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Abstract. *A stereoscopic 3-D version of the film* Avatar *was shown to 85 people who subsequently answered questions related to sickness, visual strain, stereoscopic image quality, and sense of presence. Viewing* Avatar *for 165 min induced some symptoms of visual strain and sickness, but the symptom levels remained low. A comparison between* Avatar *and previously published results for the film* U2 3D *showed that sickness and visual strain levels were similar despite the films' runtimes. The genre of the film had a significant effect on the viewers' opinions and sense of presence.* Avatar*, which has been described as a combination of action, adventure, and sci-fi genres, was experienced as more immersive and engaging than the music documentary* U2 3D*. However, participants in both studies were immersed, focused, and absorbed in watching the stereoscopic 3-D (S3-D) film and were pleased with the film environments. The results also showed that previous stereoscopic 3-D experience significantly reduced the amount of reported eye strain and complaints about the weight of the viewing glasses.* © *2012 SPIE and IS&T.*
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1 Introduction

The recent successes of stereoscopic 3-D (S3-D) films are a clear sign that stereoscopic information may offer viewers new and refreshing experiences. However, various film-, equipment-, and viewer-related parameters may either increase or decrease viewing comfort and potentially disrupt viewers' experiences, in turn affecting viewers' opinions of and future interest in S3-D presentations.[1–5] In the next sections, some of these parameters will be reviewed, and the results of an *Avatar* cinema visit will be presented.

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1.1 *Dimensions of Stereoscopic Image Quality and Sense of Presence*

Many studies of stereoscopic image quality have evaluated overall viewing experience and image naturalness in terms of the added value of stereoscopic depth information.[6–9] One component of naturalness is the greater level of detail available in stereoscopic film, which is commonly mentioned as a dimension of quality.[10,11] In addition to improvements in image quality, disparity may increase the sense of presence (a subjective experience of being in one place or environment when one is physically situated in another place).[5,12] IJsselsteijn et al.[8] reported that the use of disparity information not only increases ratings of perceived depth but also affects the naturalness of depth. Seuntiens et al.[9] concluded on the basis of their results that the viewing experience takes into account the quality of the video as well as enhancements such as 3-D and Ambilight (a surrounding glow of light that complements the colors and light intensity on all four sides of the image). Because depth and dynamic Ambilight provide more sensory information, they also increase the sense of presence. IJsselsteijn et al.[13] demonstrated that stereoscopic and motion-parallax cues increase the sense of presence when depth levels are perceived as natural whereas IJsselsteijn et al.[14] found that image motion, stereoscopic presentation, and screen size affected subjective ratings of presence, but screen size was important only when motion stimuli were used. Moreover, these authors assumed that stereoscopic presentation has a greater influence on spatial presence/physical space than on involvement/engagement.

Although emotional involvement and the experience of presence are often associated with interactive S3-D environments[15,16] non-interactive tasks such as viewing a TV program or film may increase the sense of presence, particularly when compared with still stimuli or non-stereoscopic viewing

conditions.[17–20] For instance, Pölönen et al.[17] found that S3-D film viewing differed in several ways from 2-D film experiences: the scenes of the S3-D film were more credible, the experience was psychologically more immersive and realistic, and the 3-D world triggered real emotions in viewers.[10]

1.2 *Visual Discomfort and Sickness*

Many recent papers have shown that viewing an S3-D presentation may be a comfortable experience, but the importance of visual comfort and sickness should not be underestimated.[1,21–28] For example, Kooi and Toet[2] reported that even a small amount of vertical disparity, crosstalk, and blur may cause noticeable viewing discomfort when viewing stereoscopic static images. Among other recommendations, the authors suggested that lenticular screens should only be used to display stereo images with small amounts of disparity to avoid viewing discomfort from crosstalk and the luster combination. Lambooij, IJsselsteijn, Fortuin, and Heynderickx's paper on the visual discomfort and fatigue of stereoscopic displays[1] reviewed several factors that may cause undesired effects. According to the authors, the temporally changing demands of accommodation-vergence linkage (by rapid motion in depth), 3-D artifacts resulting from insufficient depth information in the incoming data signal that yield spatial and temporal inconsistencies, and unnatural blur are the most critical factors in visual discomfort.[2,24,28]

In addition to visual fatigue, viewing an S3-D film may induce different sickness-related symptoms, particularly when strong motion scenes are used.[27,29–33] For example, Hettinger et al.[31] suggested that individuals who experience the illusion of self-motion (vection) may report an increase in simulator sickness, whereas Hettinger et al.[29] suggested that vection becomes more common with the increased use of wide field-of-view presentations of realistic imagery. However, vection may enhance task- or experience-related realism, increasing the pleasantness of the task and affecting future decisions[4,34]

In sum, added stereoscopic depth information may affect the overall viewing experience and image naturalness, thus increasing the sense of presence. However, problems in stereoscopic presentation, the nature of the task and the equipment used may, in some cases, cause visual fatigue, discomfort and sickness.

2 Aims of the Study

In our earlier S3-D cinema-related paper, we showed that stereoscopic 3-D presentations can be quite enjoyable.[17] Compared with experiences from 2-D film viewing, S3-D experiences were described as more realistic and immersive. The participants were more absorbed in watching the film, and many of them were so deeply focused on the film that they lost track of time. In addition to experiences of a stronger sense of presence, the participants reported some visual strain and discomfort. The symptom levels were low, on average, and they did not influence the pleasantness of the task or affect viewers' opinions. According to their subjective comments, more than half of the participants thought that S3-D action-type movies, games and nature documentaries benefit most from the S3-D format.

Our goal for this paper was to study people's S3-D-related experiences after viewing the sci-fi action adventure film *Avatar*[35] and compare these results with results from the music documentary *U2 3D*.[36,17]

3 Methods

3.1 *Subjects*

In this study, 85 subjects viewed *Avatar* in S3-D (72 males and 13 females aged 25–58 years; mean 37.5 years). Four participants reported problems with stereo acuity and were consequently excluded from further analysis. Ninety-three percent had some experience with S3-D applications, and 81.5% of the participants had visited S3-D cinemas before. Of those who had previously seen stereoscopic movies (66), 15 participants had also seen *Avatar* before. Most of the participants were infrequently susceptible to motion sickness (74.1%) or headaches (70.4%). Forty people wore personal eyeglasses during the film, and most of the participants felt normal before viewing the film.

3.2 *Procedure*

Because the test was conducted at a public cinema, the entire auditorium was reserved for the event. Participants were asked to choose seats and rows so that rows one through four and side seats on both sides of the auditorium were left empty. Before the film, questionnaires were distributed, and participants completed the first five pages. Questions on visual strain (VSQ),[37] sickness (SSQ),[31] differences in the experience of presence (ITQ, focus and involvement)[5] and other individual- and experience-related questions were asked. After the film and before leaving the theater, the participants again completed the VSQ and SSQ. Additionally, the Stereo 3-D movie Questionnaire (S3-DMovieQ), based on the qualitative results of Häkkinen and colleagues[10] presence questionnaires developed by Takatalo et al.[38] and other viewing experience-related questions were answered. Because one of our goals was to compare these results with previous results from the *U2 3D* film, most of the questionnaires and questions used in the *Avatar* study were similar to the questions used in the *U2 3D* study.

3.3 *Equipment*

The participants viewed a film called *Avatar* in the Tampere Plevna movie theater (491 seats), which was equipped with a Christie Digital CP-2000XB projector (3-chip DLP Cinema® technology) and capable of light output greater than 30,000 lumens and 2 K resolution. The sensation of depth was produced through XpanD's active 3-D cinema glasses.

4 Results and Discussion

4.1 *Visual Strain and Sickness*

A Wilcoxon signed ranks test revealed significant differences in before and after scores for visual strain (VSQ) ($Z = -4.236$, $p = 0.00$), disorientation (SSQ subscale) ($Z = -3.613$, $p = 0.00$), and oculomotor symptoms (SSQ subscale) ($Z = -3.960$, $p = 0.00$) (see Fig. 1). A few subjects reported a definite increase in visual strain and/or sickness-related symptoms, 13.6% reported more than three new visual strain-related symptoms, and 9.9% of the participants felt sick after the movie (increase in SSQ total symptom severity score ≥ 29.92) (see Fig. 1).

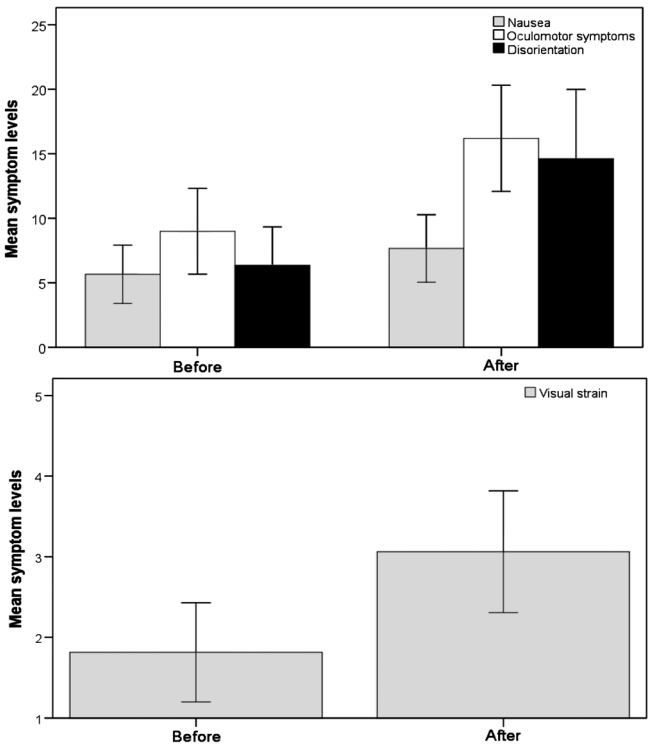

Fig. 1 Mean symptom levels (SSQ top and VSQ bottom) before and after the film. For visual strain (VSQ), an increase of 1 point means one new symptom or a mild increase in symptom severity. For SSQ nausea, the symptom weight was 9.54; for oculomotor symptoms, the weight was 7.58; and for disorientation, the weight was 13.92. Vertical lines represent standard errors.

4.2 *Viewing Experience, Image Quality and Ergonomics of the Stereo Glasses*

As Fig. 2 shows, the majority of the participants liked the film. Measurements for overall viewing experience, image naturalness and overall image quality approached the top of the scales. However, users' opinions about the physical ergonomics of the stereo glasses were clearly less positive (Fig. 2). More than 60% of the participants graded the fit (61.7%), weight (63%) and comfort (66.7%) of the glasses below the acceptance threshold level. As with head-mounted displays, it was difficult to use stereo glasses simultaneously with personal eye glasses, and the more time that elapsed, the more the glasses pressed the nose and/or other parts of the face.[39,40] Providing adjustments may improve the fit. However, because the use of stereo glasses is currently necessary at the cinemas where 3-D films are presented and the glasses must be long lasting and easy to use, adjustments are not necessarily the best solution. However, even small changes in the physical design of the glasses, such as offering glasses of different sizes or models that can be used concurrently with personal eyeglasses, would probably improve comfort and increase the overall viewing experience of 3-D movies.[40]

4.3 *Sense of Presence*

Data from 77 participants were analyzed. According to the data, viewing the film was an engaging experience (engagement, mean 4.97) for the majority of the participants (see Fig. 3). For example, the participants felt immersed and were absorbed in watching the film. The 3-D environment pleased them, and many of the participants lost track of time. The viewers did not think that the S3-D world was more real than the real world or that the world created by the 3-D effects was part of this world (see Fig. 3) (realness, mean 3.8). However, the film triggered some genuine emotions in viewers. Because film viewing is passive, the viewers did not think that they were sharing the space with the characters (co-presence, see Fig. 3) (mean 3.2).

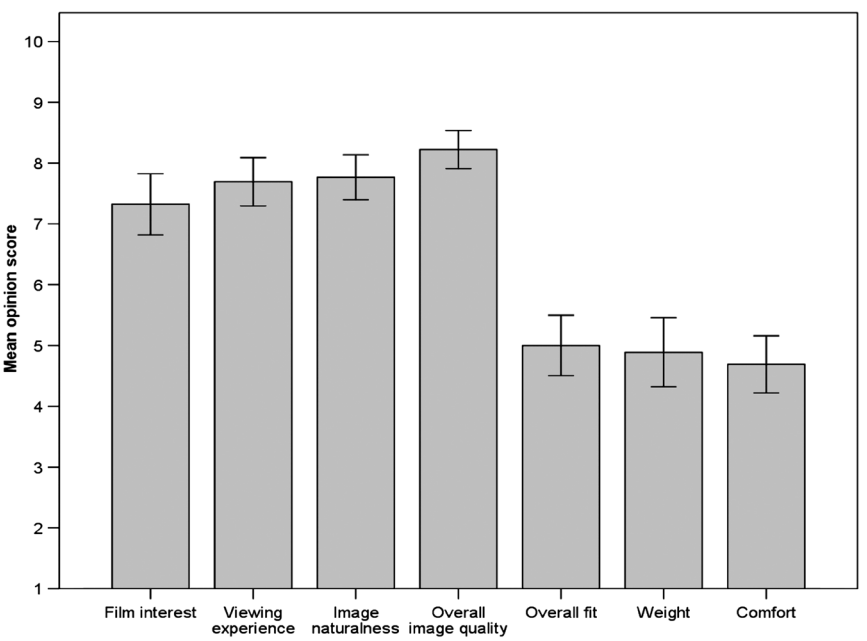

Fig. 2 Mean opinion scores for film interest, viewing experience, image naturalness, and visual quality and for glasses fit, weight and comfort. Scale is from 1 (poor) to 10 (excellent), where 6 is the acceptance threshold level. Vertical lines represent standard errors.

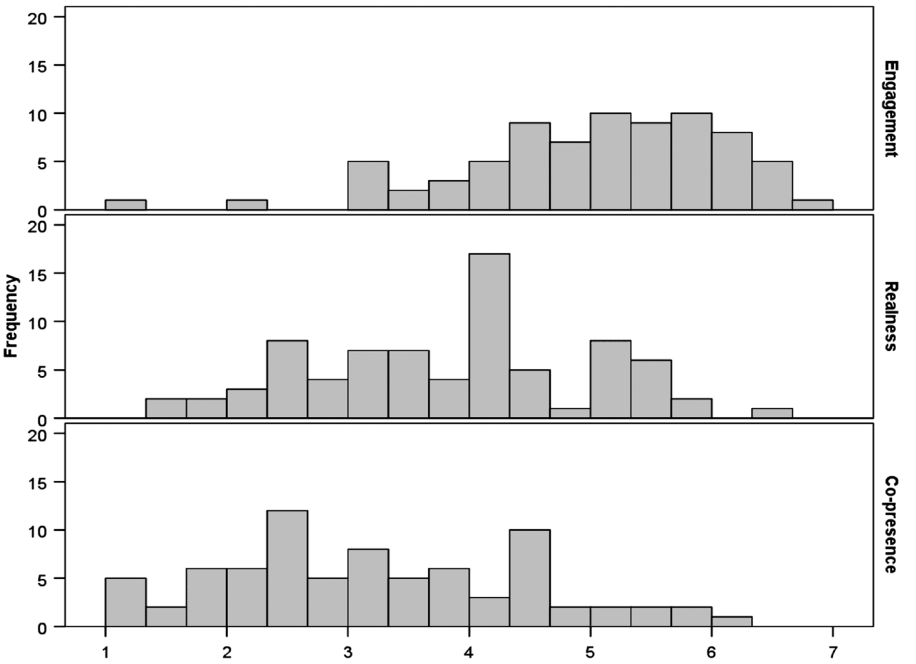

Fig. 3 Distributions of subjective opinions on engagement (focusing, loss of sense of time, enjoyment), realness (naturalness), and co-presence (sharing the space with the characters) (S3-D MovieQ). Scale is from 1 (strongly disagree) to 7 (strongly agree).

4.4 *Relationships between Measured Factors*

4.4.1 *Sense of presence*

Kendall's tau-*b* correlation procedure revealed several significant relationships between measured presence subscales and other parameters. The participants who had seen the film previously ranked it higher on all presence-related subscales (see Table 1). This result shows that previous S3-D experience does not necessarily diminish the effect of S3-D, even in the rare case where the film is the same. Positive opinion change in relation to S3-D movies, overall viewing experience, image naturalness, and overall image quality were scored higher by participants on presence-related subscales. In addition, there were positive correlations between presence subscales and individuals' immersive tendencies, including involvement (the tendency to become involved in activities) and focus (the tendency to maintain focus on current activities).[5]

Table 1 Significant correlations between presence subscales and other measured parameters ($n = 77$).

	Realness	Engagement	Co-presence
Has seen Avatar earlier	0.218[b]	0.206[b]	0.193[b]
Overall image quality	0.325[a]	0.322[a]	
Image naturalness	0.394[a]	0.297[a]	0.251[a]
Viewing experience (pleasantness)	0.356[a]	0.409[a]	0.244[a]
Opinion change	0.310[a]	0.297[a]	0.207[b]
Involvement	0.302[a]	0.270[a]	0.289[a]
Focus	0.224[a]	0.268[a]	0.257[a]

[a]Correlation is significant at the 0.01 level (2-tailed).
[b]Correlation is significant at the 0.05 level (2-tailed).

4.4.2 *Visual strain and sickness*

The participants ($n = 81$, Kendall's tau-*b* correlation test) who had previously seen an S3-D film reported fewer oculomotor symptoms ($r = -0.234$, $p < 0.05$), and their total symptom levels ($r = -0.225$, $p < 0.05$) were lower than those of participants with no previous S3-D film experience.[41] In addition, the participants with higher visual strain levels evaluated the overall image quality lower ($r = -0.195$, $p < 0.05$), and the viewing experience was reportedly less pleasant with an increase in oculomotor symptom levels (SSQ subscale) ($r = -0.207$, $p < 0.05$).[3–5]

4.4.3 *Movie interest, viewing experience and ergonomics of the glasses*

Participants who liked the movie were more satisfied with image quality and image naturalness and enjoyed the viewing experience more than participants who liked the film less (see Table 2). People who had previously seen S3-D films evaluated the weight of the glasses less negatively. Participants with personal glasses had some fitting problems.

4.4.4 *Other relationships*

The participants with higher motion sickness susceptibility scored higher on the tendency to become involved in activities ($r = 0.210$, $p < 0.05$) and the tendency to maintain focus on current activities ($r = 0.174$, $p < 0.05$). We registered the seat in which each participant was sitting, but the cinema was not full, so there were no viewers in the front or side seats. Because the participants were in the middle seats, no relationships between visual strain, sickness, rows and seats were found.

Table 2 Significant correlations between image quality, viewing experience, opinion change, and ergonomics ($n = 81$).

	How interesting the film was	Viewing experience pleasantness	Image naturalness	Overall image quality	Overall Fit	Weight	Wearing comfort
Previous S3-D cinema experience						0.195[a]	
Eye glasses					−0.205[a]		−0.243[a]
Opinion change	0.356[b]	0.246[b]	0.266[b]	0.227[a]			
Viewing experience	0.512[b]		0.485[b]	0.523[b]			
Image naturalness	0.554[b]			0.672[b]			
Overall image quality	0.507[b]						
Overall Fit						0.448[b]	0.727[b]
Weight							0.514[b]

[a]Correlation is significant at the 0.05 level (2-tailed).
[b]Correlation is significant at the 0.01 level (2-tailed).

4.5 *Comparison between* Avatar *and* U2 3D

It is logical that some film content may benefit more from the stereoscopic format. The *Avatar* cinema visit offered us a good opportunity to compare the effect of different film genres: the action, adventure and sci-fi film *Avatar* and the music documentary *U2 3D*. *Avatar*'s runtime (162 min) is almost twice as long as the runtime of *U2 3D* (85 min), allowing us to compare differences in viewing comfort and sickness.[42,43]

4.5.1 *Sense of presence*

The Mann—Whitney U test revealed several significant differences between film-related experiences, as detailed in Fig. 4 (c—f, k, l, o; for item details, see Appendix). For example, people were more focused (c; $z = -3.428$, $p < 0.001$) and absorbed (e; $z = -2.498$, $p < 0.05$) when watching *Avatar* than watching *U2 3D*. The *Avatar* environment pleased participants more (f; $z = -2.665$, $p < 0.01$) and triggered more emotions in viewers (l; $z = -2.516$, $p < 0.05$), and the viewers reported that they lost track of time more often (o; $z = -5.183$, $p < 0.001$). However, the differences between the films were small, and participants from both studies were immersed and focused on the films. Thus, the genre of the movie has some impact on the sense of presence, especially engagement, which refers to focusing, loss of sense of time and enjoyment. Co-presence and realness were evaluated similarly, although the *Avatar* scores were somewhat higher.

4.5.2 *Visual strain and sickness*

The Mann—Whitney U test revealed no significant differences between the symptom levels for *U2 3D* and *Avatar*.

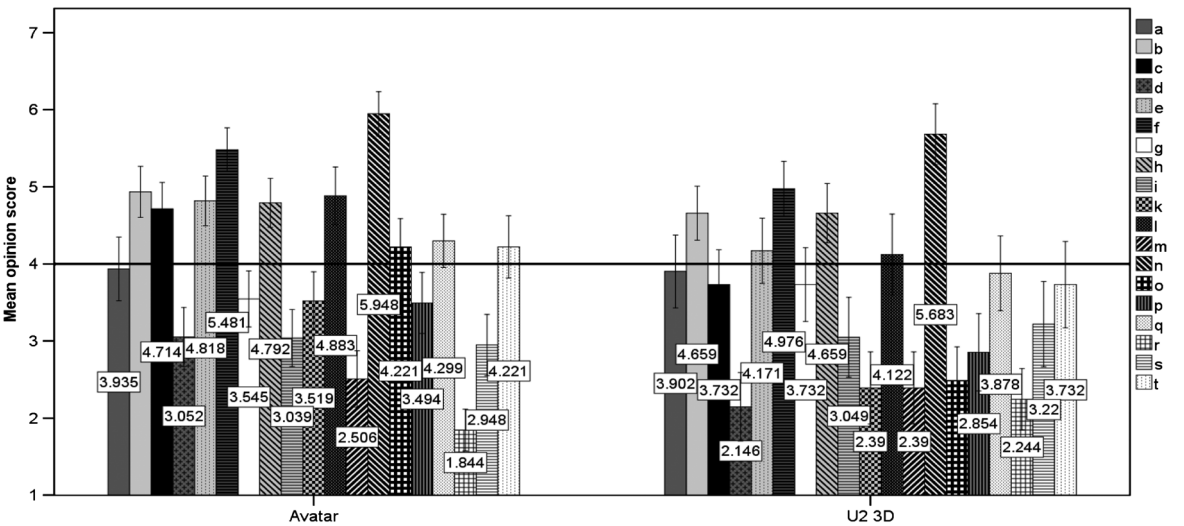

Fig. 4 Mean scores for evaluated presence experiences (*Avatar* $n = 77$, *U2 3D* $n = 41$). Scale is from 1 (strongly disagree) to 7 (strongly agree) with a reference line at 4 (neutral). Vertical lines represent standard errors. See Appendix for the questions corresponding to the letters in the figure.

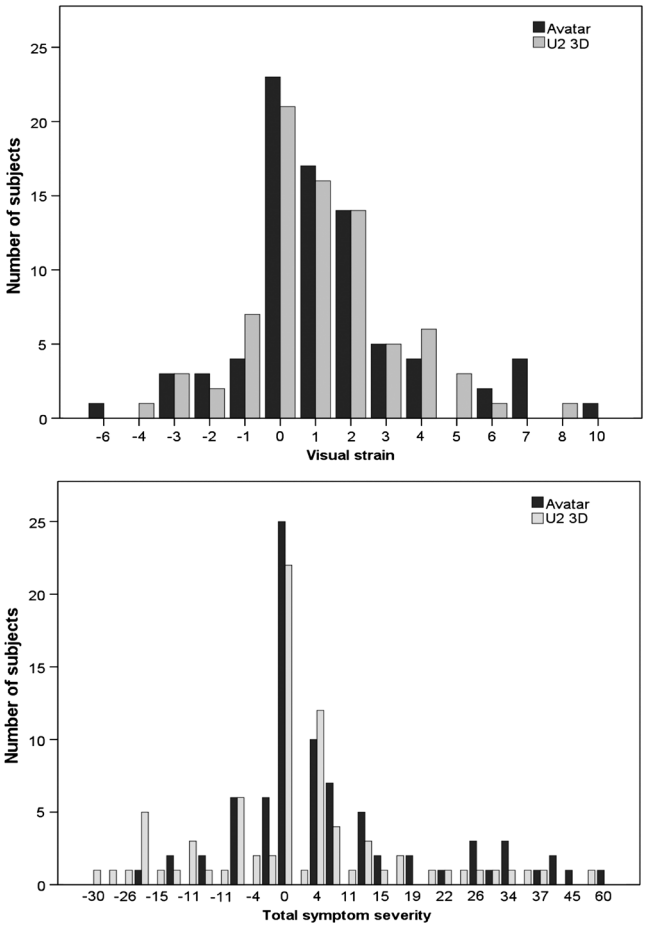

Fig. 5 Distributions of visual strain (top) and visually induced motion sickness symptoms (the sum of SSQ subscales, the symptom weight was 3.74) (bottom).

This result is interesting given the significant difference in the length of the films. As can be seen in Fig. 5, the symptom distributions were similar for both films: approximately half of the participants felt some eyestrain or an increase in visually induced motion sickness levels (the sum of SSQ subscales), whereas a few viewers reported a clear increase in symptom levels.

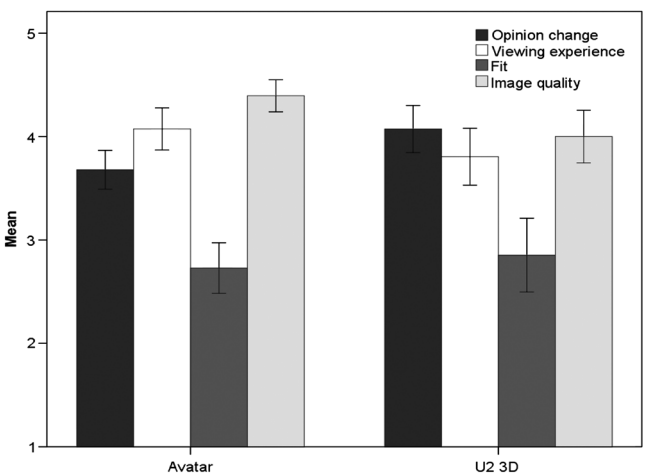

Fig. 6 Mean opinion scores for opinion change, pleasantness of viewing experience, fit of glasses, and image quality. Vertical lines represent standard errors.

4.5.3 *Opinion change, glasses fit and viewing experience*

Participants' opinions became more positive ($z = -4.036$, $p < 0.001$) following *U2 3D*. This result is logical because for the majority of the participants, *U2 3D* was their first experience with high-quality stereoscopic films; thus, the film had a major influence on participants' subjective opinions. Subsequent S3-D films will not necessarily change viewers' opinions as much as the first one if there are no distinctly different positive features. *Avatar*'s overall image quality ($z = -2.447$, $p < 0.05$) was rated higher than *U2 3D* (see Fig. 6). The difference in the pleasantness of the viewing experience ($z = -1.927$, $p = 0.054$) was close to significant, and the fit of the glasses was evaluated similarly in both studies.

5 Conclusions

The S3-D version of *Avatar* was viewed by 85 participants who recorded their experiences and opinions by responding to several questionnaires. According to the results, viewing an S3-D movie for 165 min causes some visual strain and sickness-related symptoms. However, the symptom levels were mild, on average, and were similar to the symptoms of viewing *U2 3D* for 85 min. Approximately 10% of viewers may feel sick after a relatively long S3-D presentation. Previous experience with S3-D films seems to increase viewing comfort and reduce symptoms. Thus, regardless of the film genre or viewing duration, people experience some visual strain and discomfort, but these factors have no particular influence on viewing discomfort.

In contrast to the experience of sickness, the movie's genre had some influence on participants' opinions of the sense of presence. *Avatar*, for example, triggered more emotions in viewers than *U2 3D* did. The participants were more focused and absorbed, and they lost track of time more often when viewing *Avatar*. Moreover, presence-related experiences affect how participants' opinions of S3-D movies change and how they evaluate the overall viewing experience, image naturalness, and overall image quality. Higher presence-related scores have a positive impact on viewing quality and subjective opinions. A comparison between *Avatar* and *U2 3D* supports this view: higher overall image quality and more positive opinions were associated with viewing *Avatar*, which was described as a more engaging and real experience.

Rows and seats may have some influence on viewing experience, but when people sit in the middle of the auditorium, the effect is slight. As in the *U2 3D* results, participants at the *Avatar* viewing had problems with the fit of the glasses, especially when wearing personal glasses in conjunction with stereo glasses.

In conclusion, the film genre has some influence on presence-related experiences, but it does not affect visual strain or viewing comfort. People will probably experience some visual strain with S3-D films, but symptom levels are low, on average, and are not necessarily dependent on the duration of the viewing session. Thus, viewing an S3-D film for 165 min may be an engaging and pleasant experience when viewers are interested in the type of film shown.

Appendix: Stereo 3-D movie Questionnaire (S3-DMovieQ)

a. While watching the 3-D movie, I was not aware of my "real" surroundings. *E*

b. I felt immersed by the 3-D movie. *E*

c. I was completely focused in the world created by the 3-D movie. *E*

d. The world created by the 3-D movie felt more real than the actual word. *R*

e. I was absorbed in watching the 3-D movie. *E*

f. The 3-D environment pleased me. *E*

g. I felt that I was part of the 3-D movie. *C*

h. My vision was completely focused on the 3-D movie. *E*

i. I think the world created by the 3-D effect is part of this world. *R*

j. The 3-D movie did not feel real. *R*

k. I felt that I was present in the world created by the 3-D movie. *C*

l. The 3-D movie triggered some real emotions in me. *R*

m. I felt that I was one of the characters in the 3-D movie. *C*

n. I recommend the 3-D movie experience to my friends. *E*

o. I lost track of time. *E*

p. In the 3-D world, I felt that I was interacting with people rather than with a machine. *C*

q. Everything looked real and vivid in the 3-D movie. *R*

r. I got the impression that the 3-D movie characters were aware of my presence. *C*

s. I had the feeling of sharing a common space with the characters in the 3-D movie. *C*

t. The characters in the 3-D movie felt real to me. *C*

u. I felt that the characters and/or objects could almost touch me. *C*

v. I enjoyed myself. *E*

E = engagement, *R* = realness, *C* = co-presence

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References

1. M. Lambooij, et al., "Visual discomfort and visual fatigue of stereoscopic displays: a review," *J. Imag. Sci. Technol.* **53**(3), 030201 (2009).
2. F. Kooi and A. Toet, "Visual comfort of binocular and 3D displays," *Displays* **25**(2–3), 99–108 (2004).
3. M. Pölönen, T. Järvenpää, and J. Häkkinen, "Comparison of near-to-eye displays: subjective experience and comfort," *J. Display Technol.* **6**(1), 27–35 (2010).
4. M. Pölönen and J. Häkkinen, "Near-to-eye display—an accessory for handheld multimedia devices: subjective studies," *J. Display Technol.* **5**(9), 358–367 (2009).
5. B. Witmer and M. Singer, "Measuring presence in virtual environment: a presence questionnaire," *Presence: Teleop. Virt. Environ.* **7**(3), 225–240 (1998).
6. P. Seuntiëns, I. Heynderickx, and W. IJsselsteijn, "Viewing experience and naturalness of 3D images," *Proc. SPIE* **6016**, 43–49 (2005).
7. P. Seuntiëns, Thesis: "Visual Experience of 3D TV" (Eindhoven University Press Facilities). http://alexandria.tue.nl/extra2/200610884.pdf (2006).
8. W. IJsselsteijn, H. de Ridder, and R. Hamberg, "Perceptual factors in stereoscopic displays: The effect of stereoscopic filming parameters on perceived quality and reported eye-strain," *Proc. SPIE* **3299**, 282–291 (1998).
9. P. Seuntiëns, I. Vogels, and A. van Keersop, "Visual experience of 3D-TV with pixelated ambilight," in *Proc. 10th Ann. Int. Workshop Presence*, pp. 339–344 (2007).
10. J. Häkkinen, et al., "Measuring stereoscopic image quality experience with interpretation based quality methodology," *Proc. SPIE IS&T Electron. Imag.* **6808**, 68081B (2008).
11. I. Heynderickx and R. Kaptein, "Perception of detail in 3D images," *Proc. SPIE* **7242**, 72420W (2009).
12. M. Lombard and T. Ditton, "At the heart of it all: The concept of presence," *J. Computer-Mediated Commun.* **3**(2), 20 (1997).
13. W. IJsselsteijn, et al., "Perceived depth and the feeling of presence in 3-D TV," *Displays* **18**(4), 207–214 (1998).
14. W. IJsselsteijn, H. de Ridder, and J. Vliegen, "Effects of stereoscopic presentation, image motion, and screen size on subjective and objective corroborative measures of presence," *Presence: Teleop. Virt. Environ.* **10**(3), 298–311 (2001).
15. K. Stanney, et al., "Usability engineering of virtual environments (VEs): identifying multiple criteria that drive effective VE system design," *Int. Hum. J. Comput. Stud.* **58**, 447–481 (2003).
16. S. Yoon, J. Laffey, and H. Oh, "Understanding usability and user experience of web-based 3D graphics Technol.," *Int. J. Hum.-Comput. Interact.* **24**(1), 288–306 (2008).
17. M. Pölönen, et al., "Subjective measures of presence and discomfort in viewers of color separation-based stereoscopic cinema," *J. SID* **17**(5), 459–466 (2009).
18. J. Freeman, et al., "Using behavioural realism to estimate presence: a study of the utility of postural responses to motion-stimuli," *Presence: Teleop. Virt. Environ.* **9**, 149–164 (2000).
19. J. Lessiter, et al., "A cross-media presence questionnaire: the ITC sense of presence inventory," *Presence: Teleop. Virt. Environ.* **10**(3), 282–297 (2001).
20. M. Lombard, et al., "Precence and television. The role of screen size," *Hum. Commun. Res.* **26**(1), 75–98 (2000).
21. P. Howarth, "The adverse health and safety effects of viewing visual images," *Displays* **29**(2), 45–46 (2008).
22. S. Yano, M. Emoto, and T. Mitsuhashi, "Two factors in visual fatigue caused by stereoscopic HDTV images," *Displays* **25**(4), 141–150 (2004).
23. S. Yano, et al., "A study of visual fatigue and visual comfort for 3D HDTV/HDTV images," *Displays* **23**(4), 191–201 (2002).
24. K. Ukai and P. Howarth, "Visual fatigue caused by viewing stereoscopic motion images: Background, theories, and observations," *Displays* **29**(2), 106–116 (2008).
25. M. Pölönen, M. Salmimaa, and J. Häkkinen," The effect of ambient illumination level on perceived autostereoscopic display quality and depth perception," *Displays* **32**(3), 135–141 (2011).
26. J. Häkkinen, et al., "Visual comfort with stereoscopic mobile gaming," *Proc. SPIE IS&T Electron. Imag.* **6055**, 60550A (2006).
27. J. Häkkinen, et al., "Simulator sickness in virtual display gaming: a comparison of stereoscopic and non-stereoscopic situations," *Proc. MobileHCI'06* **159**, 227–229 (2006).
28. R. Patterson and W. L. Martin, "Human stereopsis," *Hum. Factors* **34**(6), 669–692 (1992).
29. L. Hettinger, et al., "Visual display factors contributing to simulator sickness," *Proc. Hum. Factors Ergonomics Soc.* **31**(5), 497–501 (1987).
30. R. S. Kennedy, et al., "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *Intl. J. Aviation Psychol.* **3**(3), 203–220 (1993).
31. L. J. Hettinger, et al., "Vection and simulator sickness," *Mil. Psychol.* **2**(3), 171–181 (1990).
32. T. Stoffregen, et al., "Motion sickness and postural sway in console video games," *Hum. Factors* **50**(2), 322–331 (2008).
33. L. T. Hettinger and G. E. Ricco, "Visually induced motion sickness in virtual environment," *Presence: Teleop. Virt. Environ.* **1**(3), 306–310 (1992).
34. M. E. McCauley and T. J. Sharkey, "Cybersickness: perception of motion in virtual environments," *Presence: Teleop. Virt. Environ.* **1**(3), 311–318 (1992).
35. Avatar: http://www.avatarmovie.com/index.html; http://www.imdb.com/title/tt0499549/.
36. U2 3D: http://www.u23dmovie.com/; http://www.imdb.com/title/tt0892375/.
37. P. A. Howarth and H. O. Istance, "The association between visual discomfort and the use of visual display units," *Behaviour Inform. Technol.* **4**(2), 135–149 (1985).
38. J. Takatalo, et al., "Involvement and presence in digital gaming," *Proc. Fourth Nordic Conf. Hum.-Comput. Interact.* **189**, 393–396, ACM Press, New York, NY (2006).

39. S. Nichols, "Physical ergonomics of virtual environment use," *Appl. Ergonomics* **30**(1), 79–90 (1999).
40. M. Pölönen, "A head-mounted display as a personal viewing device: dimensions of subjective experiences," Thesis (Helsinki Univerity, 2010), ISBN 978-952-10-6386-2.
41. P. Howarth and S. Hodder, "Characteristics of habituation to motion in a virtual environment," *Displays* **29**(2), 117–123 (2008).
42. W. IJsselsteijn, Ridder De HH., and J. Vliegen, "Effects of stereoscopic filming parameters and display duration on the subjective assessment of eye strain," *Proc. SPIE* **3957**, 12–22 (2000).
43. V. Aaltonen and M. Pölönen, "The effect of viewing duration on visual comfort with near-to-eye displays," *SID Digest of Tech. Papers* **40** 812–814 (2009).

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