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Binocular Depth-from-Motion (BDFM)

Ai-Hou Wang

Department of Ophthalmology
National Taiwan University Hospital

7, Chung-shan S. Rd. Taipei, Taiwan 100

Binocular depth-from-motion (BDFM) is a dynamic binocular function that is not included in the clinical test battery. Clinical binocular function tests nowadays include fusion and stereopsis. The mechanism of motor fusion is vergence-from-disparity and the mechanism of stereopsis is depth-from-disparity. Both of which describe our binocular response to a static image. We live in a dynamic world. The retinal image is always in motion. Depth perception coming from the comparison of binocular retinal image motion may be utilized more often and more useful.

Kitaoji and Toyama[1] called it motion stereopsis and Laby[2] called it dynamic stereoacuity. I prefer to call it BDFM in terms of its mechanism, and also as a counterpart of depth-from-disparity as for conventional stereopsis.

Regan did intensive investigation about depth-from-motion and motion-in-depth[3]. Two kinds of motion-in-depth were investigated. To localize our selves in space, the word looming or optic flow is used[3]. To localize moving objects in space, we said depth-from-motion. Different motion-in-depth gives different combination of motion vectors over the retinas of two eyes. And conversely, from motion vectors on the retinas of two eyes there's enough information to recover the motion-in-depth (Fig.1). It should be emphasized that the 'motion' in depth-from-motion means the image motion across the retina while the 'motion' in motion-in-depth means object motion in space.

Image motion over the retina of single eye also gives depth perception. And this is the reason that I specify my topic as 'binocular' depth-from-motion.

Origin

The origin of this study came from a PC-based random-dot stereopsis test. In the title page, random-dot stereograms of different disparities were displayed consecutively (Fig.2). The hidden square thus manifested as moving in depth (Fig.3).

A stereoblind subject found that he could get the depth perception from this dynamic display. Since the square was already visible via cinematogram as viewed monocularly, recognition of the shape did not prove his depth perception. The Emmert's law reported by him nevertheless evidenced that he did perceive the depth motion. He reported that as the square came closer, it looked smaller. Emmert's law says that objects with equal size of retinal projection looks smaller when it appears closer.

When the cinematogram was paused, stereopsis-normal subjects saw the square standing still in space; while the stereoblind could no more see even the shape of the square.

It implied that besides disparity cue, motion cue gives depth perception as well.

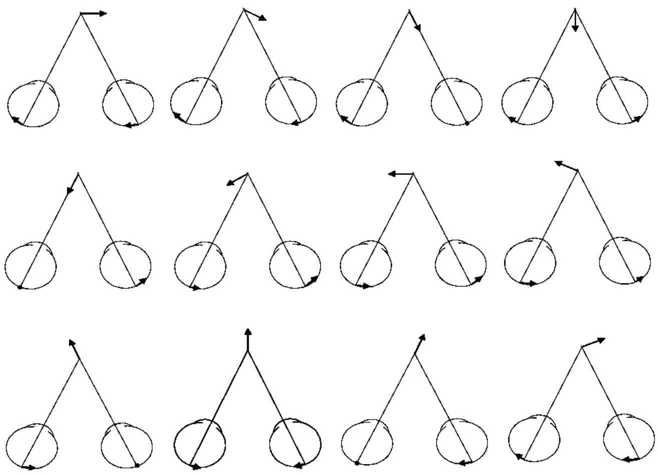


Fig. 1

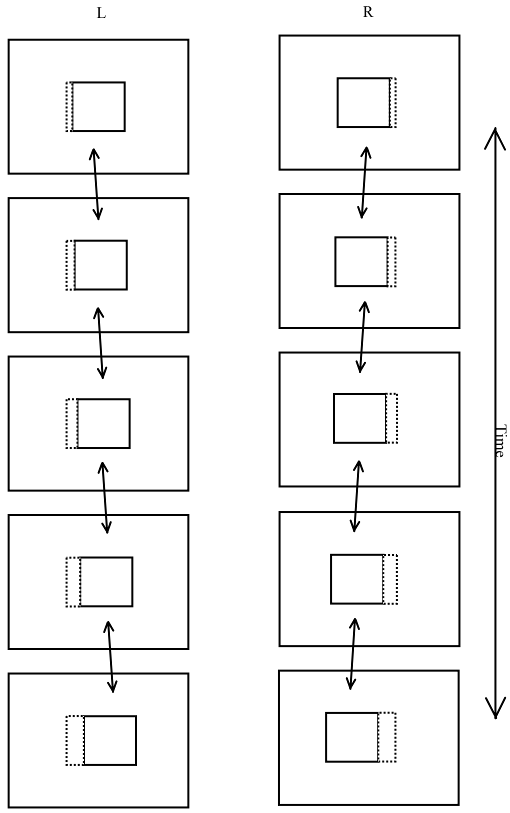


Fig. 2

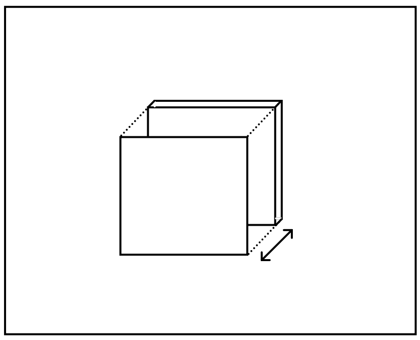


Fig. 3

Stimulator

I thus programmed a PC-based test for BDFM. The test is a 4-alternative-forced-choice (4-AFC) task. Subjects were asked to select the one square that jumped in depth, out of the other three squares that moved on the plane (Fig.4). It was constructed as random-dot stereogram and random-dot cinematogram. For the square jumping in depth, squares viewed by two eyes moved in opposite direction (Fig.5).

At time1, if square t1L and t1R are identical, it's a stereogram and has full disparity cue; if t1L and t1R are different, it's a correlogram and there is no disparity cue. The identity of t1L and t1R can be titrated from all to none by logic manipulation XOR with a spatial operator (Spat), a random-dot array of density from 0% to 50%.

For either eye, if t1R and t2R are identical, it's a cinematogram and has full motion cue; if t1R and t2R are different, it's a temporal correlogram and there is no motion cue. The identity of t1R and t2R can be titrated from all to none by XOR manipulation with a temporal operator (Temp), a random-dot array of density from 0% to 50%.

For the other three squares moving on the plane, squares viewed by two eyes nevertheless move in the same direction and give no depth information (Fig.6). The positions of the square at time1 and time2, either left or right, was randomized by the computer.

This program can test disparity cue and motion cue separately, and can titrate either cue gradually from all to none. Depth readability in any combination of disparity and motion cues can be assessed (Fig.7). But in the clinical setting we tested only three extreme conditions: (1) both disparity and motion cues, (2) motion cue only and (3) disparity cue only.

In anaglyphical setting, monocular cue from imperfect filtering may disturb the test result. Occlusion of one eye to verify we're testing binocularity is sometimes needed.

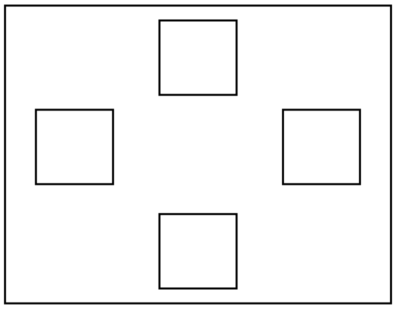
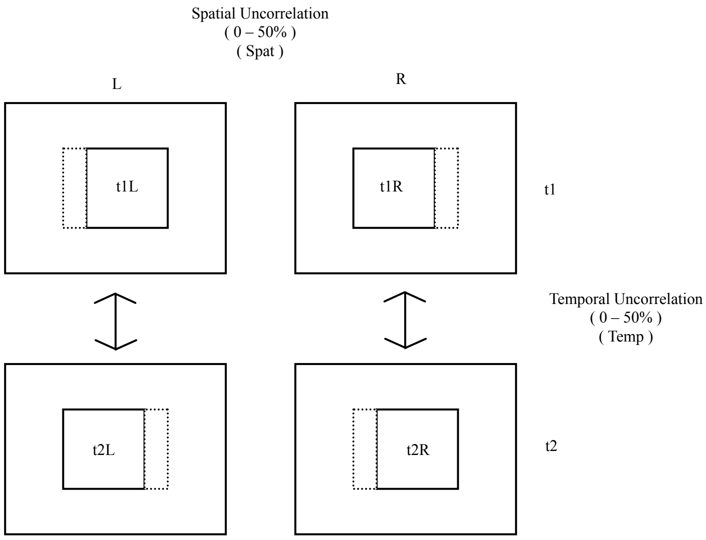


Fig. 4



t1L = t1R XOR Spat
t2R = t1R XOR Temp
t2L = t2R XOR Spat = t1L XOR Temp
= t1R XOR Spat XOR Temp

Fig. 5

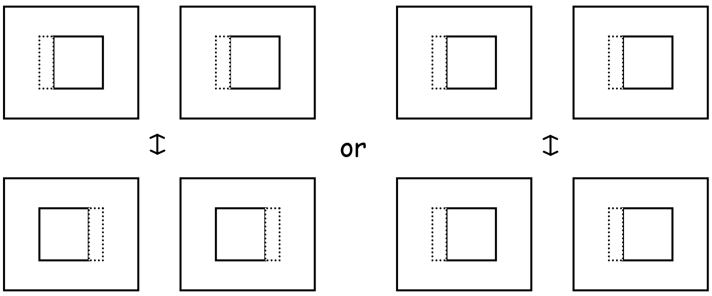


Fig. 6

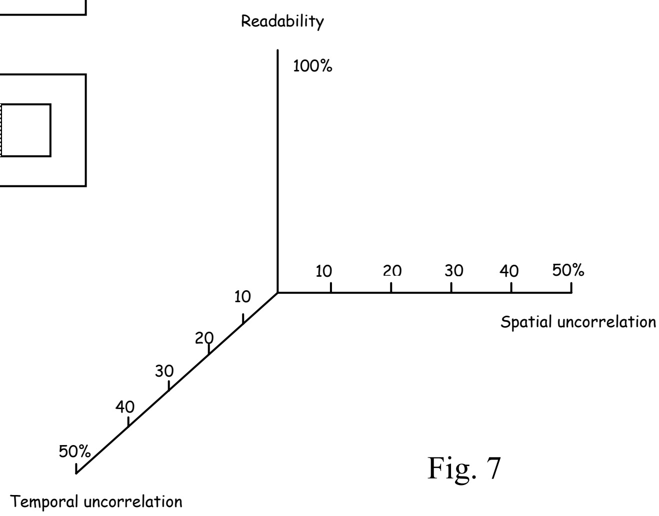


Fig. 7

BDFM of strabismic patients

I tested small angle strabismic patients, either after or without surgery, who failed gross random-dot stereopsis test as tested with NTU 35 min-of-arc random-dot stereograms. 54 patients could pass the test. They passed the one with both disparity and motion cues; passed the one with motion cue only and failed the one with disparity cue only (Fig.8). We thus knew their depth perception came from motion cue and their absence of disparity sensor verified their failure in static random-dot stereopsis test.

We concluded that for those stereopsis-deficient, BDFM might be an important mechanism of depth discrimination for their daily life. One example is that many strabismic patients who failed stereopsis test could still perceive the depth of 3D movies. Another example is that seeing pendulum with a neutral density filter over one eye they could get Pulfrich phenomenon.

Pulfrich phenomenon was used to being explained with static disparity between images over two eyes. Actually motion cue takes part as well. This can be proved with dynamic random-dot correlogram.

Among those 54 patients, 9 were early-onset strabismus as evidenced by their asymmetric naso-temporal monocular OKN or latent nystagmus. This implies that late treatment of infantile esotropia, despite it's hard to recover their stereopsis, may have functional benefits of binocularity besides mere cosmetic consideration.

Both Motion and Disparity Cues (Spat = 0% ; Temp = 0%)	+
Motion Cue only (Spat = 50% ; Temp = 0%)	+
Disparity Cue only (Spat = 0% ; Temp = 50%)	–

Fig. 8

BDFM of subjects with normal stereopsis.

They found it's harder to get depth perception with motion-cue-only than with disparity-cue-only. After learning, most of them nevertheless could read the one with motion-cue-only. But there were two subjects who could not read the one with motion-cue-only even after learning.

This implies that those who have stereopsis make use of disparity cue more, and set aside motion mechanism in their daily life, despite most of them do have BDFM in their brain.

Neurophysiology of BDFM

In daily life, most objects with motion-in-depth, such as flying mosquitos, contain both disparity and motion cues. Cumming and Parker[4] had discussed two binocular mechanisms for detecting motion-in-depth. One is from interocular velocity difference, the other is from temporal change of disparity (Fig.9). They found there was no experimental evidence that supported the existence of a mechanism sensitive to inter-ocular velocity differences. Our data, on the other hand, supported a mechanism to detect inter-ocular velocity difference, at least in strabismic patients. They didn't have disparity sensor, and consequently had no way to detect temporal change of disparity.

Clinical data from Nagoya University[5] showed that sensory fusion as tested with Worth-4-dot correlated with the presence of BDFM. In clinical practice, motor fusion is usually thought to be a prerequisite of stereopsis. Is BDFM also a prerequisite of stereopsis? Is BDFM a more primitive and fundamental binocularity than stereopsis? Or are they just two independent mechanisms for depth perception? (Fig.10) In this study, we only tested patients devoid of stereopsis to find some of them had preserved their BDFM. Is there any people who has normal stereopsis (disparity mechanism) yet is devoid of BDFM mechanism? Laby[2] showed that some stereonormals didn't have dynamic stereopsis and he stratified static stereopsis (depth-from-disparity) and dynamic stereopsis (depth-from-motion) as parallel processing mechanisms. In our series, there were two subjects with normal stereopsis could not pass the test with motion-cue-only even after learning. The relationship between motion and disparity mechanisms may need further investigation.

In our series, the largest deviation angle of those who passed BDFM test was 18Δ residual esotropia. She was 27Δ esotropic, with 9Δ base-out spectacles. This implies that the receptive field of BDFM should be larger than 18Δ.

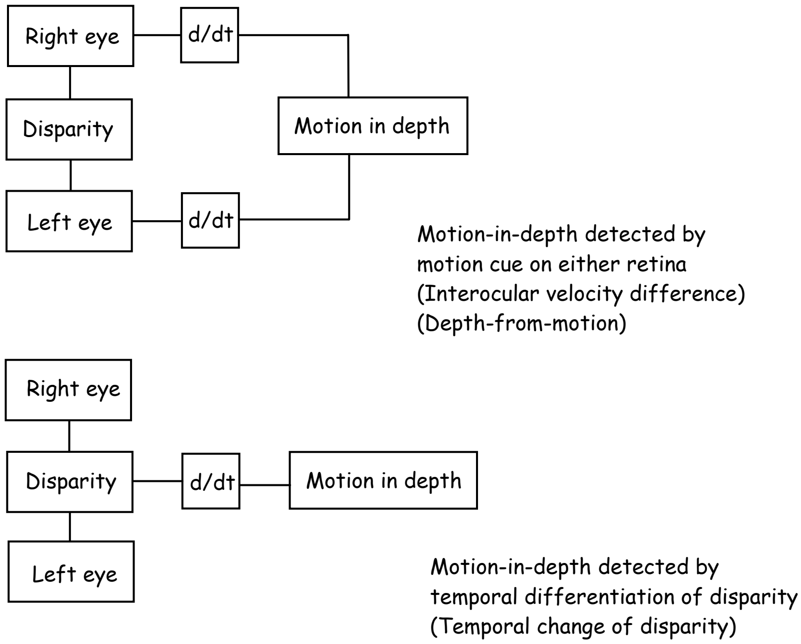


Fig. 9

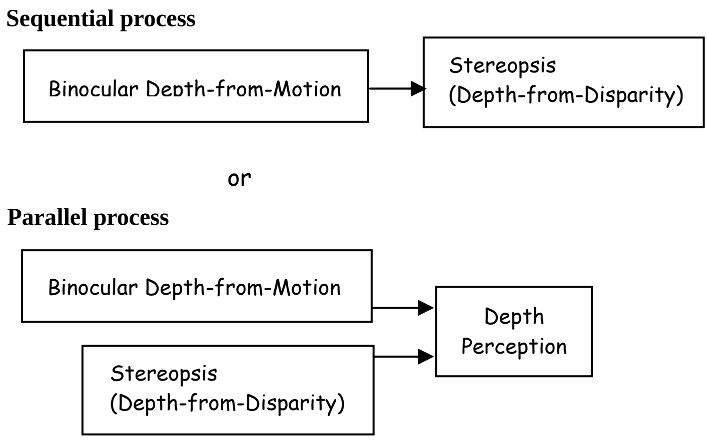


Fig. 10

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