 – Luminance angular distribution	
		5.3.1.2 M 32.1 – Measurement locations	

- Comments:
  - This alternative method will be useful, because the condition of pseudoscopic images is not necessary.

Table 9 — 3D moiré analysis

Attribute	Analysis	Measuring methods	Reporting
3D moiré	(In future standards, the requirements are established, and the analysis results are checked to fulfil the requirements.)	5.3.1.1 M 31.1 – Spot measurement	Method 1: Measurement locations: 5 (centre). Report the viewing space where the requirements are fulfilled.
		5.3.2 P 33.1 – Luminance angular distribution	Method 2: Measurement locations: 4 to 6 (Three locations in horizontal). Report the viewing space where the requirements are fulfilled.
		5.3.1.2 M 32.1 – Measurement locations	
		5.3.7.1 P 38.1 – 3D moiré	
NOTE In case that number of views on each screen location is not the same, more measurement locations can be needed.			

- Comments:
  - This analysis method is for low spatial-frequency type of moiré. For high frequency type, ISO 9241-300 series can be applied.
  - The number of measurement locations can be reduced, because the analysis results of the 3D moiré tend to be independent of the measurement location.

6.5 Future work

In Clause 6, analysis and report methods for viewing space are described. In order to establish future standards, the following issues should be resolved:

a) establishment of ergonomic requirements for the viewing space; how to obtain reliable values;

b) which measurement items should be considered for determining the viewing space.

In addition, discussions of how to make it easy for observers to find out QSVS, and how to maintain the viewing position in QSVS are also needed.

7 Further work

In this part of ISO 9241, the relation between the optical property and stereoscopy of ASDs is discussed and summarised from the viewpoint of visual fatigue. Depth cues in stereoscopy, interocular and motion parallax, classification of display, display properties according to the classification, mechanisms of two- and multi-view displays and integral display, display properties related to stereoscopy such as crosstalk and pseudostereoscopy, optical measurement methods to quantitatively identify the properties, proposal of two concepts on QVS considering the human perceptive quality in stereoscopy and procedure on how to define the proposed QVSs.

Despite a wide range of the discussion above, there still remain the following points to be discussed:

a) Display – Clause 3:

  1) whether images presented by ASDs are regarded to be continuous or discrete for both eyes when they move;
  2) how different or similar multi-view and integral displays are;
  3) stereoscopic displays close to what are adopted in the scope: temporal interlaced type, vertical parallax type, etc.;
  4) head tracking technology; worthy discussing because of its popularity in practical use;

b) Performance characteristics – Clause 4:

  1) relation between depth perception and visual fatigue in stereoscopy;
  2) how to formulate subjective testing on the relation above;
  3) definition of crosstalk;
  4) how to treat display contents to affect depth perception;

c) Measurement – Clause 5

  1) establishment of the basis of measurement technology for autostereoscopic displays;
  2) experiments for specification of measurement equipment;
  3) verification of the measurement conditions; how to treat aperture and stray light;
  4) how all the measurement items are related; ergonomic studies are needed.

d) Analysis of measured values – Clause 6

  1) establishment of ergonomic requirements for the viewing space; how to obtain reliable values;
  2) which measurement items should be considered to determine the viewing space.

All the discussion points listed above should include the consideration on the application and practical use of ASD: for what purpose, in what situation and in what manner ASDs are supposed to be used.

To establish a satisfactory international standard of ASD, its structure has to be systematic and comprehensive in corporation with image safety[1]. However, it can be said that studies of ASDs are in early phase at present and that accumulation of scientific facts is indispensable to undertake development of the standardisation.

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[1] Image safety is planned to be standardised by ISO/TC 159/SC 4 as a new project ISO 9241-391.

Annex A
(informative)

Overview of the ISO 9241 series

The 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

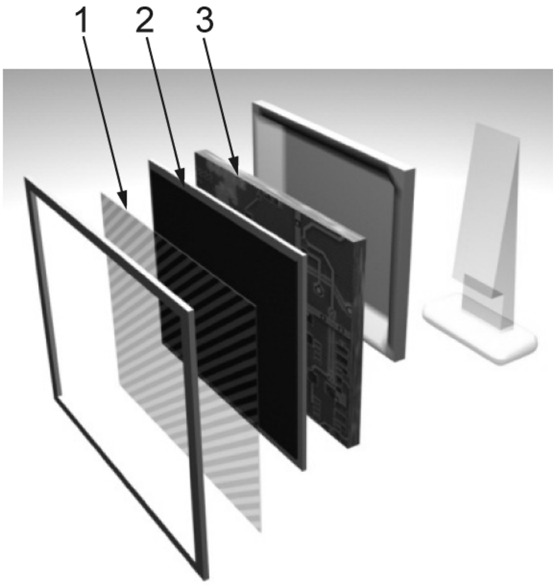
Annex B

(informative)

Head tracking technology

As one of the ways to expand stereoscopic viewing space formed by autostereoscopic displays, there exist head tracking technologies, which consist of two functions: detecting eye positions and presenting stereoscopic images correctly toward the eyes. To locate the position of observer eyes, displays with head tracking typically deploy one or more cameras and use a search method for evaluating the live images they render. Eye positions of at least one observer are calculated either in 2D or in 3D coordinates. These coordinates are used to adapt the presentation.

To present stereoscopic images corresponding to the observer's eyes positions, variety of means can be applied to the display system as shown in Fig. B.1.



Key

1 3D structure

2 display contents

3 backlight

Figure B.1 — Possible display system positions to take influence from the head tracker data on autostereoscopic displays:
(1) Enables modification of the 3D structure (e.g. barrier), its position and optical properties;
(2) Enables the re-positioning of the content;
(3) Enables applying of ray direction control and modifications of the backlighting as well as using patterned structure of backlight and light forming with optical elements

Head tracking is generally used for two-view autostereoscopic displays, but it can be applied to multi-view autostereoscopic displays. According to [49], multiple two-view parallax images are presented to multiple observers by individual head tracking. Even if an observer moves, he/she sees his/her own two-view parallax images, which are different from the others'. The multi-view autostereoscopic display is regarded as a display allowed to provide multiple two-view parallax images.

Performing objective measurements of displays with head tracking could be separated into two parts: display parameters (*e.g.* QSVS, luminance) and head tracking parameters (*e.g.* delays, accuracy). How these parameters influence each other and what are the effects on viewing ergonomics, should be investigated more.

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