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INVITED REVIEW

Potential hazards of viewing 3-D stereoscopic television, cinema and computer games: a review

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Abstract

The visual stimulus provided by a 3-D stereoscopic display differs from that of the real world because the image provided to each eye is produced on a flat surface. The distance from the screen to the eye remains fixed, providing a single focal distance, but the introduction of disparity between the images allows objects to be located geometrically in front of, or behind, the screen. Unlike in the real world, the stimulus to accommodation and the stimulus to convergence do not match. Although this mismatch is used positively in some forms of Orthoptic treatment, a number of authors have suggested that it could negatively lead to the development of asthenopic symptoms. From knowledge of the zone of clear, comfortable, single binocular vision one can predict that, for people with normal binocular vision, adverse symptoms will not be present if the discrepancy is small, but are likely if it is large, and that what constitutes 'large' and 'small' are idiosyncratic to the individual. The accommodation-convergence mismatch is not, however, the only difference between the natural and the artificial stimuli. In the former case, an object located in front of, or behind, a fixated object will not only be perceived as double if the images fall outside Panum's fusional areas, but it will also be defocused and blurred. In the latter case, however, it is usual for the producers of cinema, TV or computer game content to provide an image that is in focus over the whole of the display, and as a consequence diplopic images will be sharply in focus. The size of Panum's fusional area is spatial frequency-dependent, and because of this the high spatial frequencies present in the diplopic 3-D image will provide a different stimulus to the fusion system from that found naturally.

Introduction

In the middle of the last century, defining the characteristics of visual tasks was straightforward. Academic papers were written on paper, using a pen and ink or a typewriter; the news was delivered by newspaper, and students of Occupational Ophthalmic Optics were taught about the illumination needs of people such as watch repairers. Research at the time, including that of Weston in the UK and Blackwell in USA, demonstrated the inter-relationship between illumination, size and contrast, important then for occupations such as typist and secretary.[1] Displays which were self-luminous, rather than illuminated from an outside source, became widely available outside the workplace with the advent of cinema and television, and accompanying the use of this new technology came fears of adverse health effects in the form of damage to the eyes. Such fears resurfaced with the introduction of visual display units (VDUs) into the workplace in the 1980s[2] and again with the introduction of virtual reality headsets in the 1990s.[3]

With the introduction of stereoscopic 3-D television into the home, accompanied by the re-introduction of stereoscopic 3-D cinema, concern is being expressed about the health effects of viewing these images. Typical of the reaction to the introduction of new technology was the seizure by the Italian government of 7000 sets of 3-D glasses which Reuters[4] reported 'did not display tags proving they would not cause short-term vision problems to users'. The same concerns have been expressed about the playing of 3-D stereoscopic computer games, and Nintendo have issued a warning that their new hand-held 3DS should not be viewed in stereoscopic mode by children 6 years and under (and have provided the facility for parents to turn off the stereoscopic mode). This follows similar warnings by other manufacturers, e.g. Samsung and Sony, about the use of their 3-D stereoscopic equipment. Such warnings are bound to cause concern to the public - but are the manufacturers simply being cautious? This review examines how the visual stimulus provided by a stereoscopic 3-D system differs from that of the real world, and considers the evidence of how this difference could affect the eyes.

Historical perspective

The viewing of stereoscopic images produced on flat surfaces is far from new – Wheatstone stereoscopes[5] were common in Victorian times – but there is little in the way of historical evidence to suggest that to do so will induce adverse health effects. In the 1940s and 1950s the technology became available to provide stereoscopic cinema, and at the time there was an explosion in the number of films using these effects, but without a concurrent increase in complaints. This, of course, does not mean that problems were non-existent, only that if they were present they weren't reported or investigated to any great extent. At the time, electronic pioneers were also building the first 3-D stereoscopic televisions: it is said that Logie Baird was the first to build working devices, and stereo broadcasts took place as early as 1953.[6]

In the 1980s and 1990s the conflict between accommodation and convergence which a stereoscopic display provides was identified.[7,8] The issue was raised subsequently in the context of Head Mounted Display (HMD) use by Wann *et al.*, but without convincing supporting evidence of the conflict being problematic.[9] Although 'clinically significant' alterations in heterophoria were reported to have occurred following the use of HMDs with stereoscopic displays, the changes reported were inconsistent in direction (some eso and some exo). This is the result one would expect if no effect occurred. Statistical significance was achieved when the sign of the change was ignored – a process that could provide a statistically-significant result from 'noise' alone. Following this work, Peli[10,11] examined the effects of stereoscopic and non-stereoscopic imagery in the same HMD and found no significant difference between the conditions in either subjective or objective measures.

In order to examine whether stereoscopic 3-D TVs and cinema pose a health hazard, we need to examine the visual stimulus to determine what changes in the eye, and brain, might be expected. The value of this approach can be seen by looking back at the studies when VDUs were first introduced. To take an example, a study by Woo *et al.*[12] failed to show any effect on contrast sensitivity of viewing a VDU. However, an analysis of their stimulus (the text on the VDU) would have revealed that there were no peaks in the 2D horizontal spatial frequency spectrum, and so there should be no expectation that reading the text would alter the contrast sensitivity function. This was the result found. On the other hand, the 2D *vertical* spectrum did have peaks which corresponded to the lines of text, and Greenhouse *et al.*[13] showed that the visual system did, in fact, adapt at the appropriate spatial frequency. In Woo *et al.*'s case[12] the failure to find the effect was a result of examining the wrong thing – measuring something which would not have been expected to change. With this in mind, this review is structured to highlight the differences between the stimulus provided to the eye and brain by a 3-D stereoscopic display in comparison with everyday stimuli in order to identify aspects of vision which could be affected.

There is an expectation that either, or both, objective and subjective changes could result from viewing 3-D stereoscopic stimuli. The objective changes could be a result of adaptation, habituation, or fatigue (not all of which are necessarily problematic) and the subjective changes could be an increase (or decrease) in the prevalence or severity of various symptoms. A note of caution is needed here in terms of linking the objective and subjective changes; these may be *associated*, but a change in objective ocular status will not necessarily be *causative* of a subjective change. This then leads to the vexed question[14] of what can cause visual discomfort, or asthenopia. Clinical evidence abounds about the efficacy of the use of positive lenses to relieve the symptoms of presbyopia, and presumably the effectiveness of the lenses is because they lessen the amount of accommodation needed for a given near task, reducing the proportion of the amplitude of accommodation used. It is easy to relate this relief to other muscular systems in which reducing the effort required lessens the discomfort produced. However, in other circumstances the mechanism which produces the discomfort is less clear. In particular, it is difficult to identify a mechanism when the problem is related to the neural sensory or motor control systems, rather than the muscular system. Asthenopia associated with, for example, convergence insufficiency cannot be simply explained on the basis of approaching muscular limits if the medial recti of each eye provides a full range of version movements. What we do know, from clinical experience and Optometric studies, is that when the neurological sensory and control systems are in some way stressed, for example when viewing through high-powered prisms, asthenopic symptoms are produced.[15,16] We also know that in some cases in which the oculomotor system is, in some way, strained, the wearing of prisms can relieve the symptoms.[15,16]

In summary, there are a number of differences between the 3-D stimulus provided by artificial means and that of the everyday world. The problem facing the investigator is which of these differences *cause* visual problems, and which are simply *associated* with them. Although the issue which has given rise to the most speculation about stereoscopic displays producing ocular problems is the discrepancy between the stimulus to accommodation and the stimulus to vergence, discussed below, there are other potential causes of problems and these are considered first.

Differences between artificial 3-D visual stimuli and the everyday world

The means of presenting different images to the two eyes

The ubiquitous problem facing designers is how to present different images to the two eyes under circumstances in which the head is not fixed in position. The three most common current solutions for TV or cinema are to dissociate the eyes chromatically using coloured filters, by using polarising filters (see [17]) or by the more recent temporal solution of using shutter glasses.[18,19]

Coloured filters.

Possibly the most popular way in the past to dissociate the eyes was to use red/green or red/blue anaglyphs. Here, the use of a red filter in front of one eye, and a green or blue filter in front of the other, dissociates the eyes because they each receive light from different portions of the visible spectrum. An image for each eye can be superimposed on a single screen, and disparity between them produces a stereo percept. This approach is useful from an engineering view, because the stimulus can be generated on a normal television, but it suffers from the problems of binocular rivalry[20] in addition to the degradation of the colours experienced by the viewer. A further problem is the 'cross-talk' between the images, whereby images generated to be seen by one eye are not invisible to the other, as they should be.[21,22]

Polarising filters.

The second way of dissociating the eyes, the method in widespread use for cinema viewing both last century and this, is to use polarising filters. Two differently-polarised images are displayed, and by wearing the appropriate filter in front of each eye they both see the intended image. This system does not suffer the chromatic problems of coloured filters, but can still suffer from cross-talk.

Shutter glasses.

In the third method, the eyes are alternately presented with images, usually at a refresh rate of 50 or 60 Hz for each eye.[18,19,23] This is achieved by having a 100 or 120 Hz display which produces images for each eye one after the other, and shutter glasses which are synchronised with the display so that the correct eye always sees the image generated for it. The 50 Hz frequency is high enough to allow the integration of the two images, producing a stereoscopic percept, although it has to be noted that concerns have been expressed about photosensitive epilepsy arising from the playing of video games displayed at this frequency.[24] Having said this, it is only the monocular cells in the visual system which are being driven at this frequency, the binocular cells are being driven at 100 Hz.

The shutter glasses system is the dissociation method which is likely to achieve the most widespread acceptance in the domestic market in the immediate future, because it provides a full colour experience with little crosstalk (as long as there is low image-persistence and the synchronisation is accurate) independent of head or eye position. However, the prediction can be made that once the novelty of 3-D TV and cinema has worn off the limitations introduced by the need to wear these glasses will hinder the widespread acceptance of the technology, and this form of visual display may not experience the same universal change seen when sound equipment changed from mono to stereo presentation.

The above methods do not restrict the head location, and a person can experience the stereopsis anywhere within a room, or a cinema. If, however, the head can be fixed in position relative to the display then it is easy to provide the two eyes with different images. Seaside postcards from the last century used Fresnel prisms to achieve this, and the same 'parallax barrier' principle has been adopted recently in autosteroscopic displays. The problem with such displays is that if the head is moved slightly, then a reverse stereo effect can occur, with the left-eye image being seen by the right eye, and *vice versa*.

A better solution has been provided by the introduction of multiple-image displays, which provide a different image in different directions.[25] The use of multiple images allows the display to always provide an image to the left eye which is to the left of the one displayed to the right eye; when the head moves to the left the right eye is presented with the image previously seen by the left, but the left eye is presented with a new image which is further to the left than the previous one. The distance over which this technique will work depends upon the number of images projected, which in turn is limited by the screen technology and the bandwidth of the signal.

The perspective of the 2D images presented to the eyes

Photographers, and painters such as Wayne Thiebaud, are aware of the manner in which an image changes when the focal length of a lens is changed (see e.g.[26]). Not only does the size of the image change, but the perspective alters as well – an effect that can be seen when looking through binoculars. This is an issue which concerns designers of virtual environments and computer games because of the potential to provide images which do not match those of the real world, particularly in dynamic situations. However, there is no reason to suppose that any effects other than psychological ones, such as the changes in distance judgements that Milgram & Krüger[27] reported, would occur as a consequence. A picture might look 'wrong', but physiological systems, such as the eye movement control system, should be unaffected unless the accommodation system was stimulated in some way. Having said this, we should not lose sight of the fact that non-optical effects are known to influence both accommodation and vergence (e.g. looming, proximal accommodation and vergence[28]).

The distance between the cameras & between the eyes

Once the head has finished growing a person's inter-pupillary distance remains fixed throughout life. However, people are different sizes, and as a consequence a single 3-D display will not provide the same binocular perspective normally experienced by every viewer. In addition, the producers of stereoscopic images might deliberately use a baseline which is lesser, or greater, than normal to produce perspective effects known as Lilliputism and Giantism respectively.[29]

In normal viewing, an object in a plane other than the fixation plane, and away from the horopter, will not only be diplopic but will also be blurred. Viewing the world through a hyperstereoscope (a system of mirrors which artificially increases the inter-pupillary distance) set so that the convergence and accommodation requirements at the fixation point are normal, can produce an unnatural percept. Images in front, or behind, the fixation point provide a disparity which would normally be associated with a blurred image, but could appear sharp here. We shall come back to this issue when considering the focus of the retinal image. Using a hypersteoscope for an extended period might be expected to lead to oculo-motor changes, and alteration of AC/A ratio and horizontal phorias have recently been reported after reading text in this way for 10 min.[30] Kooi & Toet[21] reported that in their study a hyperstereoscopic setting produced a significant increase in visual discomfort. Similarly, following extensive exposure to hyperstereopsis while flying helicopters, eyestrain was a complaint recorded from four of the five participants studied by Rash *et al.*[31]

Movement in 3-D

There are two aspects to consider here. The first is that a 3-D stereoscopic image does not behave naturally when the head is moved. The relative motion of moving objects which make up the displayed image may be geometrically accurate, but the failure of binocular parallax is seen when the viewing position changes. The lack of the expected motion parallax is generally not disturbing, but it does contribute to a non-veridical experience, and will contribute to the feeling of 'flatness' described below.

The second aspect is the production of vection. Most researchers now agree that the problems faced by users of Head Mounted Displays (HMDs) are multi-factorial, and that there are many causal factors. These include the physical aspects of the display system, such as the weight of the HMD, as well as the physiological and psychological. Although presenting different images within a HMD to the two eyes could cause problems because of the accommodation-convergence mismatch, after initial concern[9,32] researchers into the problems associated with the use of Virtual Reality equipment have generally given little weight to this factor relative to that of Visually-Induced-Motion-Sickness (VIMS).

Whilst this is not the place to examine the evidence for the genesis of VIMS (see [33] for a review) its importance needs to be made clear because of the possibility of blaming the stereoscopic aspects of a display for symptoms produced, in reality, by the motion in the image. To date, two conferences have been held in which the issues have been examined, VIMS 2007 and VIMS 2009,[34,35] and the journals 'Displays' and 'Applied Ergonomics' have each devoted issues to papers in the area. VIMS comes about when the movement of an image gives rise to vection, the feeling of self-motion in the absence of true movement, leading to symptoms like those of true motion-sickness. There were many anecdotal reports of VIMS when the film 'The Blair Witch Project' was released, and one would expect VIMS symptoms to arise from viewing any film, or television programme, which provides an appropriate stimulus.[36]

This is important because an obvious way to examine the effect of the viewing of stereoscopic 3-D images is to present subjects with the same stimulus (e.g. a film) in stereoscopic and non-stereoscopic forms and compare the effects. The problem with this approach is that the stereopsis could mediate other factors – in this case the strength of the VIMS stimulus – leading to differences between the conditions which are *associated* with the stereoscopic 3-D images, but not necessarily *caused* by them.[37] The issue of image movement was examined by Yano, Emoto & Mitsuhashi,[38] who reported symptoms to be worse when a target viewed on a HD stereoscopic TV moved in depth than when it moved laterally, a result which is consistent with VIMS being a confounding factor. In Emoto *et al.*'s[37] study, participants were 'forced to view, for 1 h., stereoscopic… TV programs … including computer-graphics characters flying around in 3-D space…'. Of the twelve participants, five reported more marked visual fatigue after the stereo condition, one reported more after the non-stereo condition, and six reported a similar feeling of fatigue in the two conditions. These results are as one would expect were the changes brought about by vection, and do not provide support for alternative explanations, such as the accommodation-convergence conflict, that is in any way compelling.

Discrepancy (e.g. misalignment) between the images

Ideally, the image presented to each eye should perfectly match the geometric pattern provided by a real world stimulus, and Ukai & Howarth[39] provide examples of the problems which occur when they are not matched. Lambooij *et al.*[40,41] have provided recent reviews of the issues following the comprehensive study by Kooi and Toet.[21] In this study, participants viewed a stationary stereoscopic 3-D picture, which was subjected to 35 different transformations, including relative rotation of one image, relative magnification, change of disparity, introduction of crosstalk, and a vertical shift of one image relative to the other. Participants were shown a standard image for 3.5 s, followed by a modified image for 5 s, and had to rate the second in comparison with the first on a five-point comfort scale. Whilst Kooi and Toet[21] found a number of significant results, it is not clear exactly what the participants were assessing, having been given only the one measurement tool. Although 5s would be long enough for the person to evaluate the pleasantness or the 'ease of viewing' of the image, it is not clear that it would be long enough for asthenopia to develop in response to the image. The manipulations which produced the most distortion were rated worst, and subjects with good vision were said to be 'bothered more' than those subjects with poor vision by image misalignment. Kooi and Toet[21] conclude by saying that the factors which affect viewing comfort most strongly are vertical disparity, crosstalk and blur.

The focus of the image

In a natural environment, when an object of regard is in focus other objects in front of, or behind, it will be out of focus. This defocus provides information to the accommodation system.[42] When a 3-D display is viewed, however, the situation is different because the objects are all physically in the same plane, and so will all be equally in or out of focus optically.* This provides a cue of 'flatness' for the visual system.[43] In addition, the normal cue for the accommodation system of blur gradient, in which those objects further from, or nearer than, the object fixated will be blurred by an amount which depends upon the distance involved, will be absent. Whilst it seems clear that these cues do influence the perception of depth[43] what is not obvious is how this could lead to visual discomfort in a 3-D stereoscopic display when there is no evidence that it does so when a non-stereoscopic image is viewed.

There is a further, related, issue to do with focus and accommodation because the size of Panum's fusional areas vary with the spatial frequency content of the retinal images.[44] As a consequence, in viewing a natural scene, the spatial extent corresponding to Panum's areas will be larger both in front and behind the fixation point than they will be in the fixation plane. This is because in natural viewing the high spatial frequency content in the image is lost (through defocus) away from the fixation (and focal) plane. However, in a 3-D stereoscopic image, increasing the retinal disparity to move an object away geometrically from the fixation plane without defocusing it fails to reduce the higher spatial frequency content of the image, as would occur in the real world. The high spatial frequency content of the image over the whole screen produces an unnatural percept in which images in front, or behind, the fixation point (X in *Figure 1*) appear both diplopic and in sharp focus (panel b), unlike the normal, natural situation in which a diplopic image will be blurred (panel a).

There is no reason to discount the possibility that this in-focus image can affect the oculomotor system significantly. This is because the size of Panum's fusional areas is smaller for higher spatial frequencies,[44] and so it will provide a stronger vergence stimulus than that provided by an out-of-focus image. Okada *et al.*[45] reported that in

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*Although the image on the screen could itself be out of focus, it is usual for films and computer games to have the whole image in sharp focus.

conditions of conflict the accommodation response depended upon the spatial frequency content of the stimulus. They found that a change in retinal image blur (defocus) is readily detected when the stimulus contained high spatial frequency content, and this drives the cross-links between accommodation and convergence. However, the stimulus they used differed from that found in most 3-D cinema or TV content, which contains high spatial frequencies (because it is in focus) across the whole of the display, independent of the disparity, as shown in *Figure 1*. Hence, if the accommodation response is appropriate for the display distance, it is the vergence stimulus, containing the high spatial frequencies, that is abnormal.

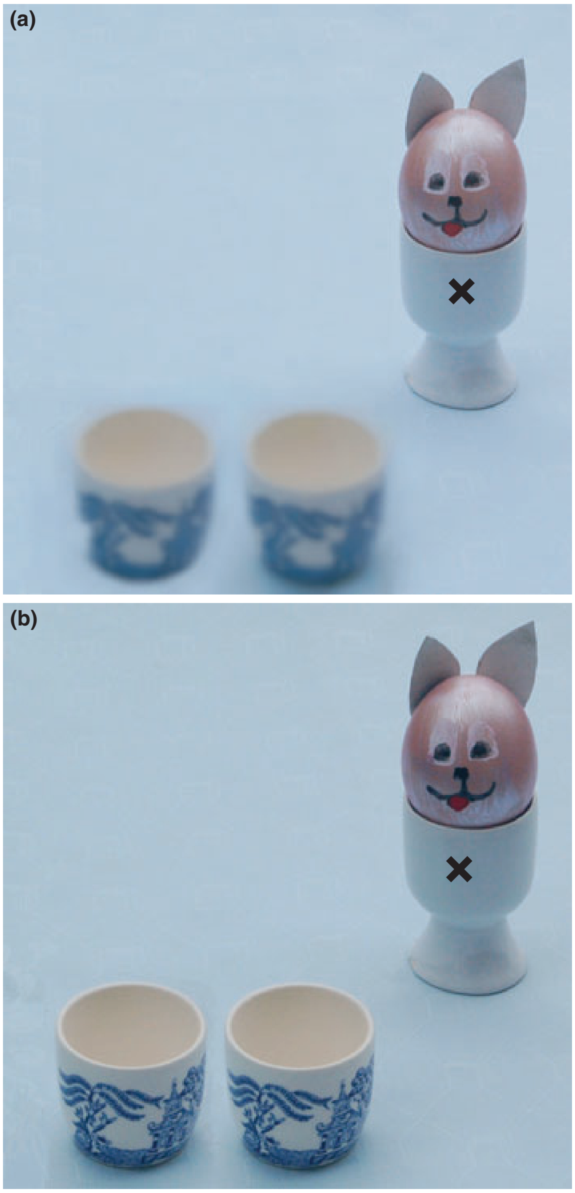

Figure 1. The non-veridical appearance of a 3-D stereoscopic display. Panel a shows the appearance to a person with normal binocular vision of two egg cups when the fixation is on the black cross. The fixated egg cup is single and in focus, but the nearer egg cup is seen as double (physiological diplopia) and out of focus. Panel (b) shows the appearance of a stereoscopic image (mimicking a television or cinema picture) produced on a flat 2D display. At the eyes the geometrical location of the images is the same as for panel (a) so the patterned eggcup again appears double because it is *geometrically* closer than the fixation point. However, both images are in sharp focus because they are *optically* at the same distance as the further eggcup.

As well as providing a non-natural stimulus, the flatness effect can give rise to headaches amongst designers, who have to decide, for example, in which plane to place sub-titles for a film, or television program (and do the optimum solutions for these different display types differ?).

The accommodation-convergence discrepancy

The difference between the stimulus to the eye provided by the natural world and that provided by a 3-D stereoscopic display which is the most commonly-mentioned in recent studies is illustrated in *Figure 2*. In the natural world, everyday objects at different distances will provide a stimulus to the accommodative system, and to the vergence system, determined by their distance to the eye, and the 45° line shows the normal relationship between accommodation and convergence, the 'Donder's Line'.[16]

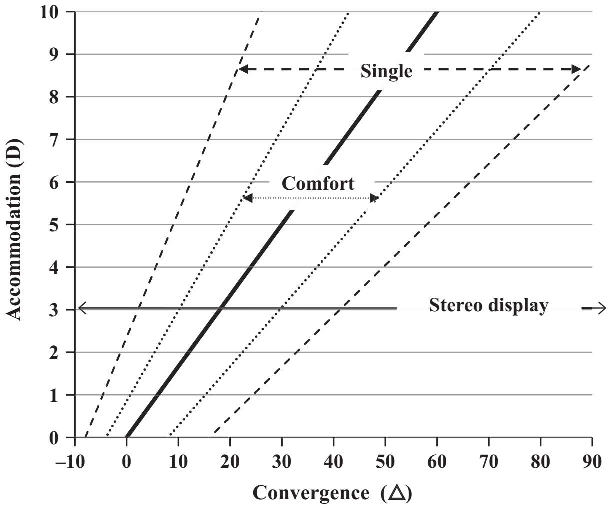

Figure 2. Zones of vision. The thick dark line ('Donder's Line') represents the accommodation and convergence demands of objects at different distances. The thin horizontal line (labelled 'Stereo display') represents the accommodation and convergence demands of a display, positioned at a distance of 1/3 m, which can provide varying disparity. The dashed arrow indicates the Zone of Clear Single Binocular Vision (ZCSBV) and the dotted arrow indicates the (hypothesised) Zone of Comfort within the ZCSBV. The slopes and positions of the lines will vary from person to person.

Images produced on a flat screen, however, will always provide the same optical stimulus to accommodation, even when different disparities are present on different sections of the screen to provide the sensation of stereopsis. This is shown in the figure as a horizontal line, parallel to the x axis. Interestingly, the use of a synoptophore for orthoptic training provides a stimulus to the eyes which moves along the same line. The synoptophore targets will be at a fixed optical distance from the eyes, and so the accommodation stimulus will be constant, but the vergence stimulus will vary depending upon the angles of the synoptophore arms. Given that the synoptophore is used in this manner to strengthen fusional reserves, it is surely not going too far to suggest that there may be beneficial ocular outcomes from the viewing of 3-D images.

The effect of the discrepancy between the optical and the vergence stimuli for accommodation is not necessarily serious, however, because both the accommodation system and the vergence system can tolerate a certain amount of imprecision. The 'comfort zone' around the 45° line represents this tolerance, which comes about because of the depth of focus of the eye and Panum's fusional areas. As long as the accommodation and vergence values are both within the dotted line in *Figure 2*, a person with normal binocular vision should be symptom-free.[38] Interestingly, it has been suggested previously[26] that the production of 'microstereopsis' in which only small on-screen disparities are allowed, will overcome the problem of the accommodation–convergence conflict.

The relationship between accommodation and convergence can also be altered by viewing the world through prisms. Although to do so will provide the same type of change as that provided by the wearing of a near prescription, or the taking off of a distance prescription by a myope, the situation in these cases is slightly different from that of viewing 3-D stereoscopic images. This is because a prism will introduce a fixed change of vergence, but will still allow accommodation and vergence to co-vary, albeit with an altered relationship between them. Hence the changes seen when prisms are introduced (prism adaptation[46–49,28]) may not truly replicate any physiological changes which come about from viewing 3-D stereoscopic displays.[49]

The experiments, and clinical research, which have led to the model described in *Figure 2* have generally been conducted over short periods. For example, the ZCSBV will be established by determining the blur and break points for base in and base out prisms at different accommodation levels,[16] a procedure which will be relatively rapid. In considering what changes may be brought about by the viewing of a 3-D TV program, a film at the cinema, or a computer game we need to ask how the parameters of the model will change over time, and this information is not yet available.

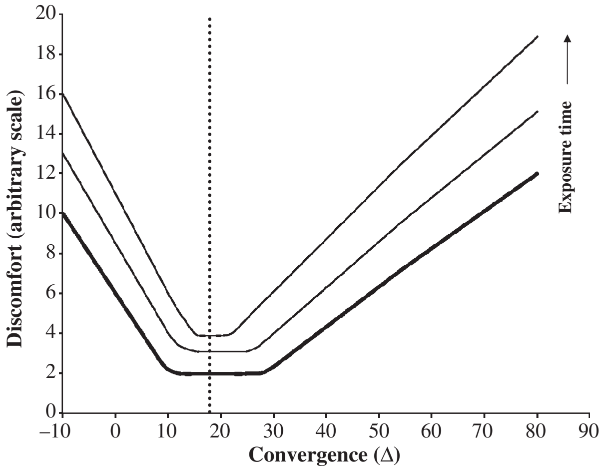

Figure 3. The suggested relationship between vergence demand and discomfort for a stereoscopic display positioned at a distance of 1/3 m for a person with an inter-pupillary distance of 60 mm. The vertical dotted line indicates the vergence demand at the plane of the display. It is hypothesised that the discomfort increases the more that the vergence demand differs from that of the display plane, and that the task itself causes increasing discomfort over time (the different curves).

We can hypothesise about these changes, on the basis that we might expect any symptoms to be greater for longer exposures. If we had a 3-D stereoscopic display positioned at a distance of 1/3 m, the stimulus would follow a cross section of *Figure 2* along the labelled horizontal line. When the disparity was outside the comfort zone, the symptoms would increase, and we could produce a function described by the lowest line in *Figure 3*.

If we now suppose that the person was undertaking a task which brought about asthenopic symptoms, and that the longer the person was exposed the worse the symptoms became, we would obtain the family of curves shown in *Figure 3*. It is suggested here that the zone of minimum discomfort decreases in width as time passes but, to date, there are no data available on this issue.

Recent experimental evidence

A comprehensive listing of recent research papers in this area has been provided by Lambooij *et al.*[40] In their review, the authors note the difference between the various terms used to describe negative effects of viewing displays, such as eyestrain, asthenopia and visual fatigue. In the current context, we can add the note of caution that adaptation (e.g. prism adaptation) is not synonymous with asthenopia.

Although concern about the viewing of 3-D images has only recently been raised in the public awareness in Europe and North America, like Visually-Induced-Motion-Sickness it has been studied far more extensively in Asia over the last decade (see [39,50–56]). Of particular note are the studies of Yano *et al.*[56] who reported the results of a study of visual fatigue and visual comfort for 3-D HDTV, and the subsequent study by Yano *et al.*[38] which produced a single curve consistent with the model shown in *Figure 2*. The latter study has been criticised by Hoffman *et al.*[57] as not providing an adequate stimulus to definitively show that the accommodation-convergence conflict causes asthenopic symptoms, but this criticism does not stand close inspection.

In the first of Yano *et al.*'s [38] experiments, six participants read passages of text, presented stereoscopically, for 64 min (which included three breaks of 3 min each) on a number of occasions. On each occasion the physical position of the text was at a distance of 108 cm but the geometrical position of the two images was at one of seven different disparities (0, ±1.9°, ±1.36°, ±0.82°) relative to the screen. Subjective discomfort responses were recorded using a nine point scale (a five point scale with subjects allowed to report a mid-position). Although a number of experimental details are not recorded (e.g. does the figure show the change over the trials, or simply the rating at the end?) the minimum subjective rating occurred after the trials in which the geometrical and physical locations of the images matched – i.e. those trials in which there was no accommodation-convergence discrepancy. There was also little difference between the rating for zero disparity and that for either +0.82° or −0.82° but the rating fell as the disparity increased thereafter. The data are consistent with the model shown in *Figure 3*. The first objection which Hoffman *et al.*[57] made was that the discrepancy between accommodation and convergence was not the only variable in the experiment, but that vergence also changed; however, it is hard to imagine how a change in vergence would produce the results found, in which the rating decreased for both relative convergence disparity and relative divergence disparity. Their second objection was that the task could have been performed monocularly, and whilst this is true, one would not expect disparity to have any effect were the test performed in that manner.

A more comprehensive study was performed by Emoto[58] which, perhaps surprisingly, failed to find statistically significant differences in subjective symptom ratings amongst the ten conditions. The participants viewed a stereoscopic version of 'Die Fledermaus' through either a fixed or a variable prism for almost an hour, and over 20 symptoms were evaluated. In contrast, Howarth[49] had previously performed two similar experiments, one using fixed and one using changed prismatic intervention, and had found very clear changes in comfort. There are a number of possible explanations for the failure of Emoto *et al.*[58] to show significant changes. As well as performing a parametric analysis on rating scale data, they only measured the symptoms at the end of the trial, and not at the beginning, and so they had no way of evaluating what changes had taken place over the trial. In addition, they only had six participants, and for parts of their experiments the participants were experiencing diplopia, and therefore were probably not experiencing the accommodation-convergence conflict.

The data which Hoffman *et al.*[57] produced provides support for the model, but there are a number of methodological issues which are problematic in this work. These researchers produced a volumetric stereoscopic display, which allowed them to present stimuli which were either 'cue-consistent' in which the focal and vergence distances matched at one of three distances, 3.21D, 2.54 D or 1.87 D[†], or 'cues inconsistent' in which the focal plane was fixed at the mid distance, and the vergence plane was ±0.67 D from this. Participants rated a number of symptoms, and these were all slightly worse in the cues-inconsistent mode than the cues-consistent. Unfortunately, symptoms were only assessed *after* the trial, and not before, so there is no way of establishing whether they changed *over* the trial. This was a common methodological error in early studies of VDU users.[59] In addition, six of the participants contributed more than one set of data to Figure 12, and five contributed more than one set to Figure 13. This is a non-trivial point, because the error bars in Figure 13 indicate that some of the participants rated the cues-consistent to be *worse* than the cues-inconsistent. The task given to the participants, which was the viewing of a random dot stereogram, apparently produced adverse symptoms, and decoupling accommodation and convergence increased these, but only slightly. That a larger effect was not found is perhaps surprising, given that the size of the discrepancy was almost 2.5° which one would expect to be well outwith the ZCSBV. In addition, although one can ask whether it was the decoupling which caused this slight increase, perhaps the more interesting question is why the coupled, *cues-consistent*, condition produced the symptoms in the first place.

A number of the studies over the last decade examining issues related to the accommodation-convergence conflict have measured changes in accommodation (e.g.[60,52]).

[†] These correspond to distances of 31.1 cm, 39.4 cm and 53.6 cm, which have vergence requirements of 11.8, 9.4 and 6.9° respectively for a participant with eyes 65 mm apart. The differences are approximately 4.2 prism Dioptres.

Ukai & Kato[61] measured all three components of the near triad when a target on a 3-D stereoscopic display jumped in depth, and they suggested that the unstable accommodative and convergence responses they recorded indicated that the participant had difficulty in fusing the binocular images because of the accommodation-convergence conflict. Torii[62] also measured accommodative and convergence responses to step changes in depth, and found variation amongst their participants, with four of the seven displaying accommodative overshoot. Following this work, Fukushima *et al.*[63] examined individual differences in dynamic accommodation responses, and reported that three of their eight participants showed accommodative overshoot whilst viewing a stereoscopic LCD. Whilst this is evidence of imprecision in accommodation control, in itself it does not provide a clear picture of a mechanism producing discomfort.

Technological involvement

Early studies[62–67] which addressed the accommodation–convergence conflict by altering the accommodative or vergence demand have not progressed significantly. A recent development[68] is a fast switchable lens synchronised to a display so that focus cues are nearly correct for the disparity involved, and this technique holds promise for producing a more realistic image. However, if it turns out that the genesis of the problem lies in the sharpness of the image content, then these modifications will do little to alleviate the symptoms experienced. It is to be expected that, ultimately, holographic imagery may take the place of 3-D stereoscopic displays, but cost and technological development currently prohibit this.

Conclusions

On the basis of our knowledge of the accommodation and oculomotor systems, we would expect 3-D stereoscopic systems to induce asthenopic symptoms in people with normal binocular vision when the discrepancy between the vergence demand and the accommodation demand was large, but not when it was small. We would also expect to find clear individual differences in the responses to a given discrepancy, with different people having different 'comfort zones' (*Figure 2*). We can also predict that there may actually be some positive consequences, the stimulus mimicking that present when a synoptophore is used to strengthen fusional reserves.

For the cinema, where the screen is effectively almost at optical infinity, if the depth of field of the eye is, say, 0.3 D[69,70] then a disparity which produces a 3-D image at any distance further than 3 m from the viewer should be within tolerance limits. On this basis alone, one would not expect 3-D cinema to produce substantial problems as a consequence of the accommodation-convergence conflict. Although problems have been reported, these figures indicate that the conflict is not the cause, and it seems more likely that they were a consequence of the motion present. Using the same numeric argument, because of the non-linearity of the Dioptric scale one might expect 3-D computer games (viewed at a closer distance) to be more problematic than stereoscopic 3-D television.

We might also expect problems to increase over time, akin to the build-up of Visually-Induced-Motion-Sickness. On the other hand, people have been shown to habituate to VIMS[71] as clinical experience shows us they do to a new prescription (and the consequent change of the accommodation-convergence relationship which the new prescription provides) and it remains to be seen whether any habituation will occur when conflict between accommodation and convergence is present. Also, as people approach presbyopia, and their amplitude of accommodation is reduced, the relationship between accommodation and convergence changes. This change is not generally thought to bring about asthenopic symptoms[15,16] (which suggests that habituation does occur) and, ironically, the use of a near addition to relieve symptoms brought about by presbyopia will actually introduce a change between the accommodation and vergence demands for the spectacle wearer, whilst at the same time relieving symptoms!

At the outset, the point was made that the stimulus to the eye needs to be analysed fully, and the discrepancy between the accommodation and vergence demands is not the only factor to consider in the viewing of these images. Indeed, the fact that the conflict is so small for both cinema and television viewing suggests that this conflict will not generate asthenopia for most people.

An additional issue is that an image located well in front or behind the screen will appear in focus, as shown in *Figure 1*. Although Watt *et al.*[43] point out that this will have a *perceptual* effect because of the cue of 'flatness', it will also provide the *oculomotor* system with an unnatural stimulus. Although most experimental work in the area has concentrated on the accommodation system, our clinical knowledge of the asthenopia associated with heterophoria and fixation disparity would suggest that perhaps the genesis of the asthenopia lies in the oculomotor system. When viewing an object at normal reading distance the cross links between the accommodation and the vergence systems will, on average, provide most of the convergence required through accommodative-convergence. A near heterophoria of a few prism dioptres would be considered normal, the remaining convergence being provided by the fusional mechanism. Why then would we expect asthenopia to occur in the example of a stereoscopic display which places the image geometrically a few prism dioptres behind the focal plane of the display, relieving the fusional mechanism of the need to work?

In summary, the visual stimulus provided by a 3-D stereoscopic display differs from that of the real world because the image provided to each eye is produced on a flat display. The distance from the screen to the eye remains fixed, providing a single focal distance, but the introduction of disparity between the images allows objects to be located geometrically in front or behind the screen. Unlike in the real world, the stimulus to accommodation and the stimulus to convergence do not match. From our knowledge of the zone of clear, comfortable, single binocular vision we can say that this discrepancy is unlikely to lead to asthenopic symptoms if it is small, but is likely to do so if it is large, and what constitutes 'large' and 'small' are idiosyncratic to the individual. However, this is not the only difference between the natural and the artificial stimuli. In the former case, an object located in front, or behind, the fixated object will be perceived as double if the images fall outside Panum's fusional areas, and it will also be defocused, or blurred. In the latter case, however, both retinal images will be sharp and so the diplopic perception is unnatural. The high spatial frequencies present in the 3-D stereoscopic display will provide a different stimulus to the fusion system from that found naturally, and clinical experience of heterophoria and fixation disparity giving rise to asthenopic symptoms[15,16] would suggest that the genesis of the symptoms lie in the fusion, and not the accommodation, system.

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