CLINICAL INVESTIGATIONS

Use of Dynamic and Colored Stereogram to Measure Stereopsis in Strabismic Patients

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Abstract: The effectiveness of movement or color has not been well studied in assessing stereopsis in patients with strabismus. We developed a new stereotest equipped with both a monochromatic dynamic random dot stereogram (DRDS) and a static-colored stereogram (SCS) and examined the stereopsis of patients with strabismus. Three-dimensional (3D) images were displayed on a liquid crystal display equipped with a parallax barrier system, allowing 3D images to be seen independently by each eye without glasses. A DRDS with maximum disparity of 3200 seconds of arc was displayed having front-rear movement. An SCS displaying cartoon characters with disparities of 400 seconds of arc was also tested and compared with the Titmus stereotest. A total of 52 strabismic patients were tested. The DRDS showed a significantly higher (P = 0.02) detection rate of stereopsis (39/52, 75%) as compared with the Titmus fly test (28/52, 54%). The SCS did not show any difference in the stereopsis detection rate (24/521, 46%) when compared with the Titmus animal test (20/52, 38%). Thus, the DRDS was useful in detecting stereopsis in patients without stereopsis on the conventional Titmus fly test, while the SCS did not show any difference when compared with the Titmus animal test. The DRDS may examine a different aspect of stereopsis from the static stereopsis measured by the Titmus stereotest or SCS. **Jpn J Ophthalmol 1998;42:101–107** © 1998 Japanese Ophthalmological Society

Key Words: Color, dynamic random dot stereogram, stereopsis, stereotest binocular separation, strabismus, three-dimensional.

Introduction

Three-dimensional (3D) motion pictures, including movies and videos for entertainment and education, are becoming ever more prevalent. Some patients with strabismus, who are judged to have no stereopsis by conventional stereotests, can enjoy 3D movies.[1,2] The 3D software usually uses large disparities, with movement and color, while conventional stereotests such as the Titmus stereotest or Lang stereotest examine principally static stereopsis with relatively small disparities using monochromatic patterns. In this study, we developed a new stereotest equipped with both a monochromatic dynamic random dot stereogram (DRDS) and a static-colored stereogram (SCS) with large disparities and studied the effectiveness of movement or color for evaluating stereopsis in patients with strabismus.

Materials and Methods

The research followed the tenets of the Declaration of Helsinki, and informed consent was obtained from all adult subjects and parents of participating children after the nature and possible consequences of the study were explained.

Test Equipment

Three-dimensional images were displayed on a 10-inch liquid crystal display equipped with an image splitter system (3D LCD image splitter display, Sanyo, Osaka)[3] allowing 3D images to be seen with-

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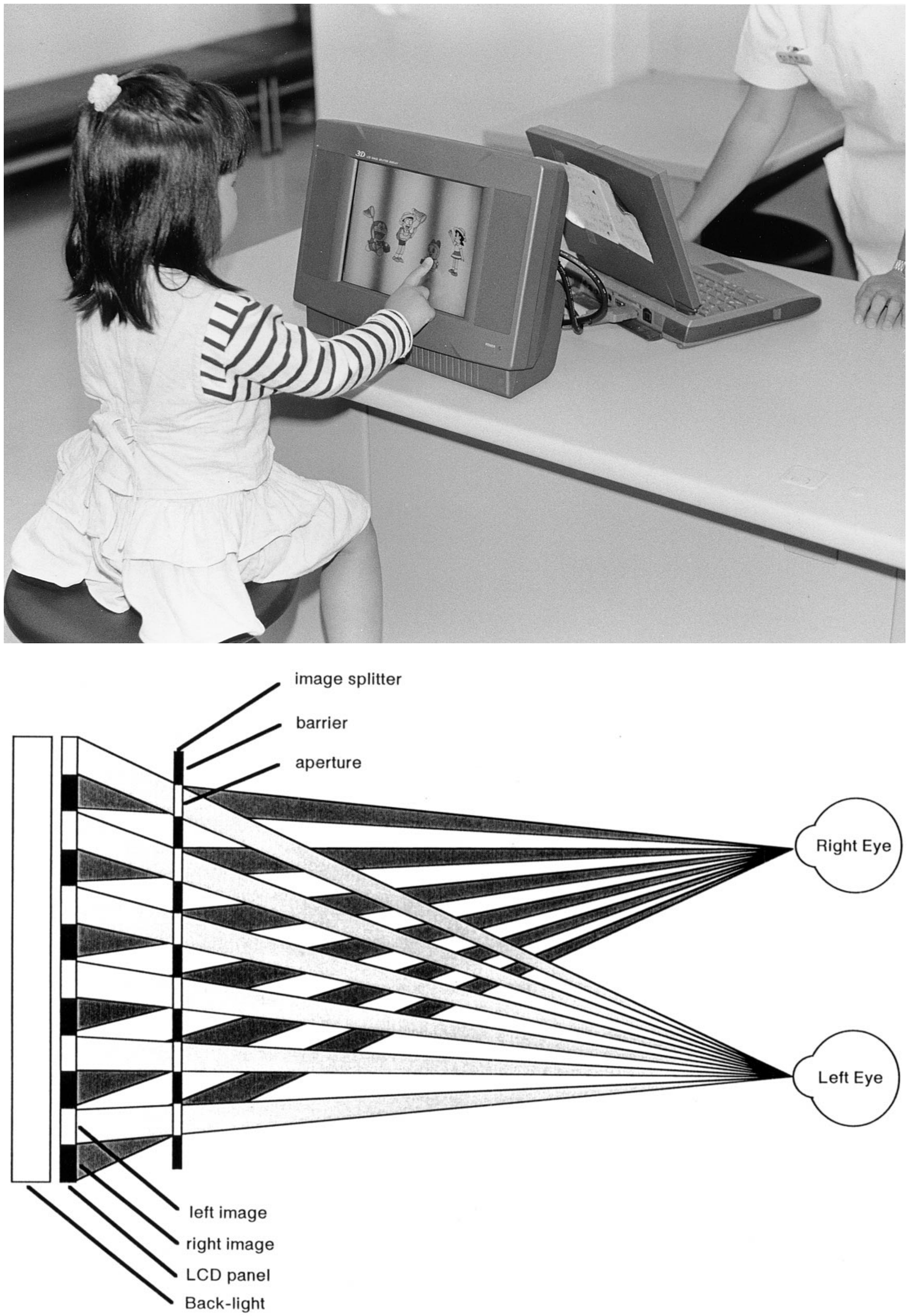

Figure 1. Images were displayed on a liquid crystal display connected to a laptop computer and seen stereoscopically without glasses (top). The principle of the image splitter system for binocular separation (bottom) is similar to the lenticular lens system used in the Lang stereotest, but images are much clearer.

out glasses (Figure 1) with a background luminance of 100 cd/m^2 and a resolution of 640 × 480 pixels. A laptop personal computer was connected to the display and software of stereograms was installed (MV100, NIDEK, Gamagohri).

Subjects viewed the screen from 50 cm. To confirm a patient's correct head position, each eye was tested independently with a check mark for the corresponding eye. When the head position was optimal, binocular separation was obtained perfectly, and cross-talk was not observed at all.

We tested both horizontal and front-rear movements of targets with the DRDS. For horizontal movement, a square with a side of 2.1° showing crossed disparity of 1200 seconds was displayed, moving to and fro at a temporal frequency of 1 Hz. For front-rear movements, a square and a circle with radius or sides of 2.1° were moved either synchronously or in counterphase at a temporal frequency of 0.5 Hz. Disparity of the circle and square changed from crossed 3200 seconds to 0 seconds (Figure 2). In both horizontal and front-rear paradigms, background disparity was set to zero.

Before testing, patterns featuring square and circle were displayed in front of patients. Patients were instructed to point to the location of the specified pattern (square or circle) that was moving. For horizontal movement, either pointing to the moving pattern (square) or confirmation of the eye movement following the target constituted the passing criteria. For front-rear movement, identifying the place of either one of the patterns (circle or square) served as the passing criterion. Patients were instructed not to move their head to prevent the use of motion parallax as a monocular cue. If a patient demonstrated stereopsis on any of the three DRDS tests, he or she was considered to have passed the DRDS.

An SCS of cartoon characters with a disparity of 400 seconds, comparable to that of the Titmus animal tests, was also displayed. One of four characters was given crossed disparity. Patients were instructed to point out the character that was in front of the others. Patients correctly identifying the displaced image in more than three out of four trials (>75%) were considered to have passed the SCS.

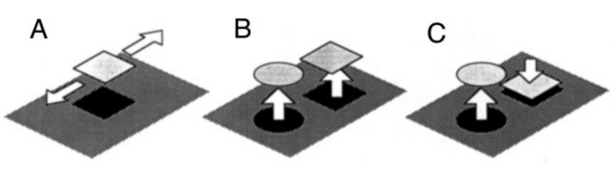

Figure 2. The dynamic random dot stereogram has three modes. Horizontal movement (**A**), front-rear synchronous movement (**B**), and front-rear counterphase movement (**C**) were displayed.

Normal Subjects

A total of 15 subjects with normal corrected vision and stereopsis, confirmed by Titmus stereo testing (40 seconds), were examined both with DRDS and with SCS testing. Ages ranged from 4 to 40 years (mean 22.0 ± 10.3 years).

Patients and Methods

A total of 52 consecutive patients with strabismus who visited Osaka University Hospital between January and June of 1995 and who could cooperate with the Titmus testing were examined.

Nineteen patients had esotropia (including six cases with associated hypertropia), one had intermittent esotropia, six had esophoria, 10 had constant exotropia (including three cases with associated hypertropia), and 16 had intermittent exotropia. Patients ranged in age from 4 to 35 years (mean 9.3 ± 5.9 years). Average angle of horizontal strabismus was 19.4 ± 12.3 prism diopters (Δ) by alternate prism cover test at 30 cm. Visual acuity of the patients was 20/20 or better in both eyes of all but four patients, and no eye had an acuity worse than 20/60.

Stereopsis was evaluated by the DRDS (n = 52) and SCS (n = 52) as well as the Titmus stereotest (n = 52) and the Lang stereotest (n = 39). In the case of DRDS, 39 patients were examined with both horizontal and front-rear mode, and 13 patients were examined with front-rear mode only. During performance of the Lang stereotests, if a patient was able to identify the target of maximum disparity (1200 inches), he or she was considered to have stereopsis.

Statistical Analysis

The McNemar test with the Yates correction was used for the paired evaluation of the results of DRDS and SCS testing. The unpaired two-tailed *t*-test was used to assess any effects of age on the results. The χ^2 test was used to evaluate the difference of achievement in DRDS testing among different groups of strabismus patients. A P value of 0.05 or less was considered significant.

Results

Normal Subjects

All 15 subjects passed three different modes of DRDS (horizontal, front-rear synchronous, front-rear counterphase) and SCS testing.

Jpn J Ophthalmol
Vol 42: 101–107, 1998

DRDS Compared With Titmus Fly Testing

On Titmus fly testing, 28 patients demonstrated stereopsis—fly(+) group—and 24 patients failed to do so—fly(−) group. In the fly(+) group, 25 patients (89.3%) passed and 3 patients (10.7%) failed DRDS testing. In the fly(−) group, 14 patients (58.3%) passed and 10 patients (41.7%) failed DRDS testing (Table 1). The detection rate of stereopsis was significantly higher with the DRDS compared with the Titmus fly test ($P = 0.015$). Among fly(−) patients, the age of patients with stereopsis by DRDS (8.7 ± 2.8 years) was not different from those without stereopsis by DRDS (7.4 ± 2.7 years).

DRDS Compared With Lang Testing

On Lang testing, 16 patients demonstrated stereopsis—Lang(+) group—and 23 failed to do so—Lang(−) group. In the Lang(+) group, all 16 patients (100%) passed DRDS testing. In the Lang(−) group, 13 patients (56.5%) passed and 10 patients (43.5%) failed DRDS testing (Table 2). The detection rate of stereopsis was significantly higher with the DRDS than with Lang testing ($P = 0.001$). Among Lang(−) patients, the age of patients with stereopsis by DRDS (9.1 ± 2.3 years) was not different from those without stereopsis by DRDS (8.3 ± 2.8 years).

SCS Compared With Titmus Animal Testing

On Titmus animal testing, 20 patients demonstrated stereopsis—animal(+) group—and 32 patients did not—animal(−) group. In the animal(+) group, 16 patients (80%) passed and four patients (20%) failed SCS testing. In the animal(−) group, eight patients (25%) passed and 24 patients (75%) failed SCS testing (Table 3). The detection rate of stereopsis was not different between the SCS and the Titmus animal test.

The Effect of Movement Pattern on DRDS Test Results

Thirty-nine patients were tested with both horizontal and front-rear movement with the DRDS. In horizontal mode, 16 patients passed—horizontal(+) group—and 23 failed—horizontal(−) group. In the horizontal(+) group, 14 patients (87.5%) passed and two patients (12.5%) failed front-rear mode. In the horizontal(−) group, 10 patients (43.5%) passed and 13 patients (56.5%) failed front-rear mode (Table 4). The detection rate of stereopsis was significantly higher on front-rear DRDS testing compared with that using the horizontal mode ($P = 0.042$). Comparing the two different types of front-rear testing, 22 patients (56.4%) passed in the synchronous mode and 19 patients (48.7%) passed in the counterphase mode, which was not significantly different.

Table 1. Results of Titmus Fly and Dynamic Random Dot Stereogram (DRDS)

	DRDS(+)	DRDS(−)	Total
Fly(+)	25	3	28
Fly(−)	14	10	24
Total	39	13	52

Table 2. Results of Lang and Dynamic Random Dot Stereogram (DRDS)

	DRDS(+)	DRDS(−)	Total
Lang(+)	16	0	16
Lang(−)	13	10	23
Total	29	10	39

Table 3. Results of Titmus Animal and Static-Colored Stereogram (SCS)

	SCS(+)	SCS(−)	Total
Animal(+)	16	4	20
Animal(−)	8	24	32
Total	24	28	52

The Outcome of DRDS Testing Based on Type of Deviation

Thirty-two patients who failed Titmus animal testing were evaluated based on the type of deviation. Nineteen patients had esotropia (including intermittent esotropia) and 13 patients had exotropia (including intermittent exotropia). In the group with esotropia, 14 patients (73.9%) passed and 5 patients (26.3%) failed DRDS testing. In the group with exotropia, five patients (38.5%) passed and eight patients (61.5%) failed DRDS testing (Table 5). The success rate of DRDS testing was significantly higher in the group with esotropia ($P = 0.046$).

Discussion

Three-dimensional motion pictures are useful for amusement, and they are ideal for instructional materials for students of all ages and in any area of study, including surgery and 3D reconstructions of radiological images. Such images create a 3D ap-

Table 4. Results of Horizontal and Front-Rear Movement in Dynamic Random Dot Stereogram

	Front-Rear(+)	Front-Rear(−)	Total
Horizontal(+)	14	2	16
Horizontal(−)	10	13	23
Total	24	15	39

pearance by using fairly large disparities with movement and with color.[1] Traditional tests evaluate stereopsis using finer, static images, and therefore new stereotests are needed to determine if patients can see these new 3D images stereoscopically.

We determined that a suitable stereotest needs to meet the following criteria: (a) patterns should be relatively large in size and in disparity, (b) the target should be bright, and (c) the presentation of separate images to each eye (binocular separation) should be similar to that encountered in everyday life. Use of a liquid crystal display with backlighting allowed us to provide a bright target and large arc size, and the parallax barrier system,[3] in which the principle in use is similar to that of a lenticular lens but the resolution is about three times better (15.7 cycles/degree for Lang and 43.6 cycles/degree for DRDS) provided images that were much clearer, closely simulating natural binocular conditions, making it unnecessary for patients to wear glasses.

A DRDS was chosen because it does not provide any monocular cues, and it allows precise judgment of a patient's stereopsis. Optimal target speed to allow detection of motion in depth was chosen based on previous reports.[4–6] An SCS was also employed to investigate whether color plays a role in stereopsis. All normal subjects passed DRDS testing, suggesting that if a subject had established fine static stereopsis, he or she may also have coarse dynamic stereopsis.

Comparing the Titmus fly and the DRDS, which have similar disparities (the maximum disparity of about 3000 seconds of arc), the detection rate of stereopsis was significantly higher in DRDS (Table 1), suggesting that motion allows subjects with subnormal stereopsis to appreciate stereopsis that they may not otherwise see, which may be useful for examining the potential of patients with strabismus to see 3D images that have large disparity with movement. Indeed, two patients (patients 6 and 10) who failed the Titmus fly but passed DRDS testing reported that they were able to enjoy 3D movies at an amusement park (Table 6).

Both the Lang and DRDS tests use random dots and can be seen without glasses. The fact that the detection rate of stereopsis was significantly higher with the DRDS (Table 2) suggests that use of motion is helpful for revealing lower levels of stereopsis. The DRDS appears to be useful in young children, as age did not affect ability to detect stereopsis when Lang testing was negative.

Comparing the Titmus animal and SCS tests, which have similar disparities (400 seconds of arc) and are both static, the detection rate of stereopsis was not different (Table 3), suggesting that, although targets featuring a character interest children for testing, color or brightness of a target does not help patients get stereopsis clues.

As for the direction of movement with the DRDS, front-rear movement showed significantly better results compared with horizontal movement (Table 4). This is consistent with the fact that motion stereopsis theoretically occurs in the front-rear plane.[7,8] However, the horizontal mode is useful for patients who cannot understand the testing procedure, because if horizontal eye movement is detected, stereopsis is evident.

Between the two different modes of front-rear movement, no significant difference existed, but synchronous movement demonstrated a trend toward a higher rate of successful detection, suggesting that identification of different targets is easier with synchronous movement.

Among patients with poor stereopsis by conventional stereotests, the success rate of DRDS testing tended to be higher in those with esotropia compared to those with exotropia (Table 5). Most patients with small-angle esotropia have central suppression scotoma with peripheral fusion;[9] however, patients with constant exotropia usually have a large suppression area in the temporal retina.[10] As the peripheral retina is sensitive to movement,[11] the DRDS may evoke peripheral stereopsis in patients with esotropia.

In this study, angle of deviation was assessed by alternating prism cover testing, which included both latent and manifest deviation. Therefore, in some DRDS(+) cases, the angle of deviation was larger than the limit of peripheral fusion (8–10 Δ); how-

Table 5. Results of the Dynamic Random Dot Stereogram (DRDS) for Patients in the Esotropia and Exotropia Groups Who Failed Titmus Animal Testing, Based on Type of Deviation

	DRDS(+)	DRDS(−)	Total
Esotropia	14	5	19
Exotropia	5	8	13
Total	19	13	32

Jpn J Ophthalmol
Vol 42: 101–107, 1998

Table 6. List of Patients

Patient No.	Age (Years)	Squint	Fly	Animal	Circle (Seconds)	Lang	DRDS	SCS	APCT(Δ)
1	5	ET	F	F	F	F	P	F	18
2[a]	9	XPT	F	F	F	ND	P	P	35
3	14	EHT	F	F	F	F	P	F	18(5)
4	8	EHT	F	F	F	F	P	F	14(4)
5	8	EHT	F	F	F	F	P	F	4(5)
6	10	ET	F	F	F	F	P	F	8
7	7	EPT	F	F	F	F	P	F	45
8[a]	8	XT	F	F	F	ND	F	F	35
9	7	EHT	F	F	F	F	F	F	25(12)
10	4	ET	F	F	F	F	F	F	40
11	11	XPT	F	F	F	F	F	F	8
12	13	EHT	F	F	F	ND	F	F	16(3)
13	15	XT	F	F	F	ND	P	F	50
14	8	ET	F	F	F	F	P	P	35
15	7	XHT	F	F	F	ND	P	P	14(14)
16[a]	4	ET	F	F	F	F	F	F	30
17	11	ET	F	F	F	F	P	F	20
18	6	EHT	F	F	F	F	F	P	25(5)
19	7	XT	F	F	F	F	F	F	8
20	6	ET	F	F	F	F	P	F	10
21	6	ET	F	F	F	F	P	P	14
22	6	XT	F	F	F	F	F	F	14
23	8	XT	F	F	F	ND	F	F	18
24	7	ET	F	F	F	F	P	P	8
25	16	ET	P	F	200	ND	P	F	16
26	4	XHT	P	F	400	F	P	P	8(8)
27	22	ET	P	F	800	F	P	F	12
28	12	ET	P	F	F	F	P	F	8
29	6	XPT	P	F	F	F	F	P	35
30	8	XPT	P	F	F	ND	P	F	35
31	4	XT	P	F	F	F	F	F	10
32	4	XPT	P	F	F	P	P	F	20
33	7	XPT	P	P	100	P	P	P	55
34	8	EP	P	P	100	P	P	P	8
35	26	XPT	P	P	140	P	P	P	10
36	7	EP	P	P	140	ND	P	P	18
37	6	EP	P	P	140	P	P	P	4
38	5	XPT	P	P	200	P	P	P	18
39	6	XPT	P	P	200	ND	P	P	30
40	6	XPT	P	P	200	P	P	P	35
41	7	EP	P	P	200	P	P	P	12
42	6	EP	P	P	400	P	P	F	8
43	13	XPT	P	P	50	P	P	P	20
44	6	XPT	P	P	80	P	P	P	18
45	10	XPT	P	P	80	P	P	P	20
46	4	XPT	P	P	80	P	P	P	20
47	5	XPT	P	P	80	P	P	P	10
48	35	XPT	P	P	80	P	P	P	16
49	12	EP	P	P	80	P	P	F	4
50	8	XPT	P	P	800	ND	P	F	14
51	24	XHT	P	P	800	F	F	F	4(16)
52	10	ET	P	P	F	P	P	P	20

DRDS: dynamic random dot stereogram, SCS: static-colored stereogram, ET: esotropia, EP: esophoria, EHT: esotropia with hypertropia, EPT: intermittent esotropia, XT: exotropia, XPT: intermittent exotropia, XHT: exotropia with hypertropia, F: failed testing, P: passed testing, ND: not done, APCT: denotes horizontal (vertical) deviation measured at 30 cm.

[a] Patient had amblyopia.

ever, manifest deviation observed during examination was smaller than those values.

Previous studies comparing random dot stereogram to conventional stereotest with monocularly visible contours in strabismus patients showed poorer stereopsis with random dot stereogram.[12] In this study, DRDS showed a higher success rate than the Titmus fly test, which has monocularly visible contours. This discrepancy may stem from the fact that, in addition to the dynamic aspect of this test, binocular dissociation with parallax barrier in DRDS is less compared with polarized glasses used in the fly test.

The DRDS test estimates stereopsis based on binocular disparity and motion without monocularly visible contours; in the natural environment, however, other depth cues such as shadow and texture are available. Therefore, even individuals who failed the DRDS test might have some degree of depth perception in everyday life.

The results of recent neurophysiological experiments show that there are two relatively independent visual pathways in the central nervous system. One is the ventral pathway (P-stream), which processes fine, static information including color, and the other is the dorsal pathway (M-stream), which processes coarse, dynamic information.[11] Because our DRDS test uses relatively large, coarse, moving images as stimuli, it probably stimulates the M-stream. In contrast, the Titmus test uses principally fine, static images to test for stereopsis and therefore probably stimulates the P-stream.

It has also been reported that fusional tolerance is larger for random dot testing than for line targets.[13] These strands of evidence support our conclusion that the DRDS test can demonstrate weak stereoscopic capability not possible using conventional tests of stereopsis.

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