To CD or not to CD: Is there a 3D motion aftereffect based on changing disparities?

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Abstract

Recently, T. B. Czuba, B. Rokers, K. Guillet, A. C. Huk, and L. K. Cormack, (2011) and Y. Sakano, R. S. Allison, and I. P. Howard (2012) published very similar studies using the motion aftereffect to probe the way in which motion through depth is computed. Here, we compare and contrast the findings of these two studies and incorporate their results with a brief follow-up experiment. Taken together, the results leave no doubt that the human visual system incorporates a mechanism that is uniquely sensitive to the difference in velocity signals between the two eyes, but—perhaps surprisingly—evidence for a neural representation of changes in binocular disparity over time remains elusive.

Keywords

3D motion; motion aftereffect; binocular vision; changing disparities; interocular velocity difference; stereomotion

Introduction

The perception of motion through depth has received renewed attention lately, due to an accumulation of evidence that a binocular mechanism for such 3D motion uses motion signals *per se* as its input primitive (as opposed to the spatial position signals used by disparity-based stereopsis). Two articles on this topic, one by Czuba, Rokers, Guillet, Huk, and Cormack (2011) and one by Sakano, Allison, and Howard (2012), were recently

published in this journal. Because the two papers are so strikingly similar, we thought it would be worthwhile to compare and integrate the two sets of results.

Both papers used adaptation paradigms to establish the presence of a motion aftereffect (MAE) through depth (i.e., directly toward or away from the observers), and both papers used similar stimulus manipulations to isolate the contributions of the disparity-based cue (changing disparity or "CD") from the velocity-based cue (interocular velocity difference or "IOVD"). One difference in methodology was that Sakano et al. (2012) used the subjective duration of the MAE and the percentage of trials on which the MAE was reported as their dependent measures, whereas Czuba et al. (2011) used a 2AFC motion-nulling paradigm that yielded full psychometric functions from each observer for each condition. A second difference was that, in our original experiments, we adapted observers to large-field unidirectional 3D motion moving toward or away from the observer as shown on the left side of Figure 1A. In contrast, Sakano et al. focused on a bidirectional adaptation stimulus consisting of oppositely moving stimulus regions above and below fixation.

Crucially, both papers found strong evidence for an IOVD mechanism that compares velocity signals between the two eyes to extract three-dimensional motion. This, along with a spate of recent papers by several other groups (e.g., Brooks, 2002; Fernandez & Farell, 2006; Nefs, O'Hare, & Harris, 2010; Shioiri, Kakehi, Tashiro, & Yaguchi, 2009, Shioiri, Nakajima, Kakehi, & Yaguchi, 2008), is an important convergence of evidence because the IOVD mechanism is a radically different kind of binocular computation; one that is distinct from the long-appreciated mechanism of stereopsis, and its confirmed existence has important theoretical and practical consequences for vision science.

However, one critical discrepancy between the two papers is that Sakano et al. (2012) found no evidence for a disparity-based (CD) contribution to the 3D MAE, whereas Czuba et al. (2011) did find that a 3D MAE could be produced by changing disparities, albeit one that was much smaller than that produced by IOVDs. To determine whether either of the two methodological differences mentioned above could explain our disparate findings, we conducted a follow-up experiment in which observers adapted to both toward and away motion simultaneously (Figure 1A, right side), in the spirit of the bidirectional geometry of Sakano et al. As in our previous experiment, we employed a 2AFC motion-nulling methodology to measure the magnitude of the resulting motion aftereffects. Adaptation stimuli consisted of random dot stereograms moving at 0.6°/s in opposite directions in the two eyes—generating percepts of 3D motion directly toward or away from the observer. The CD cue was isolated by dynamically updating dot positions on every display frame (60 Hz) while maintaining steadily changing disparities consistent with a plane of dots moving through depth. The "Full" Cue stimulus consisted of coherently moving binocularly paired dots, which inherently contained both CD and IOVD cues to 3D motion (for further details and stimulus examples see Methods section of Czuba et al., 2011). The only departure from our previously published methods was that test stimuli were randomly presented in either the upper or lower—but not both—hemifield on every trial. The logic is that the presence of an effect in this follow-up experiment would indicate that the 2AFC motion-nulling methodology is required to reveal the smaller CD MAE. Conversely, the absence of an effect would imply that adapting to a large unidirectional CD-isolating stimulus yields measurable CD-based aftereffects that were not present when adapting to different directions of motion in different parts of the visual field.

The results of this experiment are shown in Figure 1B, which compares them to the corresponding data from our original 3D MAE paper. Bar graphs depict MAE magnitudes, as measured from the shift in point of subjective equality following adaptation. MAE magnitudes resulting from unidirectional adaptation toward or away from the observer are

shown on the left (solid outlines; replotted from Figure 13 of Czuba et al., 2011), while the corresponding MAEs from bidirectional adaptation (dashed outlines) are shown on the right side of the graph. Clearly, there remains a strong 3D MAE for Full Cue stimuli (orange bars) that contain both IOVD and CD cues, but the CD-isolated MAE (cyan bars) is now absent.

We note that Sakano et al. also did not find a CD MAE using unidirectional stimuli in a later experiment (Experiment 3, Stimulus Cases 2 and 3). However, the moving portion of those displays were very small and were placed on a large, static, disparity pedestal (see Figure 7 of Sakano et al., 2012). The constellation of these results points to a CD mechanism that requires both large and unidirectional 3D motion to elicit a motion aftereffect. The presence of a CD MAE, albeit under limited conditions, confirms that a stereomotion display with no coherent monocular motions can still generate directional signals in the visual system (Norcia & Tyler, 1984).

In conclusion, two independent groups of investigators used very similar psychophysical adaptation paradigms to reveal the presence of a mechanism that uses the difference in velocity between the two eyes to compute 3D motion. This IOVD mechanism is distinct from classical stereopsis in that it does not rely on fine positional differences between the eyes (and hence does not need to solve the classical "correspondence problem"). There was a disagreement, however, about whether the CD cue is able to produce a 3D MAE (and, presumably, contributes to 3D motion perception as a true directional signal). Comparison of our original and follow-up experiments suggests that 3D MAEs from isolated CD cues can be elicited with large unidirectional stimuli but are much weaker (or even absent) for bidirectional and/or smaller adaptation stimuli. Whether this implies surprisingly large spatial summation in the sensory mechanisms that encode CD (Brooks & Stone, 2006), capacity or resolution limits in higher level mechanisms, or other factors is a current topic of work in our laboratory. Regardless of the etiology of the dependence of CD MAEs on spatial stimulus properties, the delicate nature of MAEs based on changing disparities (once thought to be the primary binocular cue to 3D motion) further emphasizes the renewed focus on the IOVD cue.
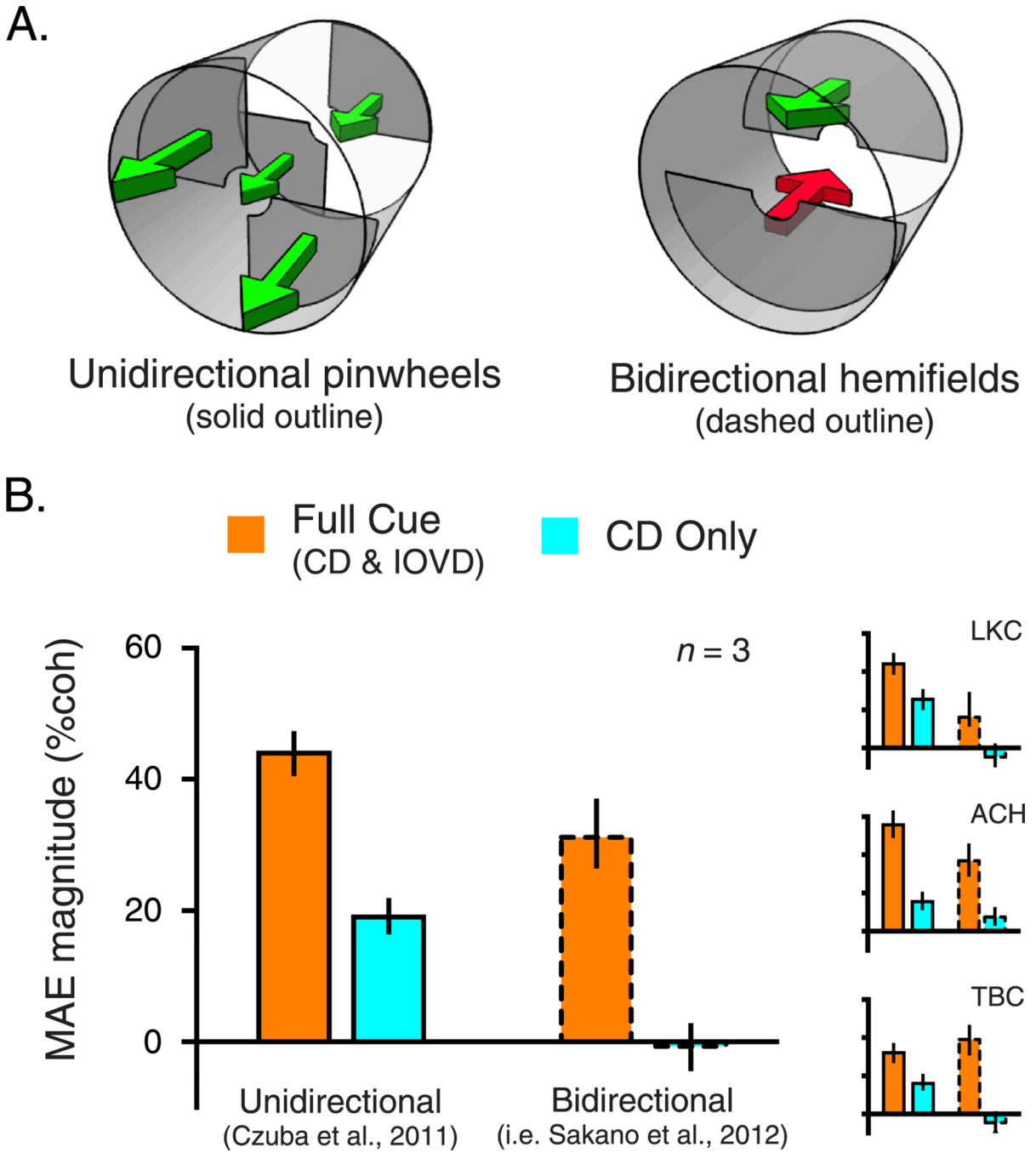
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A.

Unidirectional pinwheels
(solid outline)

Bidirectional hemifields
(dashed outline)

B.

Full Cue (CD & IOVD)   CD Only

n = 3

MAE magnitude (%coh)

60

40

20

0

Unidirectional
(Czuba et al., 2011)

Bidirectional
(i.e. Sakano et al., 2012)

LKC

ACH

TBC

Figure 1.
(A) Schematics of unidirectional adaptation stimuli used by Czuba et al. (2011) and bidirectional stimuli similar to Sakano et al. (2012). (B) Bar graphs of MAE magnitude, as estimated from the test motion coherence at which observers were equally likely to report seeing toward or away motion (the point of subjective equality). Orange bars correspond to "Full Cue" adaptation stimuli containing *both* binocular cues ("3D-planar" condition of Czuba et al.; "RES" condition of Sakano et al.). Cyan bars correspond to CD-isolating adaptation stimuli ("CD" condition of Czuba et al.; "DRES" condition of Sakano et al.). Error bars represent 95% confidence intervals on the bootstrapped distribution. Individual subject data are shown in the three smaller bar graphs to the right of the main figure.