Regular Papers

Evaluation of Visual Fatigue in Viewing a Depth-fused 3-D Display in Comparison with a 2-D Display

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Abstract

The depth-fused 3-D (DFD) display developed in NTT has been found to have the same level of visual fatigue as a conventional 2-D display. The DFD display presents depth information using a stack of two LCDs. We subjectively and objectively examined the visual fatigue it induces compared with 2-D displays. We found that (1) there were no statistically significant differences between 2-D images and DFD images in terms of impairments of visual functions and that (2) subjects responded more quickly when viewing DFD images than viewing 2-D images.

1. Introduction

Developing a three-dimensional (3-D) imaging method for a simple and practical 3-D display is important for producing a realistic virtual world. Many display methods including integral photographic, holographic, volumetric, and stereoscopic methods have been investigated, but the first three are not yet practical because they need a lot of complicated image data. Only the stereoscopic display using two stereoscopic images has reached a practical stage. However, it is well known that stereoscopic 3-D displays based on binocular disparity*1 lead to visual fatigue [1]-[4] as compared with conventional 2-D displays or the real 3-D world. This is because the lens accommodation*2 does not match the vergence*3 point, which moves freely in 3-D space, as shown in **Fig. 1** [1], [3].

We have developed a new 3-D display using the depth-fused 3-D (DFD) visual illusion in which two overlapped images with many edges displayed at different depths can be perceived as a continuous 3-D image [5]-[9]. A compact DFD display, which simply consists of stacked LCD displays, can be developed by using the summation of polarization changes in two LCDs [10]-[12].

With respect to visual fatigue, we can assume that the DFD display may have an advantage because we arrange it to have multiple images with comparatively narrow gaps (for example, 3 min. of arc) in the depth direction. In this study, we tested this assumption by evaluating visual fatigue in terms of subjective and objective effects on visual functions when

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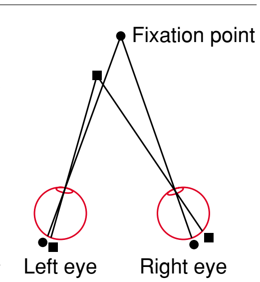
*1 Binocular disparity: The positional difference between the two retinal projections of a given point in space. This positional difference results from the fact that the two eyes are laterally separated and therefore see the world from two slightly different vantage points.



*2 Accommodation: The ability of the eye to adjust its focal length by changing the shape of the lens.

*3 Vergence: Vergence eye movements cause the foveae of both eyes to point at a near object. (The fovea is the center part of the retina. This tiny area is responsible for our central, sharpest vision.) This means that each eye rotates in the opposite direction (i.e., the right eye to the left and the left eye to the right) when converging on a near object.

DFD images and 2-D images were observed.

2. Concept of DFD display

The fundamental perceptual phenomenon involved in the DFD display [5] is reviewed in **Fig. 2**. It is composed of two processes: (i) depth-fusing to an apparent image with one depth by overlapping front and rear images from the midpoint of the observer's eyes and (ii) continuous-depth perception by changing the luminance ratio between front and rear images.

The concept of the DFD display [6] is reviewed in **Fig. 3**. When the luminance ratio between front and rear images is changed at each pixel according to the depth (b) and the front and rear images are overlapped (a), an apparent image with continuous depth can be observed (c). This was described in detail in our previous report in NTT Technical Review [11].

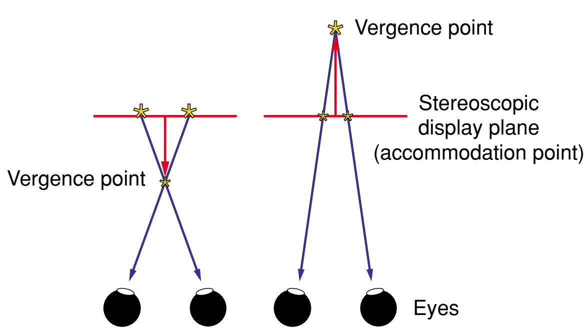


Fig. 1. Vergence point and lens accommodation with stereoscopic 3-D display.

3. Experimental method

3.1 Experimental apparatus and task

The DFD display system that we used for evaluating visual fatigue is shown in **Fig. 4**. It consists of a DFD display, an ordinary PC with a video card that outputs two signals for the two planes of the DFD display, a 2-D display for operation, and a speaker to audibly indicate correct or incorrect answers. The DFD display has two LCDs as two planes with a gap of 5 mm. When we tested the visual fatigue before and after viewing the 2-D display, only the front LCD was activated in the DFD display. The distance between the subject and the display was 40 mm.

The experimental task is illustrated in **Fig. 5**. The subjects were ten healthy people, none of whom had any eye problems other than ametropia*4, 24–48 years old (average: 29.4). Front, middle, and rear stimuli consisting of three white squares were presented at random depth positions on a DFD display with a 4-inch diagonal. As the cue to judge which

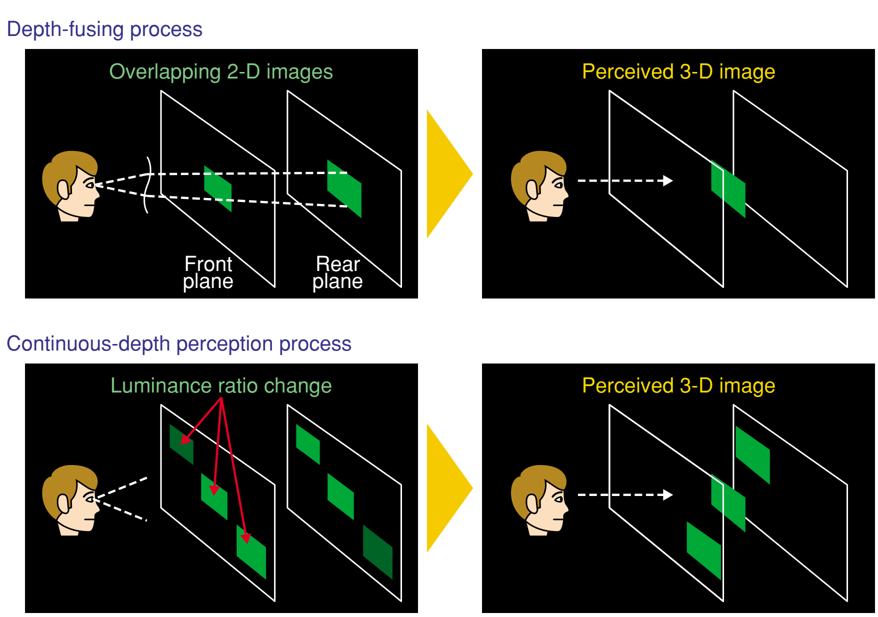


Fig. 2. Fundamental perceptual phenomenon in DFD.

*4 Ametropia: An eye abnormality, such as nearsightedness, farsightedness, or astigmatism, resulting from faulty refractive ability of the eye.

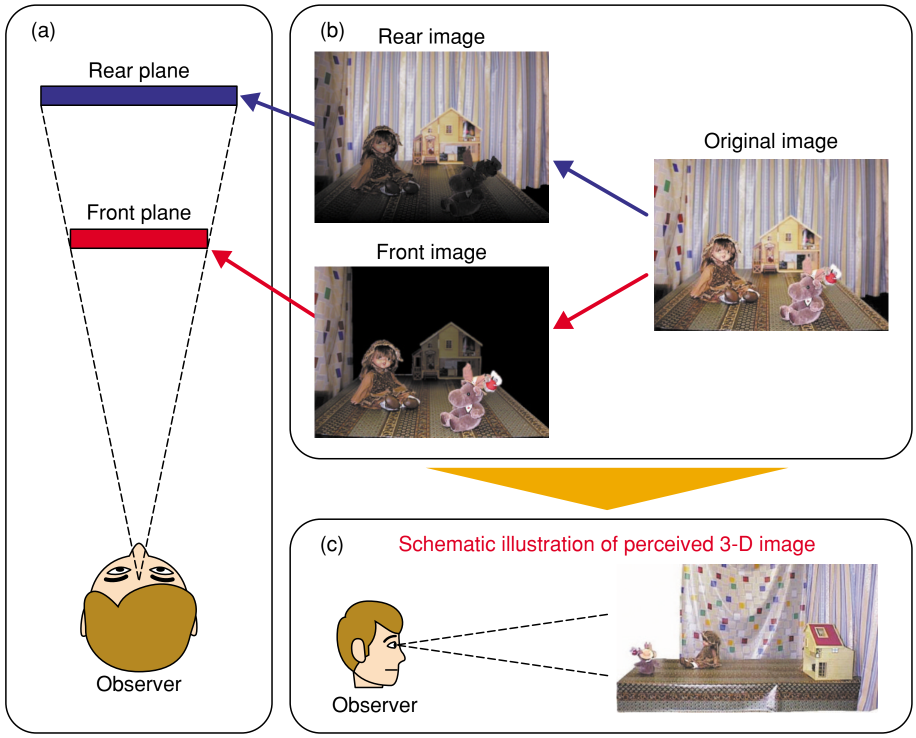


Fig. 3. Concept of DFD display.

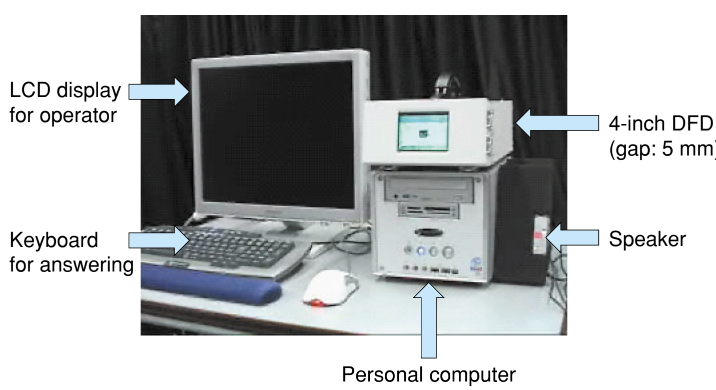


Fig. 4. DFD evaluation system.

stimulus was front, middle, or rear in testing the 2-D display, the sizes of stimuli were changed in three levels. When the DFD display was tested, the judgment cues were the size and perceived depth in three ranks. In the task, subjects had to indicate the position of the middle stimulus by pushing one of three keys on the keyboard. After the key was pressed, another set of stimuli was immediately presented. Subjects were instructed to do as many sets as possible in a given time. As we wanted to evaluate the visual fatigue for a comparatively long time, the experiment time was set to 20 minutes. To keep subject motivation high during testing and to minimize the resting time, we told the subjects that they would be ranked by the total number of answers and the correct answer ratio. These instructions to subjects were also useful for evaluating how quickly a subject could do the task in viewing a 2-D and DFD display.

3.2 Subjective tests

Subjective tests based on a questionnaire (10 items) provided various indices of visual fatigue after the above task. Each question had five ranks, for example, from feeling no fatigue "1" to feeling very strong

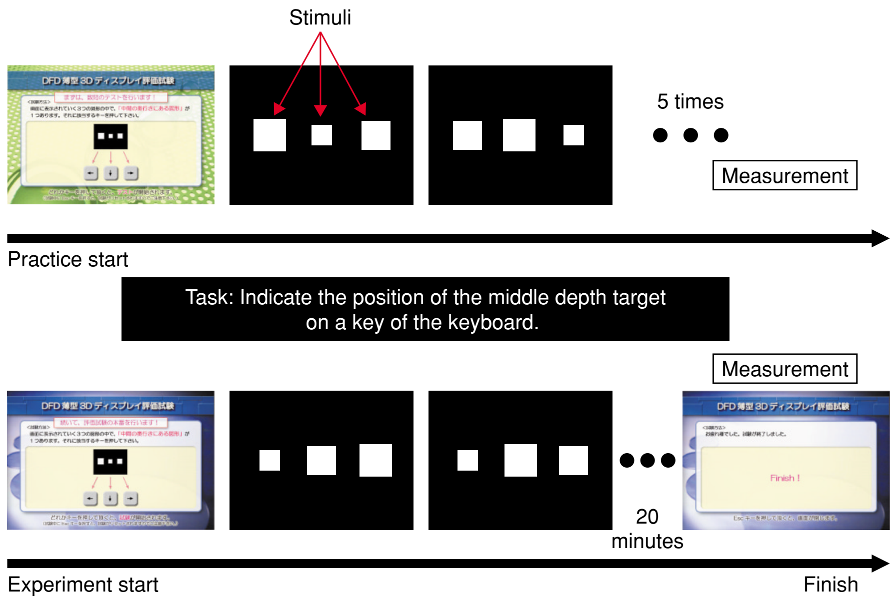


Fig. 5. Experimental task (DFD or 2D).

fatigue "5" when fatigue was asked about. The conventional indices of visual fatigue were selected as fatigued, bleary, hazy, painful, dull, heavy, vomitous, nauseated, dizzy, and sleepy, which have conventionally been used for subjective tests of visual fatigue after viewing a 2-D visual display terminal (VDT) or stereoscopic 3-D display.

3.3 Objective tests

The visual fatigue after viewing a 2-D VDT (such as a cathode ray tube or projection display) or stereoscopic 3-D display (such as parallax barrier, lenticular lens, polarization glass, or liquid crystal shutter type) has been reported to affect visual functions, producing for example a decrease in visual acuity, myopia of the refractive state, decrease in the amount of accommodative response, decrease in pupil diameter, decrease in pupil-constriction ratio, decrease in flicker-free frequency, increase in accommodative deviation, increase in high-frequency component of accommodation fluctuation, and increase in delay time of accommodation change [1]-[4], [13]-[20]. As indices of our objective tests for visual fatigue in 2-D and DFD displays, we selected low-contrast acuity, refractive state, accommodative response, pupil-constriction ratio, and lens accommodation fluctuation. The low-contrast acuity was visual acuity in viewing a low-contrast "Landolt C"*5 using a 10% ETDRS (early treatment of diabetic retinopathy study) chart. The refractive state means how far a subject's eye focused on when the stimulus was set to infinity, evaluated by ARK-730A (NIDEK). The accommodative response was the maximum change in lens accommodation, evaluated by ARK-730A (NIDEK). The pupil-constriction ratio indicated how much the pupil constricted due to a change in accommodation to the near stimulus, evaluated by TriIRIS (Hamamatsu Photonics). The lens accommodation fluctuation was the amount of high-frequency component of accommodation fluctuation when the accommodation was set to a low diopter*6 value (= 1/m), for example, 0 to 0.75 diopters, which was evaluated by AA-1 (NIDEK).

Objective tests were measured before and after the task. To judge whether the results before and after the task were different, we statistically calculated the paired t-test*7.

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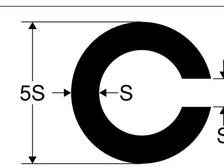
*5 Landolt C: A broken circle used as the test object in distinguishing visual acuity. The width of the gap in the circle is equal to the breadth of the black line and one-fifth the circle diameter.



*6 Diopter: A unit of measurement of the refractive power of lenses equal to the reciprocal of the focal length measured in meters.

*7 Paired t-test: The two-sample t-test is used to determine whether two population means are equal. For a paired t-test, the data is dependent, i.e., there is a one-to-one correspondence between the values in the two samples, such as the same subject measured before and after a process change or the same subject measured at different times.

4. Results

The results of subjective testing are shown in **Fig. 6**. The horizontal axis indicates evaluation items and the vertical axis indicates the scores, each of which is an average calculated from the answers of all subjects because all subjects had the same tendency for each evaluation item. The item "fatigued" had the highest score (2-D: 3.4, DFD: 3.3), and the high-scoring items were "sleepy" (2-D: 2.9, DFD: 3.0), "bleary" (2-D: 2.6, DFD: 2.6), "dull" (2-D: 2.4, DFD: 2.1), and "hazy" (2-D: 2.3, DFD: 2.2). The results indicate that viewing was fatiguing, but the results for both 2-D and DFD displays were much the same; that is, there were no significant differences between 2-D and DFD displays.

Figure 7 shows an example of the objective test results before and after trials with either the 2-D display or DFD display. The horizontal axis indicates the subjects by their initials and the vertical axis shows that subject's refractive state. These results also demonstrate that the 2-D and DFD displays both produced the same objective levels of fatigue under the experimental conditions we were using.

Table 1 show the results of all objective tests before and after trials with 2-D and 3-D displays. "P" is the statistical result of a paired t-test, which means the error probability if two results before and after the task are judged to be different. That is, when "P" is sufficiently small, two results before and after the task are different.

We found no significant differences between the objective-test results before and after the 2-D task, except for the accommodative response result

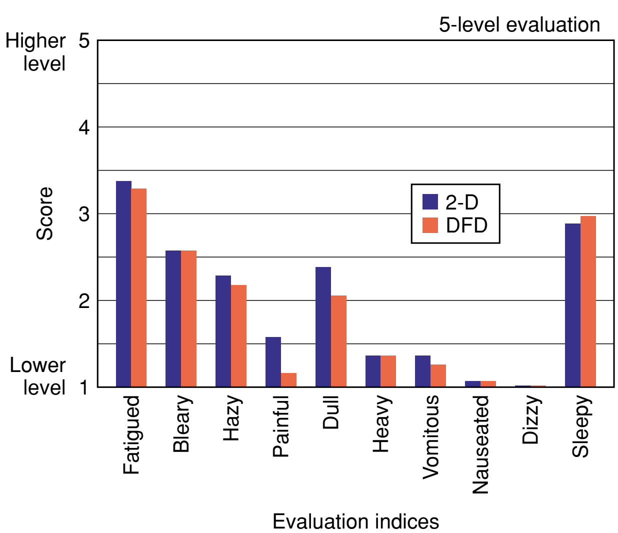


Fig. 6. Results of subjective testing.

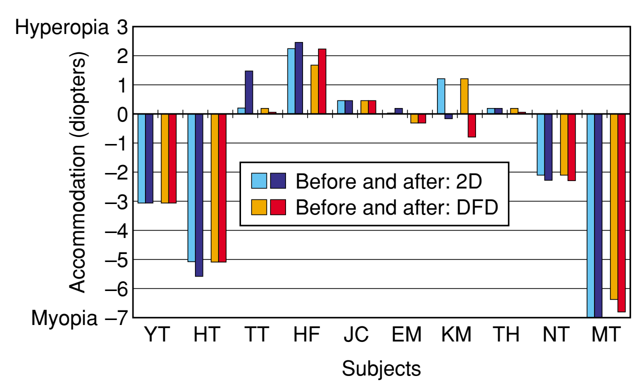


Fig. 7. Results for refractive state.

Table 1. Results of objective tests before and after 2-D and DFD trials.

	2-D trial			DFD trial		
	Before	After	Error probability (P)	Before	After	Error probability (P)
Low-contrast acuity (10%ETDRS chart) (Log MAR unit)	0.01 ± 0.11	0.02 ± 0.08	0.460	0.01 ± 0.08	0.03 ± 0.10	0.182
Refractive state (diopters)	–1.50 ± 2.82	–1.30 ± 3.08	0.269	–1.50 ± 2.57	–1.53 ± 2.73	0.811
Lens accommodation (high-frequency component)	47.29 ± 6.12	47.28 ± 5.86	0.989	47.32 ± 7.80	44.85 ± 6.06	0.153
Accommodative response (diopters)	2.12 ± 0.55	1.74 ± 0.67	0.021	2.05 ± 0.78	1.81 ± 0.65	0.181
Pupil-constriction ratio (%)	55.90 ± 10.36	56.16 ± 14.48	0.923	52.48 ± 10.10	53.67 ± 12.17	0.495

("P" is the statistical result of a paired t-test, which means the error probability if two results before and after the objective tests are judged to be different.)

(P<0.05 is sufficiently small), which means that a decrease in accommodation response occurred in the 2-D task. Results for the DFD task were the same as those for the 2-D task, except for the accommodative response result (P>>0.05), which indicates that a decrease in accommodative response did not occur in the DFD task.

As shown in **Table 2**, there were no significant differences between the results of changes before and after the 2-D and DFD trials (P>>0.05). Thus, subjects were affected to the same degree by 2-D and DFD images both subjectively and objectively.

In addition to subjective and objective evaluation, we examined the total number of answers and the correct answer ratio for 2-D and DFD displays in our experiments (**Table 3**). The total number of answers indicates how quickly a subject could respond. There were no significant differences between 2-D and DFD displays in terms of correct answer ratio. Nevertheless, the total number of answers obtained with the DFD display was considerably more (1.23 times) than with the 2-D one. This is because the depth judgment cues were both stimulus size and apparent depth in the DFD display in contrast to the single cue of stimulus size in the 2-D display.

The results demonstrate that the DFD is no more fatiguing than a comparable 2-D display. Furthermore, while it is no less fatiguing, it does enable subjects to judge depth information more quickly using the DFD display.

5. Conclusion

We evaluated visual fatigue in subjects using 2-D and DFD displays. The results show that: (1) visual fatigue from DFD display is at the same level as that from a 2-D display and (2) subjects responded more quickly when viewing DFD images than when viewing 2-D images.

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Table 2. Changes before and after 2-D and DFD trials.

	Average change before and after 2-D trial	Average change before and after DFD trial	Error probability (P)
Low-contrast acuity (10%ETDRS chart) (Log MAR unit)	–0.01 ± 0.06	–0.02 ± 0.04	0.856
Refractive state (diopters)	–0.20 ± 0.54	0.025 ± 0.32	0.225
Lens accommodation (high-frequency component)	0.02 ± 3.34	2.43 ± 4.98	0.103
Accommodative response (diopters)	0.38 ± 0.43	0.24 ± 0.53	0.361
Pupil-constriction ratio (%)	–0.26 ± 8.29	–1.19 ± 5.29	0.779

Table 3. Total number of answers and correct answer ratio for 2-D and DFD.

	2-D total number	DFD total number	2-D correct ratio (%)	DFD correct ratio (%)
MK	1553	1633	99.42	99.76
TO	1250	1643	99.28	97.57
TH	1098	1169	99.09	99.91
TM	1293	1659	97.68	95.12
ME	1278	2027	96.87	94.23
FH	1205	1497	96.35	98.06
HT	1375	1611	96.00	96.59
TY	1633	2099	95.53	96.38
TT	1632	1754	94.12	98.52
Average	1368.5	1676.9	97.15	97.35
Standard deviation	194.1	274.9	1.86	1.95

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