Survey of perceptual quality issues in three-dimensional television systems

Lydia Meesters, Wijnand IJsselsteijn and Pieter Seuntiëns

TU/e, Eindhoven University of Technology,
P.O. Box 513, 5600 MB Eindhoven, The Netherlands

ABSTRACT

Three-dimensional television (3DTV) is often mentioned as a logical next step following high-definition television (HDTV). A high quality 3-D broadcast service is becoming increasingly feasible based on various recent technological developments combined with an enhanced understanding of 3-D perception and human factors issues surrounding 3DTV. In this paper, perceptually relevant issues, in particular stereoscopic image quality and visual comfort, in relation to 3DTV systems are reviewed. We discuss how the principles of a quantitative measure of image quality for conventional 2-D images, based on identifying underlying attributes of image quality and quantifying the perceived strengths of each attribute, can be applied in image quality research for 3DTV. In this respect, studies are reviewed that have focussed on the relationship between subjective attributes underlying stereoscopic image quality and the technical parameters that induce them (e.g. parameter choices in image acquisition, compression and display). More specifically, artifacts that may arise in 3DTV systems are addressed, such as keystone distortion, cross-talk, cardboard effect, puppet theatre effect, and blur. In conclusion, we summarize the perceptual requirements for 3DTV that can be extracted from the literature and address issues that require further investigation in order for 3DTV to be a success.

Keywords: 3DTV, stereoscopic artifacts, image quality, visual comfort, measurement paradigms

1. INTRODUCTION

Three-dimensional television (3DTV) is often mentioned as a logical next step following high-definition television (HDTV). Although the idea of stereoscopic television was already demonstrated in the 1920's by John Baird, it took until the 1980's before experimental 3DTV was presented to a large audience in Europe. The public was highly interested despite the fact that glasses were needed to view the programmes and the image quality was poor due to the applied red/green anaglyph technique.[1] Over the years a consensus has been reached that the introduction of 3DTV can only be a lasting success if the perceived image quality and the viewing comfort is at least comparable to conventional television. In addition, 3DTV technology should be compatible with conventional television to ensure a gradual transition from one system to the other.[2,3] This is becoming increasingly feasible because of recent technological developments, as well as an enhanced understanding of 3-D perception through human factor studies.

In this paper we present the state of the art of perceptual quality issues in 3DTV technology. First, a brief overview is presented of the currently applied technology in stereoscopic image content generation (stereoscopic image acquisition and 2D-to-3D image conversion algorithms), 3-D compression methods, and (auto)stereoscopic displays. Secondly, we discuss perceptually relevant issues in relation to 3DTV systems, with a particular emphasis on perceived image quality and visual comfort. With regard to this we review measurement paradigms used to identify and measure perceived attributes underlying image quality in 3DTV (e.g. focus groups or psychophysical scaling methods such as proposed in the ITU-R 500-10 and ITU-R BT.1438 recommendations). Next, we discuss how an image quality model for conventional 2-D images can be modified to suit image quality research for 3DTV. Such an image quality model is intended as a tool to describe the effect and the relationship between technical image parameters and the perceived attributes underlying image quality. Related to this model we discuss artifacts in 3DTV systems (e.g. keystone distortion, cross-talk, cardboard

---

Send correspondence to Lydia Meesters, e-mail: l.m.j.meesters@tue.nl, telephone: +31-(0)40-2473531.

effect, puppet theatre effect, and blur) and their relationship to the perceived image quality and visual comfort. Finally we summarize the perceptual requirements for 3DTV that can be extracted from the literature and address the issues that require further investigation in order for 3DTV to be a success.

2. 3DTV BROADCAST SYSTEM

Three-dimensional television is becoming increasingly feasible because of recent advances in 3-D content generation, 3-D coding and 3-D display technology. Section 2.1 provides a description of different techniques to generate 3-D content. Various 3-D image compression and (auto)stereoscopic display techniques are discussed in sections 2.2 and 2.3, respectively. Section 2.4 reflects the considerations and objectives taken within the European IST ATTEST project (Advanced Three-dimensional Television System Technologies) to integrate these different modules in a commercially feasible 3DTV broadcast chain that is 2-D compatible and flexible for different display types and viewing conditions.

2.1. Content generation

Most stereoscopic content is obtained by a dual camera configuration where the left-eye and the right-eye view are recorded separately by two cameras taken from a slightly different perspective. Shooting parameters such as camera base distance (distance between the two cameras), convergence distance (distance of the cameras to the point where both optical axis intersect) and camera lens focal length can be used to scale the horizontal disparity and thus the degree of perceived depth. Two dual camera configurations can be distinguished: (i) the parallel camera configuration, and (ii) the toed-in camera configuration, also called converging cameras. The geometry of such dual camera configurations in relation to the display and the viewer is explained in Woods et al.[4] These authors recommend a parallel camera configuration to avoid geometrical distortions like the keystone distortion and depth plane curvature. A drawback of dual camera configurations is that for each left and right view a separate sequence is generated. In terms of compatibility with a conventional 2-D broadcast system a double bandwidth is needed if the video streams would be transmitted uncompressed.

Recently, 3-D cameras have been introduced that register one conventional RGB view and an accompanying depth map, containing the corresponding depth of each image point. For example, the Zcam™ and the AXI-Vision camera, developed by 3DV and NHK, respectively, can be used as a camera add-on to an existing 2-D broadcast camera to generate such a depth map.[5, 6] The principle of the Zcam™ is that a succession of short light pulses (10 ns) transmitted in the direction of a real-world 3-D scene reflect back to the camera when the light collides with objects. Hence, for each pixel the measured depth corresponds inversely with the measured amount of energy. From such an RGB depth-annotated sequence a left and a right eye view can be reconstructed, although since only one view is registered the drawback of this method is that occluded image regions can not be retrieved correctly.[3]

Stereoscopic content is sparse. Moreover, existing stereoscopic content was mainly intended for viewing on a large screen. Hence, the parallax between the left and the right-eye image reduces such that the depth impression is lost when this material would be viewed on a small 3-D television.[7] Furthermore, the entertainment industry needs to make large investments in new 3-D cameras or add-on depth modules to compile the massive amount of stereoscopic video needed for broadcast purposes. It is probably not realistic that this will be accomplished in a short time-frame. Therefore, 2D-to-3D conversion algorithms that transform 2-D video into 3-D video would increase the amount of video material suited for stereoscopic viewing considerably. Furthermore, existing 2-D movies can be viewed as a novel stereoscopic film. In principle, 2D-to-3D conversion algorithms derive a depth map from a 2-D still image or video sequence. Only a limited amount of the monoscopic video can be converted automatically into 3-D video if depth estimation techniques such as (i) depth from motion and (ii) structure from motion are used.[8] Dynamic Digital Depth Research Pty Ltd developed a semi-automatic algorithm to recover a depth map of a monoscopic video.[8] Within the European ATTEST project effort has been spent in developing 2D-to-3D conversion algorithms that require minimal manual intervention.[9]

2.2. 3-D Compression

Most 3-D compression schemes are developed for stereoscopic pictures or video that consist of two views taken from a slightly different perspective of a three-dimensional scene. The principle of compression schemes utilizing disparity estimation is to exploit the high correlation between the image information in both views by predicting one view (target) from the other view (reference). Hence, the reference view is in general coded with a traditional 2-D compression method whereas the target view can be represented by disparity vectors. Two basic categories of stereoscopic coding schemes using disparity estimation can be distinguished: (i) intensity based methods and (ii) feature based methods. The former determine the disparity on the basis of corresponding image intensities while the latter methods use image features such as edges or objects.[10–13] Intensity based methods and in particular block-based disparity estimation approaches are mostly used. The principle of block-based disparity estimation is to divide one of the views (target) into non-overlapping blocks with a fixed size of NxN pixels (e.g. 8x8 pixels). For each NxN pixel block the most similar block in the other view (reference) is determined by means of an error criterion (e.g. mean-squared-error) that expresses the best corresponding match. A block-based disparity estimation approach that incorporates the perspective distortions due to the camera configuration is suggested by Seferidis and Papadimitriou.[14] The disparity-compensated transform-domain predictive coding (DCTDP) is a block-based method that takes into account the possible intensity differences between the left and the right view which could impede the disparity estimation process.[15] One of the drawbacks of compression schemes using block-based disparity estimation is that occluded regions cannot be represented by the reference image and disparity vectors alone. No true matching blocks can be identified for areas (e.g. objects or image borders) in the target image that are occluded in the reference image. Effective compression methods to handle occlusion are for instance based on quadtree decomposition.[14, 16, 17] Furthermore, in tradeoff for a small increase in bit-rate also compression methods are proposed that code and transmit the residual image (the difference between the reconstructed target image and the reference image).[18]

If a 3-D image is represented as a depth-annotated RGB sequence (resulting from e.g. Axi-Vision camera or Zcam™), a dense depth map is provided instantly. These depth maps can be used to identify regions of interest (ROI) that can be coded at suitable resolutions to achieve the best image quality for a given bit-rate.[19] Hence, important image regions can be coded at a higher bit-rate than less important image regions.

Another stereoscopic coding approach is based on theories of binocular suppression. The assumption that the final percept is dominated by the high quality component of a stereo pair is exploited to achieve compression. Thus, when one view of the stereo image is of high image quality the other view can be degraded without introducing visible distortions in the binocular percept.[15, 20] However the impact of coding distortions on the perceived stereoscopic image quality of such an asymmetric stereoscopic image pair depends on the visual appearance of the distortion, where blockiness appears to be much more disturbing than blur.[21, 22]

For 3-D multi-view broadcast applications compression schemes are proposed to exploit the inter-view redundancy. A major reduction of the data can be obtained by compressing the original multiviews into a smaller number of key views with sufficient disparity information. At the receiver side, intermediate views can be reconstructed from these sparse number of key views and the disparity information. The image quality of the reconstructed views depends amongst other things on whether occluded areas can be recovered from the coded key views and the disparity values. A number of authors[23–26] have proposed different coding schemes for multi-view sequences.

2.3. Stereoscopic and autostereoscopic displays

Since the introduction of Wheatstone's stereoscope the concept of displaying two separate dissimilar images to each eye brought forth many techniques to realize a stereoscopic display. The distinguishing features between stereoscopic displays are (i) the method applied to separate the left and the right eye view, (ii) whether look-around capabilities are implemented and (iii) the number of viewers that can watch a stereoscopic sequence simultaneously. Usually a distinction is made between stereoscopic and autostereoscopic displays. In the former case the viewer wears an optical device to direct the left and the right image to the appropriate eye (aided viewing) while in the latter case the technique to separate both views is integrated in the display (free viewing). Extensive reviews of (auto)stereoscopic displays are given by Sexton and Surman[27] and Pastoor and Wöpking.[28]

Stereoscopic displays with aided viewing (e.g. polarized glasses) are widely used and can be time-parallel or time-sequential. In time-parallel displays the left and the right eye views are displayed simultaneously on one or two screens depending on the image separation technique. Techniques used to direct the distinct views to the appropriate eye in a time-parallel display system are (i) location multiplexing, (ii) anaglyph or color-multiplexing, and (iii) polarization multiplexing. Location muliplexing is one of the oldest techniques and redirects the separately generated left and the right view to the appropriate eye through separate channels. The Wheatstone and Brewster stereoscopes are early examples of this method. At present, this technique is for instance applied in stereoscopic head-mounted displays, used in virtual reality. Anaglyph or color-multiplexing is also one of the primitive image separation techniques. The left and the right view are filtered with near-complementary colors and viewed through respective color-filter glasses to direct both views to the appropriate eye. Although, the technique is cheap and has been applied in experimental broadcast sessions in Europe, the color rivalry effect and poor image quality restrict its practical use in broadcast applications.[1] Polarization multiplexing uses polarized light for image separation. The hardware configuration may consist of two monitors or projectors covered with linear or circular polarizing filters and is viewed with polarized glasses to maintain separate left and right eye views. Furthermore, polarization can be applied to separate spatially multiplexed polarized images that are presented on a single monitor. The spatially multiplexed image contains alternating horizontal lines representing the left and the right eye view and are viewed with accordingly alternating polarized glasses.

In a time-sequential or time-multiplexed display the image separation of the left and the right view is maintained by presenting them in rapid alternation. The stereo pairs are viewed with synchronized shuttering glasses which open alternately for the appropriate eye while closing the other eye's view. This system exploits the human visual systems characteristic of integrating a stereo pair across a time-lag of up to 50 ms. Additionally, stereoscopic displays are proposed that combine time-multiplexing and polarization-multiplexing. The left and the right eye view are presented simultaneously on the screen but the image separation is maintained by means of time-alternating left-right circular polarization. By means of accompanying polarized glasses the left and the right eye view are channelled to the appropriate eye. A commercial product based on this technique is the Z-screen from Stereographics. The main advantages of this system are the use of light-weight, inexpensive polarized glasses and reduced crosstalk.

Autostereoscopic displays supporting free viewing are probably best suited for an application such as 3DTV. In a home-environment the need for glasses can be unpractical and limits the viewers' freedom of movement. The main categories of autostereoscopic displays that can be distinguished are: (i) direction multiplexed, (ii) volumetric and (iii) holographic displays. Direction multiplexed displays can differ in the optical effect (e.g. diffraction, refraction, reflection and occlusion) used to direct the left and right eye view to the appropriate eye. Historically, parallax barriers and lenticular systems are primarily used stereoscopic techniques and examples of the occlusion and refraction approaches, respectively. A drawback of such direction multiplexed displays is that the 3-D image is only perceived correctly under a restricted horizontal viewing angle. A broader horizontal viewing angle can be achieved by multi-view displays, where a number of discrete views are presented across the viewing area. Though volumetric and holographic displays could potentially realize the most optimal 3-D free-viewing experience they suffer from various drawbacks that preclude them from being practically feasible as a 3DTV application at this point in time. An important drawback in volumetric displays is that solid objects tend to look transparent. Holograms have the disadvantage that coherent light is required in the recording and reproduction process. Technical implementations of both displays are discussed comprehensively by Sexton and Surman[27] and Pastoor and Wöpking.[28]

2.4. 3DTV broadcast chain

Several options are possible to integrate the current technological advances in 3-D content generation, 3-D compression and (auto)stereoscopic displays into a 3DTV broadcast service (see figure 1). The aim of the European project ATTEST is to provide a novel concept of a 3DTV broadcast chain which is commercially feasible, backwards compatible with traditional 2-D television formats, novel (auto)stereoscopic displays and different viewing conditions. Moreover, the different modules of the ATTEST broadcast chain will be optimized to one another.

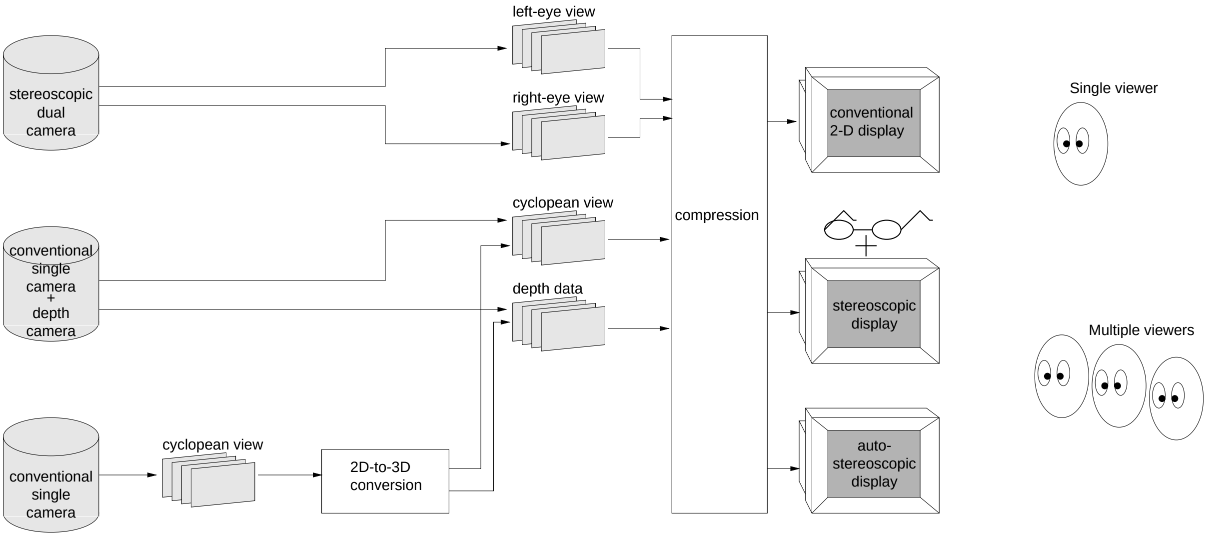

Figure 1: Separate modules in a 3DTV video chain

Within ATTEST a 3-D camera is being developed to record a conventional RGB video signal with additional depth data for each image point. Additionally, effort is spent to develop 2D-to-3D video conversion algorithms to provide sufficient content for a 24 hours broadcast service. Furthermore, 3-D compression schemes are being developed within the existing MPEG standards such that they remain compatible with exiting 2-D MPEG decoders. Therefore, the depth data obtained from the 3-D camera or 2D-to-3D conversion algorithms will be transmitted through one or more enhancement layers. Also, both single user and multi user autostereoscopic displays are being developed.

The acceptance of a novel 3DTV broadcast service depends to a large extent on the users' responses towards such a system. Therefore, it is vital to have a clear understanding of the home viewing experience of 3DTV, both looking at the potential added value and the potential drawbacks for the users. Within ATTEST, perceptual evaluations are conducted of the individual modules as well as the entire 3DTV broadcast chain to arrive at a set of requirements and recommendation for an optimal 3DTV system.

3. EVALUATION PARADIGMS

Subjective assessment methods for the perceptual evaluation of monoscopic and stereoscopic television pictures have become widely accepted. Predominantly, psychophysical experiments are used to measure and quantify perceptual attributes such as perceived image quality, perceived depth and perceived sharpness. Explorative studies, e.g. to explore viewers' unbiased reactions to conventional television or a novel three-dimensional television, are conducted to a lesser degree. In the next sections we describe how explorative studies can be performed and how they can contribute to a better evaluation of new media like 3DTV. Furthermore, a brief discussion of the ITU recommendation 500-10 psychophysical scaling paradigms is given and we discuss the need for measurements in a home environment.

3.1. Explorative studies

Evaluation criteria used to test conventional media like 2DTV are not necessarily applicable to new media. New perceptual constructs could be needed to fully explore the benefits and drawbacks of a new technology. Therefore explorative studies are better suited to get a deeper understanding of the added value and underlying perceptual constructs of a novel technology such as 3DTV.

By means of explorative studies no direct subjective ratings are acquired but instead the unbiased attitudes, feelings and reactions towards 3DTV are explored. An example are focus groups, extensively used in market research, where naive subjects participate in small discussion groups to express and share their experience of the viewed stereoscopic image system. The experiment leader moderates the discussion and gives guidance if necessary. Other methods such as the think-aloud procedure or co-discovery method, adopted from usability studies, are also suited to gather unbiased viewer's reactions to new technologies.

Freeman and Avons[29] used focus groups to explore viewers' reactions to conventional 2DTV and novel 3DTV. The results showed that viewers report, with respect to stereoscopic sequences, a sense of "being there" before this concept was raised by the moderator. Furthermore, this feeling of "being there" was related to attributes such as realism, naturalness, and involvement. A second aim of the focus group was to identify programme types suited for 3DTV. In general, subjects preferred action movies and live events such as sports, theatre and concerts. Programme types such as news, soaps, documentaries and talk shows were thought of as inappropriate for 3DTV. Moreover, subjects indicated that they would like to decide on a program-by-program basis whether they wanted to watch it in 3-D or 2-D.

Explorative studies can also be used to arrive at a better understanding of the attributes underlying a multi-dimensional concept like image quality, naturalness or presence. Bech et al.[30] proposed the RaPID (Rapid Perceptual Image description) method. The approach is based on the Descriptive Analysis method and assumes that observers can describe the attributes underlying a multi-dimensional perceptual construct like image quality by means of standard words. As the authors pointed out, the attributes are defined by the observers and are not necessarily equal to those used by engineers or experts in the field. Moreover, the words used to describe an attribute may be specific to each language.

In summary, explorative studies can be used to (i) collect unbiased viewers's descriptions of the sensations evoked by a stereoscopic image system, (ii) investigate the added value of new image systems, e.g. 3DTV, without imposing predefined appreciation criteria such as image quality, and (iii) determine the attributes that may underlie concepts such as image quality, naturalness and presence, without directed questions.

3.2. Psychophysical scaling paradigms

Psychophysical scaling paradigms can be used to measure and quantify perceptual concepts such as sharpness or image quality. The scaling concepts and perceptual attributes are known a priori and the stimulus set is manipulated such that variations in the sensations of the particular attribute are measurable. Two types of psychophysical assessment methods can be distinguished: (i) performance-oriented methods and (ii) appreciation-oriented methods.[31] The former is applicable whenever the purpose of the application is to facilitate a certain task, for instance a detection task. Appreciation oriented assessment methods are applicable in appreciation oriented applications, such as stereoscopic television, where the goal is to generate images that are as "pleasing" as possible. The emphasis is on visual comfort associated with the images. For instance, it is strenuous to watch a television program containing excessive binocular disparities. Watching programs that induce diplopia requires a great deal of effort and viewers experience this as unpleasant.

Appreciation oriented subjective assessment of stereoscopic television pictures is described in the ITU-R BT.1438 recommendation.[32] The subjective assessment methods are adopted from the ITU-R BT.500-10 recommendation for conventional monoscopic television.[33] The proposed assessment methods are used to measure overall perceived impairment or image quality of degraded still images and image sequences. The same experimental paradigms can be applied to obtain ratings of the perceived strengths or sensation of attributes such as sharpness, depth, eye-strain, naturalness, or presence. In general three different approaches are proposed: the double-stimulus-continuous-quality-scale method (DSCQS), single-stimulus methods and stimulus-comparison methods.

In DSCQS observers assess the overall image quality for a series of stereoscopic images presented separately in time (see figure 2). Alternately, an unimpaired stereo image (reference) and an impaired stereo image (test) are shown. For both stereo images (reference and test) observers assess the overall picture quality separately. Eventually the DSCQS assessment results are the difference in scores between the reference and test image. In single-stimulus scaling the overall picture quality of each stereoscopic image in the stimulus set is assessed individually. In stimulus-comparison scaling, again a series of stereoscopic images are presented sequentially in time. In this procedure, observers assign a relation between two successive stereoscopic images. In order to

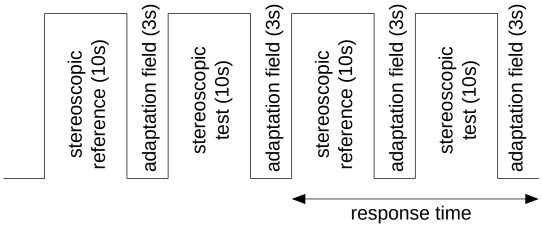

Figure 2. ITU-R BT.500-10 recommendation: double-stimulus-continuous-quality-scale method. Alternately, an unimpaired stereo image (reference) and an impaired stereo image (test) are shown. The reference and test image are presented twice. During the second presentation the subjects are asked to judge the perceived image quality of the reference and the test image separately.

Table 1: ITU-R BT.500-10 recommendation rating scales

single stimulus quality scale		DSIS and single stimulus impairment scale	
5	excellent	5	imperceptible
4	good	4	perceptible but not annoying
3	fair	3	slightly annoying
2	poor	2	annoying
1	bad	1	very annoying

comparison scale	
-3	much worse
-2	worse
-1	slightly worse
0	the same
1	slightly better
2	better
3	much better

restrict the number of observations, often just a sample of all possible combinations of stereo images in a stimulus set is used. The same single-stimulus and stimulus-comparison methods can be used to assess impairment. In the double-stimulus-impairment scale method (DSIS) again a series of stereoscopic images are presented in time (alternately a stereoscopic reference and test image). However, the assessors are asked to judge only the test image, "keeping in mind the reference".[33]

The scaling methods impose different grading scales to assess the perceived image quality. In DSCQS, a continuous graphical scale is used to avoid forcing subjects to answer within too coarse a category. The scale is often labelled with verbal terms such as *excellent*, *good*, *fair*, *poor*, and *bad*, to guide the observer. For single-stimulus, stimulus-comparison and DSIS the usually applied rating scales such as verbal or numerical categories are given in Table 1. The subjects express the perceived image quality, the impairment, or the relation between two stereoscopic images by placing the presented stimuli in one of these categories.

Average observer's quality judgements can be obtained by a number of different analysis methods. Methods such as averaging the judgements across observers by defining a confidence interval indicating the individual differences are specified by the ITU. More complex judgment models were proposed by Torgerson.[34] An application of such a model is described in Boschman.[35]

The subjective assessment methods described above are used to obtain a single judgement of the overall image quality of still pictures or short video sequences of 10 seconds. An alternative assessment method, single stimulus continuous quality evaluation (SSCQE), was proposed to obtain continuous time-varying quality judgements of longer stereoscopic video sequences. Subjects continuously assess the picture quality by moving a hand-held slider. A subject indicates excellent image quality when the slider is positioned at the top of the grading scale, and bad image quality is indicated by moving the slider to the bottom. SSCQE is used to asses video that contains scene-dependent and time-varying impairment, for example introduced by compression. Furthermore, television is usually watched for longer periods, so SSCQE is the most appropriate way to mimic home viewing conditions. This method of assessment has been applied in the context of 3DTV by IJsselsteijn et al.[36] to continuously assess observers' sense of presence, depth, and naturalness, and more recently by Yano et al.[37]

3.3. The need for measurements in the home

The previously described evaluation methods, and especially psychophysical scaling, are designed for subjective testing in a controlled testing environment where viewers are asked to carry out predefined tasks. Given the measurements and experiences acquired from such experiments, user-requirements can be specified for 3DTV. However, validation of some requirements and certainly the impact of a novel service such as 3DTV on viewing behavior as well as the interaction among behavior, technology and content can only be realistically addressed through studies performed in a home-environment situation.

For instance, conventional television, VCR (Video Cassette Recorder) and most recently ITV (Interactive Television) revealed that the type of medium and its technological implementation can lead to changes in the viewing behavior of people. The small screen size and fuzzy images inherent to the television sets of the 1950's were the predominant technological factors that imposed people to sit close to the television screen. This changed in the 1970's when affordable large television screens were introduced that allowed viewers to sit farther back from the screen. Another change in viewing behavior was observed when households were equipped with multiple television sets and television viewing became part of everyday life. Over the years, watching television shifted from a group activity, with focussed attention to the broadcast program, towards a more individual and background activity. Nowadays people watch television while performing all kinds of activities such as cooking, dressing, or talking on the telephone.[38] The question is how 3DTV will fit into existing viewing patterns or how viewing behavior will evolve. A number of studies showed that stereoscopic video adds "a feeling of being there" to the viewing experience. Judging from the content preference people expressed for 3DTV, one may have doubt whether this will become a background activity as easily, but if it does, the feeling of presence may be diminished significantly. Clearly, we need data from sustained field trials to be able to judge the impact of the introduction of 3DTV on viewing behavior in the home.

4. STEREOSCOPIC IMAGE QUALITY

The acceptance and success of a 3DTV broadcast system depends on how well the system performs. Perceived image quality is one of the evaluation criteria to asses the performance of an image system such as 3DTV. Hence, the 3DTV systems' parameters can be tuned and optimized to the customers quality preference. However, subjective testing is time-consuming and needs to be repeated for each new parameter setting. Therefore, if subjective tests can be substituted by algorithms that predict the customers quality judgements this could contribute to a low cost 3DTV design cycle. For conventional television pictures a number of quantitative image quality measures have been proposed to ultimately replace subjective testing. Nevertheless, before a quantitative measure of 3DTV image quality can be implemented, a deeper understanding is needed of the relationship between the technical parameters and the perceived image quality. In section 4.1 we discuss how the principles of a 2-D image quality modelling approach can be used to gain insight into the relationship between 3DTV parameters and perceived image quality. Typical impairments associated with 3DTV are discussed in section 4.2.

4.1. Image quality model

A number of quantitative image quality measures for conventional 2-D pictures are based on the understanding that image quality is a multi-dimensional attribute. The first step in these quality measures is to obtain descriptions of the subjective attributes of image quality, such as blur, noise or blockiness. These descriptions can be obtained by, for instance, focus groups or the RaPID method as described in section 3. Thereupon, the perceived strengths of these attributes can be quantified by means of psychophysical scaling. By means of perception rules, such as the Minkowski summation, the measured attributes strenghts can be related to the overall perceived image quality.[39] To implement an image quality measure that predicts the perceived image quality, a technical characterization of subjective attributes, such as blur and blockiness is needed.[40–42] The visibility of the attribute strengths can be quantified from the reference image, usually the original, and a processed version of it.[40] At present, much effort is spent on developing single-ended measures, which quantify the degree of impairment directly from the processed image and do not require an original image. For example, estimation algorithms based on the Hermite transform were used to estimate the perceptual strength of blur and noise or blockiness directly from the processed image.[43,44] Engeldrum[45] applied this approach in the Image Quality Circle to relate the technological parameters of a 2-D imaging system to the customers quality preference.

The perceived image quality of 3DTV pictures is also a multi-dimensional attribute. The attributes underlying image quality could be identified and quantified by means of explorative studies and psychophysical scaling, respectively. For instance, the stereoscopic image quality is degraded by image artifacts such as cross-talk, keystone distortion, blur and blockiness. However, an image quality model of stereoscopic television pictures should not only consist of attributes that degrade the perceived image quality but should also take into account the added value of perceived depth. The positive contribution of depth to the perceived image quality was demonstrated for uncompressed stereoscopic images and blur-degraded images.[46,47] Also, human observers seem to prefer DCT-coding impaired stereoscopic images over the monoscopic originals, even though the perceived impairment was rated as perceptible and slightly annoying.[48] On the other hand, when observers were asked to rate the perceived image quality of images compressed with the DCT-based methods MPEG-2 and JPEG, depth seemed not to increase the image quality.[22,49] This might be caused by the stimulus set or the scaling paradigm. For instance, when viewers judge unimpaired stereoscopic images against their monoscopic counterparts, the added value is clearly recognized. However, when image coding impairments are introduced, in particular DCT-coding distortions, observers may anchor their judgements on the most salient variations in the stimulus set. Except for the perceived degree of an image artifact (e.g. the key-stone distortion, cardboard effect or blur) also the experienced visual discomfort may degrade the perceived image quality. For instance, excessive disparities can cause eye-strain and therefore degrade the perceived image quality.[46] Thus to relate the technical parameters of a 3DTV service to the customers quality preference, image impairments, visual discomfort and the added value of depth should be taken into account. Because of this, some attributes underlying stereoscopic image quality may have a negative effect on image quality while others may have a positive effect on image quality. Therefore, most probably a combination rule such as the Minkowski summation is not sufficient in a stereoscopic image quality model. Furthermore, Meegan et al.[50] demonstrated that binocular summation rules are needed to quantify the perceived strength of for instance blur and blockiness if the left and right views of a stereoscopic image pair are compressed at a different degree.

In the next section we discuss typical stereoscopic image artifacts that may degrade the perceived image quality.

4.2. Stereoscopic image impairments

Typical stereoscopic image impairments induced by the camera configurations, compression methods and (auto)stereoscopic displays include: keystone distortion, depth-plane curvature, cross-talk, size distortions, cardboard effect, picket fence effect, image flipping and shear distortion. Moreover, a stereoscopic image or sequence may also suffer from conventional coding image impairments such as blur and blockiness. Below we discuss the possible causes of these impairments and their effect on the perceived image quality and visual comfort.

Woods et al.[4] reviewed several stereoscopic distortions including *keystone distortion* and *depth plane curvature.* These are typically introduced in a stereoscopic image due to a converging camera configuration where the left and the right camera are positioned at an angle towards each other. In this case, the imaging sensors of the two cameras are directed towards slightly different image planes. This results in a trapezoidal picture shape in opposite directions for the left and right-eye camera recordings. In a stereoscopic image the opposite oriented trapezoidal picture shapes of the left and the right image may induce incorrect vertical and horizontal parallax. This incorrectly introduced vertical parallax is the source of *keystone distortion.* The *keystone distortion* is most noticeable in the image corners and increases with increasing camera base distance, decreasing convergence distance, and decreasing lens focal length. Incorrectly introduced horizontal parallax is the source of *depth plane curvature*, whereby objects at the corner of the image appear further away from the observer compared to objects in the middle of the image. Perceptually, *keystone distortion* and *depth plane curvature* may have a negative effect on appreciation oriented assessments.[46] Furthermore, in Woods et al.[4] it was demonstrated that vertical parallax and thus *keystone distortion* may cause eye-strain.

The *puppet theatre effect* is an annoying miniaturization effect, making for instance people look like animated puppets.[51, 52] Visual size distortions result if the angular retinal size of a displayed object and its perceived distance do not covary as in real world conditions. In the real world a change in angular size is corresponding to a change in distance. Yamanoue[52] showed that orthostereoscopic shooting and display conditions (i.e. simulating human viewing angles, magnification, and convergences in the most natural way possible) do not cause the *puppet theatre effect.* Interestingly, Harper and Latto[53] investigated body image distortion in photographic images and found that with full orthostereoscopic image capture and projection there was a relative 'slimming' effect of binocular disparity for both human and abstract shapes, as compared to monoscopically presented images, in which case objects and people appeared fatter. One of the reasons for this may be the larger occluded background area for objects and people viewed monoscopically. These results suggest that the orthostereoscopic technique used in the Harper and Latto experiments appear to offer some advantages in veridical perception over 2-D representations of the same scene.

Crosstalk or *image ghosting* in stereoscopic displays may be caused primarily by (i) phosphor persistence of a CRT-display and (ii) imperfect image separation techniques by which the left-eye view leaks through the right-eye view and vice versa. *Crosstalk* is perceived as ghost, shadow or double contours and though the amount of *crosstalk* in a system is usually quite low it can lead to headaches.[51] *Crosstalk* due to phosphor persistence may occur in time-sequential displays when the left and the right view are displayed alternately and the image intensity leaks into the subsequent view. Thus, the right eye also receives a small proportion of the left-eye view. With image separation techniques such as polarization or shutter glasses it is impossible to completely separate the left and the right eye view. Additionally, for linear polarization techniques an incorrect head position of an observer (e.g. tilted head) also causes annoying *image ghosting.* This is avoided in circular polarization techniques. Pastoor[51] demonstrated that the annoyance of *crosstalk* increases with increasing contrast and disparity values. The author suggests that the *crosstalk* of a display should not cross a threshold of 0.3%. Woods and Tan[54] introduces a *crosstalk* model which incorporates phosphor afterglow and shutter leakage. Moreover, an algorithm to compensate for *crosstalk* in stereoscopic images was proposed by Konrad et al.[55] The authors showed that suppression of *crosstalk* enhances the visual comfort. Except for stereoscopic displays with aided viewing also autostereoscopic displays suffer from *crosstalk.* This is mainly due to the latency in the directional lenses to support motion parallax.

A typical stereoscopic distortion affecting the perceived depth is the *cardboard effect.* A *cardboard effect* can be caused by image acquisition parameters (e.g. camera base distance and convergence distance) or compression parameters resulting in a coarse quantization of disparity or depth values.[48, 56] This results in a depth percept whereby the objects appear flat as if the scene is divided into discrete depth planes. The effect can be compared to the scenery in a theatre.[48] The flattening of objects in a scene evokes an unnatural depth percept. If the *cardboard effect* is caused by acquisition parameters it can be avoided or reduced by increasing the binocular parallax.[56] In case the *cardboard effect* is due to the quantization of disparity values it can manifest itself also as torn-up objects such that a coherent object is represented in several depth planes and perceived as a disjointed object. Temporal discontinuous depth mismatches can occur if an object or parts of an object are assigned to different depth layers in time, which results in a flickering depth percept. Schertz[48] showed that scenes with torn objects were judged as more annoying than if the objects are reunited by reducing the depth resolution. Therefore, choosing a suitable number of depth layers is a subtle issue, where higher resolution does not always imply better quality.

The *shear distortion* is typically experienced with stereoscopic displays that allow only one correct viewing position[4].[57] For most stereoscopic displays a stereoscopic image can only be viewed correctly from one particular viewpoint. If the observer changes his viewing position the image seems to follow the observer and therefore appears perspectively distorted. Objects with uncrossed disparity move in the same direction of the observer and objects with crossed disparity seem to move in the opposite direction. This is experienced as unnatural since in real life an object remains stationary while the observer is allowed to move his head and look at it from slightly different positions. The *shear distortion* can be avoided by headtracking where the presented stereoscopic image changes accordingly to the viewpoint of the observer.

Typical autostereoscopic display artifacts are *picket fence effect* and *image flipping.* Both artifacts are perceived if the observers move their head laterally in front of the display. The *picket fence effect* is the appearance of vertical banding in an image due to the black mask between columns of pixels in the LCD. *Image flipping* indicates the noticeable transition between viewing zones which leads to discrete views and is experienced as unnatural compared to the continuous parallax experienced in the real world.[27]

Except for the typical stereoscopic image impairments as described above, conventional image impairments, such as *blockiness* and *blur*, may be introduced if existing 2-D compression algorithms are instantly applied on the left and right components of a stereo image pair or incorporated in a stereoscopic compression algorithm (e.g. in combination with disparity compensation). Hence a number of stereoscopic coding distortions can have the same physical characteristics as those introduced by monoscopic compression algorithms. DCT-coding is a widely applied compression method for monoscopic images and human observers seem more tolerant to DCT-coding distortions in stereo than in non-stereo images.[48, 58] However, Tam et al.[22] showed that the image quality of MPEG-2 coded stereoscopic sequences is equal or less than the image quality of their non-stereo version.

DCT-coding can introduce impairments such as *blockiness* and *blur*. *Blockiness* is caused by coarse quantization of block-transformed DCT-coefficients. The independent coding of NxN pixel blocks gives rise to different characteristics and degrees of coding errors between adjacent blocks. These different coding errors manifest as discontinuities at neighboring block boundaries. The sudden intensity changes are most conspicuous in uniform regions and primarily caused by the coarse quantization of the lower-order DCT-coefficients.[59] *Blurring* is caused by coarse quantization of the higher-order DCT-coefficients that can be related to low-pass filtering. This suppression of high spatial activity in an image results in a smooth percept that suffers from loss of spatial detail and reduced sharpness of object edges and textured areas.[59]

One of the theories in stereoscopic image compression is that the binocular percept is dominated by the high quality component. This suggests that one component can be kept at the desired image quality while the other component can be degraded. The effect of asymmetric coding, where the left- and the right-eye image contain a different degree of distortion, on the perceived stereoscopic image quality seems to depend on the distortion type. The image quality of stereo images with a different degree of *blur* in the left and the right-eye image seems to be dominated by the high quality component. However, if both components are degraded by *blockiness*, the perceived stereoscopic image quality seems to be an average of the image quality of the left and the right-eye view[50]

5. 3DTV REQUIREMENTS AND FURTHER RESEARCH

Although stereoscopic displays are widely used for professional applications and in cinema, their application to home entertainment, and in particular TV, has lagged behind. The widespread introduction and acceptance of digital broadcasting makes the transmission of a stereoscopic signal increasingly feasible. Proponents of 3DTV have argued that 3DTV will bring the viewer a wholly new experience, a "fundamental change in the character of the image, not just an enhancement of quality".[60]

It is a widely held belief that 3-D television should be autostereoscopic. The main reason for this is that the need to wear glasses is unacceptable in a home situation where television is usually watched casually, i.e. with many interruptions for telephone calls, conversations, making a sandwich, or engaging in other activities with TV as a simultaneous background activity. Having to take a pair of spectacles on and off constantly is a nuisance.

Most current autostereoscopic displays, on the other hand, tend to restrict the viewer to a fairly rigid viewing position, in terms of the angle under which the stereoscopic imagery can be perceived without geometrical distortions or substantial artifacts (e.g. cross-talk or picket-fence effects). Stereoscopic TV should be able to provide good quality stereo pictures to multiple viewers who are free to move throughout the room. Current developments in multiview autostereoscopic displays[61, 62] provide hope that such a system may be feasible in the not too distant future.

In addition to the requirements mentioned above, any stereoscopic system should also be able to display monoscopic images without problems, and with an image quality that is at least comparable but preferably superior to current TV sets. Other important considerations include cost[*], and size[†] of the stereoscopic television system.

The acceptance, uptake and commercial success of a 3DTV broadcast service depends for a large extent on the users' experiences with and responses towards the system. Therefore, it is important to have a clear understanding of the potential added value and drawbacks of a 3DTV broadcast service for the users. A stereoscopic image quality model could contribute to a 3DTV low cost design cycle and the technological parameters can be optimized to the customers quality preference. Finally, prototype systems need to be tested outside the controlled laboratory space, for it is the long-term, real world use of 3DTV that will prove its impact.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the IST-2001-34396 project "ATTEST".

REFERENCES

1. R. Sand, "3-DTV - a review of recent and current developments," *IEE Colloquium on stereoscopic television* , pp. 1–4, 1992.
2. P. Harman, "An architecture for digital 3D broadcasting," *Proceedings of the SPIE* **3639**, pp. 254–259, 1999.
3. M. Op de Beeck and A. Redert, "Three dimensional video for the home," *Proceedings of EUROIMAGE ICAV3D 2001, International Conference on Augmented, Virtual Environments and Three-Dimensional Imaging* , pp. 188–191, 2001.
4. A. Woods, T. Docherty, and R. Koch, "Image distortions in stereoscopic video systems," *Proceedings of the SPIE* **1915**, pp. 36–48, 1993.
5. M. Kawakita, K. Lizuka, T. Aida, H. Kikuchi, H. Fujikake, J. Yonai, and K. Takizawa, "Axi-vision camera (real-time distance-mapping camera)," *Applied Optics* **39**, pp. 3931–3939, 2000.
6. G. Iddan and G. Yahav, "3D imaging in the studio (and elsewhere ...)," *Proceedings of the SPIE* **4298**, pp. 48–55, 1994.
7. P. Harman, "Home based 3D entertainment - an overview," *Proceedings of International Conference on Image Processing* **1**, pp. 1–4, 2000.
8. P. Harman, J. Flack, S. Fox, and M. Dowley, "Rapid 2D to 3D conversion," *Proceedings of the SPIE* **4660**, pp. 78–86, 2002.
9. C. Fehn, P. Kauff, M. Op de Beeck, F. Ernst, W. IJsselsteijn, M. Pollefeys, L. van Gool, E. Ofek, and I. Sexton, "An evolutionary and optimised approach on 3D-TV," *IBC 2002* , 2002.
10. M. Strintzis and S. Malassiotis, "Review of methods for object-based coding of stereoscopic and 3D image sequences," *IEEE International Symposium on Circuits and Systems* **5**, pp. 510–513, 1998.
11. H. Aydinoglu and M. H. Hayes, "Stereo image coding: A projection approach," *IEEE Transactions on Image Processing* **7**, pp. 506–516, 1998.
12. T. Naemura, M. Kaneko, and H. Harashima, "Compression and representation of 3-D images," *IEICE Trans. Inf. & Syst.* **E82-D**, pp. 558–567, 1999.
13. J. Jiang and E. A. Edirisinghe, "A hybrid scheme for low bit-rate coding of stereo images," *IEEE Transactions on Image Processing* **11**, pp. 123–134, 2002.
14. V. Seferidis and D. Papadimitriou, "Improved disparity estimation in stereoscopic television," *Electronics Letters* **29**, pp. 782–783, april 29 1993.
15. M. G. Perkins, "Data compression of stereopairs," *IEEE Transactions on Communications* **40**, pp. 684–696, 1992.
16. S. Sethuraman, M. W. Siegel, and A. G. Jordan, "A multiresolutional region-based segmentation scheme for stereoscopic image compression," *Proceedings of the SPIE* **1429**, pp. 265–274, 1995.

---

[*] Not surprisingly, stereoscopic displays will be significantly more expensive than monoscopic displays.

[†] Many of the systems proposed today require a housing size that is not acceptable for domestic settings.

17. H. Aydinoglu and M. H. Hayes, “Performance analysis of stereo coding algorithms,” *IEEE International Conference on Acoustics, Speech, and Signal Processing,ICASSP-96* **4**, pp. 2191–2195, 1996.
18. H. Yamaguchi, Y. Tatehira, K. Akiyama, and Y. Kobayashi, “Stereoscopic images disparity for predictive coding,” *International Conference on Acoustics, Speech, and Signal Processing, 1989. ICASSP-89* **3**, pp. 1976–1979, 1989.
19. O. Grau, S. Minelly, and G. Thomas, “Applications of depth metadata,” in *IBC2001*, September 14-17th 2001.
20. W. D. Reynolds and R. V. Kenyon, “The wavelet transform and the suppression theory of binocular vision for stereo image compression,” *3rd IEEE Interational Conference on Image Processing* **1**, pp. 557–560, 1996.
21. L. B. Stelmach and W. J. Tam, “Stereoscopic image coding: Effect of disparate image-quality in left- and right-eye views,” *Signal Processing: Image Communications* **14**, pp. 111–117, 1998.
22. W. Tam, L. Stelmach, and P. Corriveau, “Psychovisual aspects of viewing stereoscopic video sequences,” *Proceedings of the SPIE* **3295**, pp. 226–235, 1998.
23. B. L. Tseng and D. Anastassiou, “A theoretical study on an accurate reconstruction of multiview images based on the viterbi algorithm,” *International Conference on Image Processing, ICIP-95* **2**, pp. 378–381, 1995.
24. M. Siegel, S. Sethuraman, J. S. McVeigh, and A. Jordan, “Compression and interpolation of 3D-stereoscopic and multi-view video,” *Proceedings of the SPIE* **3012**, pp. 227–238, 1997.
25. D. Tzovaras, N. Grammalidis, and M. G. Strintzis, “Disparity field and depth map coding for multiview 3D image generation,” *Signal Processing: Image Communication* **11**, pp. 205–230, 1998.
26. G.-C. Chang and W.-N. Lie, “Multi-view image compression and intermediate view synthesis for stereoscopic applications,” *IEEE International Symposium on Circuits and Systems, ISCAS-2000* **2**, pp. 277–280, 2000.
27. I. Sexton and P. Surman, “Stereoscopic and autostereoscopic display systems,” *IEEE Signal Processing Magazine* , pp. 85–99, May 1999.
28. S. Pastoor and M. Wöpking, “3-D displays: A review of current technologies,” *Displays* **17**, pp. 100–110, 1997.
29. J. Freeman and S. Avons, “Focus group exploration of presence through advanced broadcast services,” *Proceedings of the SPIE* **3959**, pp. 530–539, 2000.
30. S. Bech, R. Hamberg, M. Nijenhuis, C. Teunissen, H. L. de Jong, P. Houben, and S. K. Pramanik, “The RaPID perceptual image description method (RaPID),” *Proceedings of the SPIE* **2657**, pp. 317–328, 1996.
31. J. A. J. Roufs, “Perceptual image quality: Concept and measurement,” *Philips Journal of Research* **47**, pp. 35–62, 1992.
32. ITU, “Subjective assessment of stereoscopic television pictures,” *Recommendation BT.1438* , 2000.
33. ITU, “Methodology for the subjective assessment of the quality of television pictures,” *Recommendation BT.500-10* , 2000.
34. W. S. Torgerson, *Theory and methods of scaling*, John Wiley & Sons, New York, 1958.
35. M. C. Boschman, “Difscal: A tool for analyzing difference ratings on an ordinal category scale,” *Behavior Research Methods, Instruments, & Computers* **33**, pp. 10–20, 2001.
36. W. IJsselsteijn, H. de Ridder, R. Hamberg, D. Bouwhuis, and J. Freeman, “Perceived depth and the feeling of presence in 3DTV,” *Displays* **18**, pp. 207–214, 1998.
37. S. Yano, S. Ide, T. Mitsuhashi, and H. Thwaites, “A study of visual fatigue and visual comfort for 3D HDTV/HDTV images,”
38. J. Carey, “The evolution of TV viewing,” *Fourth Annual TV Meets the Web Seminar, Amsterdam* , 2002.
39. H. de Ridder, “Minkowski-metrics as a combination rule for digital-image-coding impairments,” *Proceedings of the SPIE* **1666**, pp. 16–26, 1992.
40. S. A. Karunasekera and N. G. Kingsbury, “A distortion measure for blocking artifacts in images based on human visual sensitivity,” *IEEE Transactions on image processing* **4**, pp. 713–724, June 1995.

41. V. Kayargadde and J.-B. Martens, “Perceptual characterization of images degraded by blur and noise: Model,” *Journal of the Optical Society of America A* **13**, pp. 1178–1188, June 1996.
42. J. M. Libert and C. P. Fenimore, “Visibility thresholds for compression-induced image blocking: Measurement and models,” *Proceedings of the SPIE* **3644**, pp. 197–206, 1999.
43. V. Kayargadde and J.-B. Martens, “Perceptual characterization of images degraded by blur and noise: Experiments,” *Journal of the Optical Society of America A* **13**, pp. 1166–1177, June 1996.
44. L. Meesters, “Predicted and perceived quality of bit-reduced gray-scale still images.” Ph.D. dissertation, Eindhoven University of Technology, The Netherlands, 2002.
45. P. Engeldrum, *Psychometric Scaling*, Imcotek Press, Winchester, Massachusetts, USA, 2000.
46. W. IJsselsteijn, H. de Ridder, and J. Vliegen, “Subjective evaluation of stereoscopic images: Effects of camera parameters and display duration,” *IEEE Transactions on Circuits and Systems for Video Technology* **10**, pp. 225 –233, 2000.
47. A. Berthold, “The influence of blur on the perceived quality and sensation of depth of 2D and stereo images,” tech. rep., ATR Human Information Processing Research Laboratories, 1997.
48. A. Schertz, “Source coding of stereoscopic television pictures,” in *IEE Inter. Conf. on image processing and its applications*, pp. 462–464, (Maastricht, The Netherlands), April 7-9 1992.
49. P. Seuntiëns, L. Meesters, and W. IJsselsteijn, “Perceptual evaluation of JPEG coded stereoscopic images,” *Proceedings of the SPIE* **5006**, 2003.
50. D. V. Meegan, L. B. Stelmach, and W. J. Tam, “Unequal weighting of monocular inputs in binocular combination: implications for the compression of stereoscopic imagery,” *Journal of Experimental Psychology: Applied* **7**, pp. 143–153, 2001.
51. S. Pastoor, “Human factors of 3D imaging: Results of recent research at Heinrich-Hertz-Institute Berlin,” *ASIA Display’95 Conference* , 1995.
52. H. Yamanoue, “The relation between size distortion and shooting conditions for stereoscopic images,” *Journal of the SMPTE* , pp. 225–232, April 1997.
53. B. Harper and R. Latto, “Cyclopean vision, size estimation and presence,” *Presence: Teleoperators and Virtual Environments* **10**, pp. 312–330, 2001.
54. A. J. Woods and S. Tan, “Characterising sources of ghosting in time-sequential stereoscopic video displays,” *Proceedings of the SPIE* **4660**, pp. 66–77, 2002.
55. J. Konrad, B. Lacotte, and E. Dubois, “Cancellation of image crosstalk in time-sequential displays of stereoscopic video,” *IEEE Transactions on Image Processing* **9**, pp. 897–908, 2000.
56. H. Yamanoue, M. Okui, and I. Yuyama, “A study on the relationship between shooting conditions and cardboard effect of stereoscopic images,” in *IEEE Transactions on Circuits and Systems for Video Technology*, **10**, pp. 411–416, 2000.
57. S. Pastoor, “Human factors of 3D displays in advanced image communications,” *Displays* **14**, pp. 150–157, 1993.
58. J.-Y. Chen, Z. Liwei, and S.-Q. Ding, “The effect of JPEG coding scheme on the perceived quality of 3-D images,” *SID symposium* **29**, pp. 1211–1214, 1998.
59. M. Yuen and H. Wu, “A survey of hybrid MC/DPCM/DCT video coding distortions,” *Signal Processing* **70**, pp. 247–278, 1998.
60. C. Smith and A. Dumbreck, “3-D TV: The practical requirements,” *Television: Journal of the Royal Television Society* , pp. 9–15, January/February 1988.
61. C. van Berkel and J. Clarke, “Characterization and optimization of 3D-LCD module design,” *Proceedings of the SPIE* **3012**, pp. 179–186, 1997.
62. A. Travis, “Autostereoscopic 3-D display,” *Applied Optics* **29**, pp. 4341–4342, 1990.