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Cue conflict between disparity change and looming in the perception of motion in depth

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ABSTRACT

We hypothesized that it is the conflict between various cues to distance that have produced results purportedly showing that vergence eye movements induced by disparity change are not an effective cue for depth. Single and compound stimuli were used to examine the perceived motion in depth (MID) produced by simulated motion oscillations specified by disparity, relative disparity, and/or looming. Estimations of the extent of MID and binocularly recorded eye movements showed that the vergence induced by disparity change is indeed an effective cue for motion in depth in conditions where looming information does not conflict with it. When looming and disparity are in conflict, looming is the stronger cue.

1. Introduction

Whether vergence eye position (or vergence eye movements induced by disparity change) serve as a cue to egocentric distance is a long-standing controversy in the history of visual science. The theoretical statement can be traced back to Descartes (1637/1902) and Berkeley (1709/1910). Descartes (1664/1972) thought of binocular vision as analogous to a blind man holding two sticks and argued that the angular positions of the two eyes provide "through a natural geometry" (in translation of Descartes by Hall, 1972, p. 62) information about the location of an object (see Fig. 1). Consistent with this hypothesis, Berkeley wrote: " … the two *optic axes* … concurring at the *object*, do there make an *angle*, by means of which, according as it is greater or lesser, the *object* is perceived to be nearer or further off (p. 14 original italic)."

Although an apparently simple and straightforward hypothesis, it has been controversial from its first two experimental tests. Wundt's (1862) experiment using a vertical thread placed at a distance ranging form 40 to 180 cm concluded that convergence serves as a cue to distance in the absence of other cues. Soon after, however, Hillebrand (1893) challenged the conclusion. Hillebrand used three pairs of threads presented in a haploscope, one pair appearing in the center with no retinal disparity, another pair with crossed disparity, and yet another with uncrossed disparity. In different conditions, the angular separation between two outer fused stimuli ranged from 3° to 20°, and the distance between the stimuli to the center of the rotation of the eyes varied from 10 to 35 cm. Rotating the arms of the haploscope symmetrically (thus changing the vergence angle) "had no influence on the localization of the threads ahead, on, or behind the 'core surface' (p. 41)."

Fast forwarding to more current literature there are still claims and counter-claims for the vergence hypothesis. Numerous studies controlling the distance cues of image size and luminance provided supporting data (Bingham & Pagano, 1998; Foley, 1977; Mon-Williams & Tresilian, 1999; Pagano & Bingham, 1998; Tresilian, Mon-Williams, & Kelly, 1999; Viguier, Clément, & Trotter, 2001) and Richards and Milller (1969) concluded that, for some observers but not for others, vergence is a reliable cue to distance. The counter-claims to the vergence hypothesis are not as numerous (Erkelens & Collewijn, 1985; Regan, Erkelens, & Collewijn, 1986), but are based on persuasive data. Erkelens and Collewijn, and Regan et al. produced and measured vergence eye movements by oscillating a pair of extended dot textures in a stereoscope to simulate motion in depth from disparity and found no change in perceived distance.[1]

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[1] There is controversy as to whether the wallpaper illusion supports the vergence hypothesis. Brewster (1844), Helmholtz (1962), Lie (1965), and Ono, Mitson, and Seabrook (1971) claimed the hypothesis to be valid, but Logvinenko and Belopolskii (1994), Logvinenko, Epelboim, and Steinman (2001), and Logvinenko and Steinman (2001) claimed the opposite. See Kohly and Ono (2002) for their counter-argument against the claim made by Logvinenko and colleagues.

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Fig. 1. Descartes' (1664/1909) view of binocular vision (translation by Hall, 1972, p. 62): "Notice also that if the two hands *f* and *g* each hold a stick, *i* and *h*, with which they touch object K, although the soul is otherwise ignorant of the length of these sticks, nevertheless because it knows the distance between the two points *f* and *g* and the size of angles *fgh* and *gfi*, it will be able to know, as if through a natural geometry, where object *K* is".

A possible resolution to this long-standing controversy was offered by Howard (2008), Nefs and Harris (2007), and Kohly and Ono (2002), and involves consideration of the conflict between cues that specify changes in simulated distance in the stimuli used to test the hypothesis. Just as looming or the change in retinal image size is a strong cue to change in distance, the lack of looming or an isotropic change in retinal image size is a cue for the absence of motion in depth (MID); the lack of change in perceived distance found by Erkelens and Collewijn (1985) and Regan et al. (1986) indicates that no looming is a stronger cue than vergence eye movements. This cue conflict hypothesis, along with the findings by Howard (2008) and Gray and Regan (1996) that a small stimulus is a poor looming stimulus, accounts for the discrepant findings discussed above. Wundt (1862) used a single thread whereas Hillebrand (1893) used stimulus configurations ranging from 3° to 20°. The more recent studies that supported the vergence hypothesis used a small stimulus whereas the ones that counter it used large random-dot fields.

The aim of this study is to examine the cue conflict hypothesis by replicating and extending the conditions employed by Howard (2008). We extended his conditions in three different ways. First, in addition to the modulation of absolute disparity, we explored the effects of looming when concordant or in conflict with disparity. Second, because monitoring the movements of the eyes is essential for demonstrating that vergence is a cue for depth, we recorded eye movements to explore their relationship with perceived motion in conditions of cue conflict and when conflict with looming is removed. Third, we explored the motion induced in a stationary object by another object moving in depth (Erkelens & Collewijn, 1985; Erkelens & van Ee, 1997; Regan et al., 1986) which we found to be a very strong effect in some of our earlier work on induced vergence (Allison, Howard, & Fang, 2004).

To examine the perception of MID from simulated oscillations in depth specified by absolute and relative disparity and by looming we used two stimuli that exhibit no effect of looming: a small dot for which the looming effect would be absent or minimal and a large radial grating for which looming does not change the proximal size. We also used a large random-dot texture for which no looming is a cue for the absence of motion. In order to study the interaction (or lack of it) between looming and disparity cues in the generation of percepts of motion in depth, simulated MID was specified by: (a) absolute disparity (with no looming), (b) by looming (with absolute disparity unchanging), or (c) by both looming and absolute disparity changing. When both looming and disparity signaled MID, they could be concordant (in phase) or conflicting (180° phase difference). Eye movements were recorded binocularly.

2. Methods

2.1. Observers

Ten observers, five men and five women, between 22 and 55 years old participated. All were naïve as to the purpose of the experiment except for the two observers who were authors. All observers had normal or corrected-to-normal visual acuity and normal stereopsis. In addition to the psychophysical measurements, eye-movement recordings during all test conditions were obtained with a subset of four emmetropic observers. Written informed consent was obtained for each observer in accordance to the principles of the Declaration of Helsinki.

2.2. Stimuli

The three stimulus elements used in this experiment were: (a) a red dot, (b) a 50% green and black random-dot texture, (c) a four-cycle green and black square-wave radial grating (Maltese cross). The dots were 13 min arc in diameter. The random-dot texture subtended 18.6° by 18.6° when portrayed in the plane of the screen, i.e., when not subject to looming during simulated approach or recession. The elements of the random-dot texture were 13 by 13 min arc squares randomly assigned to be either green or black. For the radial grating, masks with irregular but roughly circular shaped apertures (average radius 26.38°) near each eye prevented observers from viewing the ends of the lines so that when the radial texture loomed due to simulated motion in depth, its overall size change was not apparent. The aperture never occluded the random-dot texture and hence there was no accretion or deletion of elements.

The stimuli were presented either as single stimuli or as compound stimuli consisting of the red[2] dot superimposed on the random-dot texture. So that the dot could be better seen when superimposed on the random-dot texture, it was centered on a 3.44° by 2.86° rectangular window left black in the middle of the texture. Illustrations of the stimuli are shown in Fig. 2.

The experiments were conducted using a large format Wheatstone stereoscope. Observers viewed the images through the two mirrors set at ±45° to the frontal plane so that the fused image appeared 100 cm directly ahead of the observer. After reflection off the stereoscope's mirrors, the luminance of the dot was 1.32 cd/m^2 and the luminance of the green superpixels of the random-dot stimulus and the green sectors of the radial grating 3.34 cd/m^2. The masks surrounding the stimuli were matte black so that only the fused textured stimulus was visible. Care was taken to eliminate any stray light and the projector controls were set to achieve a maximum black level (luminance of less than 0.01 cd/m^2). All luminance measures were made with a Konica-Minolta LS-110 photometer.

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[2] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

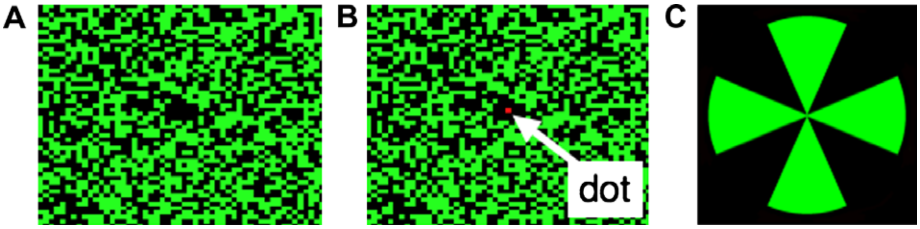

Fig. 2. Illustrations of three of the stimuli used. Panel A: random-dot texture, which covered the entire surface of the stereoscope. Panel B: random-dot texture with superimposed dot. Panel C: radial grating which extended beyond the edges of the near aperture.

2.3. Apparatus

2.3.1. Stimulus display

Images were back-projected onto two screens, one to the left and one to the right of the observer, via BARCO 808 projectors (Barco N.V., Belgium) with a resolution of 1280 × 1024 × 100 Hz. Each display was driven by a separate graphics workstation in a Linux-based graphics cluster. The stimuli were rendered in real-time using OpenGL and the custom VE application programming interface (Robinson et al., 2002) using a cluster of Linux-based PC workstations. Custom software and genlocked video cards (Nvidia Quadro FX 3000G, NVidia Corp. Santa Clara CA) were used to maintain synchronisation of the distributed graphics workstations.

Simulated motion in depth (MID) was portrayed using disparity and/or a perspective transformation which simulated the looming perspective seen at the cyclopean eye. Disparate textures were identical for the two eyes but were horizontally translated equal and opposite amounts in the left and right images. We used the projective geometry calculations of the graphics card to simulate/create the perspective transformation of the texture during simulated approach and recession, but will use the term ‘looming’ to describe this change in retinal size for convenience.

2.3.2. Eye movement recording

A binocular, infrared video eye-tracking device was used to monitor the position of both eyes (VTS, Series 2000, EL-MAR Inc., Toronto, Ontario, Canada). The VTS provides real-time estimates of vertical and horizontal positions of both eyes as well as pupil size at 120 Hz. The VTS is based upon estimation of the distance of multiple corneal reflections to the center of the pupil (Allison, Eizenman, & Cheung, 1996) and has system noise with standard deviation of less than 0.05° and a linear range of ±40° horizontally and ±30° vertically. The eye position is sent to the graphics cluster over a RS232 serial port at a baud-rate of 38400 bps. Raw digital estimates of eye position are recorded directly to disk for off-line analysis. Each session started with a calibration procedure.

2.4. Procedure

The profile of the disparity oscillations was triangular with alternating positive and negative constant velocity periods of 1.26°/s at a frequency of 0.5 Hz, resulting in an simulated MID oscillation of approximately 36 cm specified by a peak-to-peak disparity of 1.26°. For the looming simulation, the approach and recession transformations were set so that they would equate the amplitude and velocity of the disparity oscillations.

Observers were seated with the head supported by a chinrest at the center of the stereoscope. They were instructed to judge the magnitude of the peak-to-peak MID of the stimuli (i.e., the dot, the random-dot texture, or the radial grating) using a 30 cm ruler as an aid. For those stimuli that included the dot and random-dot texture separate estimates of the MID for each were required. To determine the sign of the response (in-phase or in counter-phase with the simulated motion) observers indicated verbally when the stimulus (or a component) appeared near or far from them and this was correlated to the stimulus by the experimenter. An experimental session consisted of 44 self-paced trials presented in four blocks of 11 trials in random order within each block. Before the test began, the observers were shown the three stimuli in Fig. 2 and were instructed to fixate the center of the display.

2.5. Stimulus conditions

MID was simulated by either disparity or looming and the stimuli were either single (i.e., either the dot, the random-dot texture or the radial grating appeared) or compound (i.e., the dot and the random-dot texture appeared simultaneously), but not all the combinations of stimuli and simulated MID were presented (see Table 1).[3] Preliminary observations showed that looming was imperceptible or nearly so for the dot; therefore, we only studied disparity-induced MID oscillations with it (stimulus condition 1). For the random-dot texture we measured perceived depth during MID oscillations specified by disparity only (stimulus condition 2), looming only (stimulus condition 3), and both concordant (stimulus condition 4) and conflicting disparity and looming (stimulus condition 5). For the radial grating we studied MID from disparity (stimulus condition 6) and included looming only as a control (stimulus condition 7) given that any looming results in an identical grating (recall that its outer edges were not visible due to the mask).

In the compound stimulus conditions when the dot and the random-dot texture were presented simultaneously, four conditions were selected: (a) static dot/disparate texture (stimulus condition 8); (b) disparate dot/static texture (stimulus condition 9); (c) disparate dot/concordant looming texture, where the simulated MID of the dot was in the same direction as that of the texture but specified by a different cue (stimulus condition 10); and (d) static dot/concordant disparate and looming texture, where disparity and looming specified the same direction of MID for the random-dot texture (stimulus condition 11). The eye movement trials for the four emmetropic observers tested this way were identical except that binocular eye movements were continuously recorded in addition to the psychophysical measures.

3. Results

For the estimates of the extent of MID in cm, univariate analyses of variance with a Geisser-Greenhouse conservative *F* statistic are reported here, but the same results were found using the *F* approximation of Wilks’ Lambda in multivariate analysis. For multiple comparisons, family-wise error was controlled using a Bonferroni approach. An alpha level was set at 0.05 for all statistical tests.

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[3] As Howard (2008) rightly points out, the effects of a cue are not eliminated when its value is set to zero. The stimulus cues for MID shown in Table 1 are only a shorthand for specifying the aspects of the stimuli that were modulated in the various stimulus conditions. For instance, in stimulus condition 2 for the random-dot texture, modulations of disparity-specified MID, but this stimulus condition also provided a looming cue that specified no motion.

Table 1
Stimulus conditions and their MID components with mean vergence gain and phase ($n = 4$).

Condition	Elements	MID modulated by	Gain (±SD)	Phase (deg ± SD)
Single stimuli				
1	Dot	Disparity	0.84 (±0.14)	12.13 (±66.39)
2	Texture	Disparity	0.98 (±0.17)	43.14 (±35.80)
3	Texture	Looming	0.13 (±0.15)	14.09 (±13.04)
4	Texture	Disparity + looming, concordant	1.13 (±0.27)	36.68 (±9.09)
5	Texture	Disparity + looming, conflicting	0.97 (±0.12)	24.75 (±13.56)
6	Radial grating	Disparity	0.98 (±0.29)	33.87 (±7.80)
7	Radial grating	Looming	0.05 (±0.11)	5.93 (±8.42)
Compound stimuli				
8	Dot + texture	Disparate dot + static texture	0.58 (±0.32)	20.55 (±7.44)
9	Dot + texture	Static dot + disparate texture	0.57 (±0.45)	25.15 (±15.06)
10	Dot + texture	Disparate dot + looming texture, concordant	0.65 (±0.20)	28.26 (±24.43)
11	Dot + texture	Static dot + disparate and looming texture, concordant	0.46 (±0.32)	17.04 (±16.54)

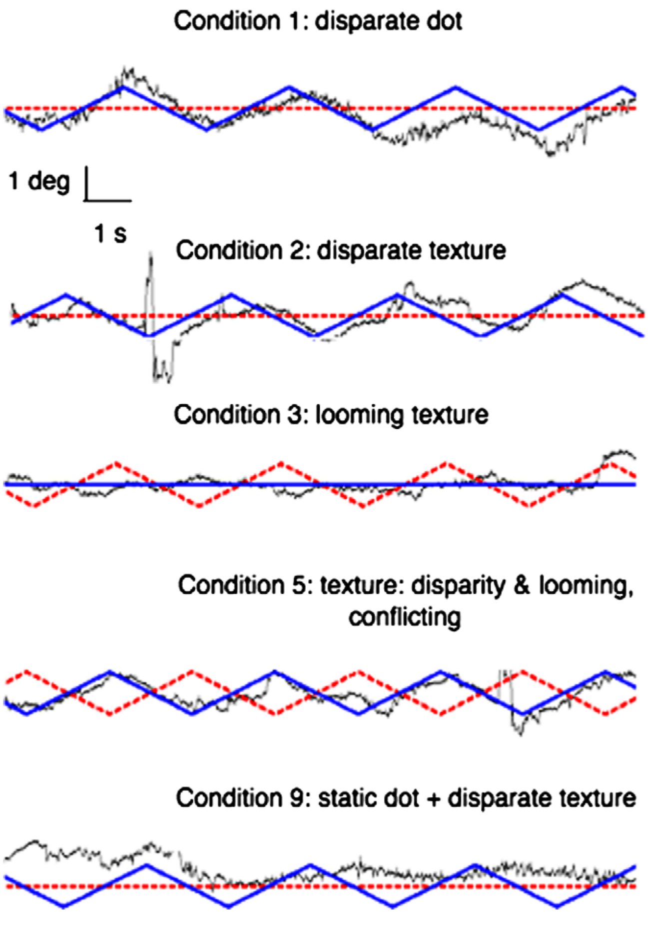

Fig. 3. Sample vergence movements for stimulus conditions 3, 1, 2, 9 and 5. Thick solid lines show the disparity stimulus, dashed lines the looming stimulus, and the thin trace the vergence eye movements.

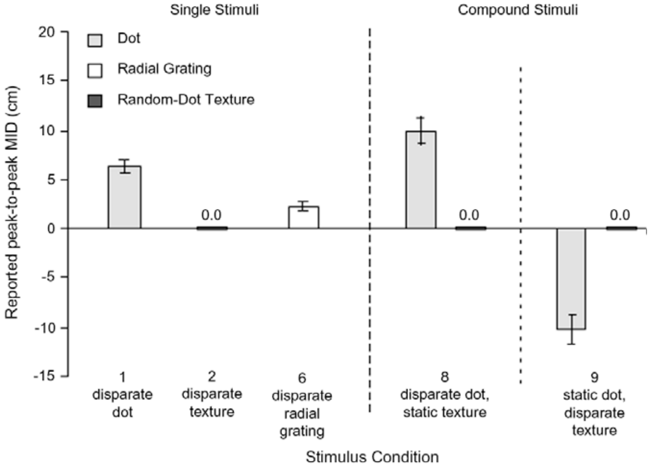

Fig. 4. Mean peak-to-peak MID estimates for disparity oscillations imposed on single (dot, radial grating, and random-dot texture) and compound stimuli (dot plus random-dot texture). Disparity change oscillations were 1.26° peak-to-peak. Positive values indicate that the perceived depth was in-phase with the disparity oscillations; negative values indicate apparent depth in counter-phase with disparity. Errors are 95% CI.

From the recorded eye movements, the right horizontal position was subtracted from the left to provide a vergence signal. Table 1 shows the mean vergence gain and phase data for the four participants whose eye movements were recorded and Fig. 3 shows examples of those eye movements.

3.1. Disparity-specified MID for single stimuli

The left hand section of Fig. 4 shows the mean MID estimates for the single stimuli with imposed oscillations of disparity (stimulus conditions 1, 2 and 6). A one-way analysis of variance yielded a significant effect of stimulus condition on the perceived MID ($F(2,117) = 96.98$, $p < 0.001$). For all observers, the largest reported peak-to-peak MID was obtained with the dot (6.28 ± 0.43 cm, mean ± SEM) (stimulus condition 1), followed by the radial grating (2.26 ± 0.36, mean ± SEM) (stimulus condition 6). All estimates were in-phase with the simulated MID. In general, the dot stimulus was reported as fused but, for some observers, became diplopic at the extreme disparities.[4] Vergence eye movements for this stimulus generally tracked but lagged the stimulus (see Table 1 and Fig. 3, first trace).

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[4] Supplementary data were obtained from eight of the observers plus two additional ones in four trials each of MID specified by a peak-to-peak disparity of 2°. The results are consistent those obtained with a disparity of 1.26° but diplopia was commonly reported. The largest reported peak-to-peak MID in-phase with the simulated MID was obtained for the dot (9.96 ± 0.62 cm, mean ± SEM), followed by the radial grating (4.46 ± 0.41 cm, mean ± SEM) and lastly by random-dot texture (.40 ± 0.20 cm, mean ± SEM). Although the perceived MID was larger than that obtained with a disparity of 1.26°, it was still significantly smaller than the simulated depth. For the compound stimuli containing relative disparity between the dot and the random-dot texture, regardless of whether the dot or the random-dot texture was disparate, the dot rather than the texture appeared to move. When the random-dot texture had zero disparity and the dot had simulated MID from disparity, the reported MID of the dot was (16.75 ± 1.43 cm, mean ± SEM) and the random-dot texture's appeared stationary. Similarly, when the changing disparity was imposed on the random-dot texture but not on the dot, the texture appeared stationary while the dot appeared to move in depth (15.83 ± 1.08 cm, mean ± SEM) in a direction opposite to the predicted (but not apparent) MID of the random-dot texture.

With disparity specifying MID for the random-dot texture (stimulus condition 2), no observer reported perceiving MID. Observers reported that the stimulus seemed either stationary, appeared to expand or contract, or exhibited a small amount of lateral instability, but did not appear to approach or recede. Diplopia was not reported. Eye movements in this stimulus condition were as robust as those for the dot (see Table 1 and Fig. 3, second trace) but, despite similar eye movements, the percepts were very different: there was clear MID for the dot but no MID for the large random-dot texture.

All observers reported that the radial grating moved in depth in phase with the disparity oscillations (stimulus condition 6). Although the reported MID (2.26 ± 0.36 cm, mean ± SEM) was significantly smaller than that reported for the dot, it was significantly greater than zero. Diplopia was not reported although some observers reported that the stimulus appeared to stretch into the distance in a manner consistent with a perspective interpretation of the radial grating as a corridor or tunnel. The 'tunnel' appeared deformed during the imposed disparity oscillation such that its center approached and receded causing it to apparently stretch and contract in depth. As in the other two disparity-defined cases, vergence eye movements generally tracked the stimulus but lagged.

3.2. Looming-specified MID for single stimuli

As predicted, most observers reported no MID for the radial grating (stimulus condition 7). Only two observers reported seeing consistent MID and another reported it in one trial but not in the other three. Due to the equivalence of the radial stimulus at multiple scales we expected no perceptual looming when viewed through the aperture; however, since we did render an expanding condition on the screen, presumably these observers were detecting small motion artefacts most likely related to errors in antialiasing of the sharp edges of the radial grating.

For the random-dot texture (stimulus condition 3) all observers reported MID with a mean perceived depth of 16.0 ± 0.86 cm (mean ± SEM). This MID was apparent even though no systematic vergence movements were made in response to the looming stimulus (see Table 1 and Fig. 3, third trace; this observer's MID response was 25 cm).

3.3. Looming and disparity specifying concordant or conflicting MID for the random-dot texture

When disparity and looming were combined in the random-dot texture, the percept was dominated by the looming cue (Fig. 5). When disparity and looming were concordant (stimulus condition 4), strong MID percepts were obtained in the predicted direction. A one-way analysis of variance yielded a significant effect of depth cue on the absolute values of the perceived MID in cm for the random-dot texture ($F(3,156) = 115.42$, $p < 0.001$). The reported MID in the concordant condition was 17.1 ± 0.91 cm (mean ± SEM) which was not significantly different from that obtained in the looming only condition (16.0 ± 0.86 cm). When looming and disparity-specified conflicting MID (180° phase difference) (stimulus condition 5), perceived MID was always in the direction of the looming component. The reported depth in the conflicting condition was 15.4 ± 0.85 cm (mean ± SEM) indicating that the conflicting disparity cue may have had a small influence. The value of the smaller reported depth, however, was not significantly less than in the concordant or looming only conditions. In short, the absolute values of the estimates of the MID for conditions 3, 4, and 5 were approximately equal indicating that looming is the strongest cue.

In contrast to its influence on the percept, looming appeared to have little influence on the observers' eye movements. Looming alone generated little vergence (see Table 1 and Fig. 3, third trace, though the observer reported that the texture had a 20 cm MID on this trial). We did not expect vergence eye movements in this condition, since it would break binocular fusion. Had the looming stimulus been presented monocularly, however, the vergence eye movements might have occurred. When the looming was in conflict with disparity, vergence tracked the disparity signal albeit with some lag (see Table 1 and Fig. 3, fourth trace; the observer reported that the random-dot texture had a 35 cm MID in this trial, with the percept in phase with the looming component).

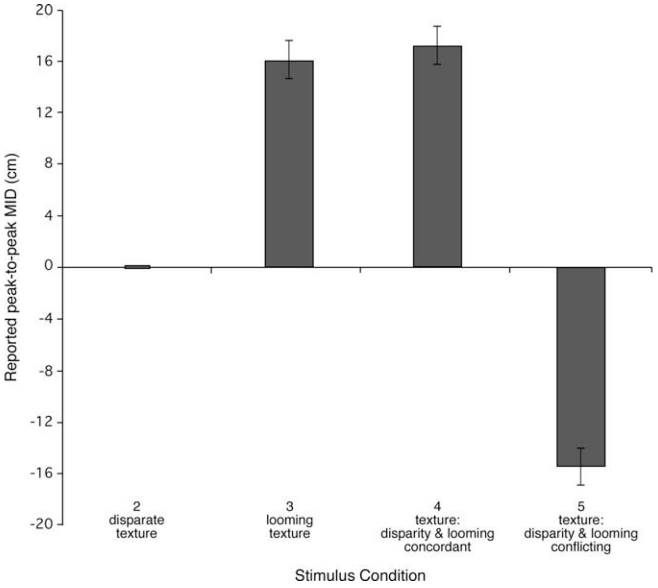

Fig. 5. Reported peak-to-peak MID for the random-dot texture. Imposed disparity or equivalent looming oscillations were 1.26° peak-to-peak. Errors are 95% CI. Positive values indicate that the perceived depth was in-phase with the disparity oscillations or, in the case of condition 3 (disparity constant), in-phase with the looming oscillations. Negative values indicate apparent depth was in counter-phase with disparity (condition 5).

3.4. Disparity specifying MID for compound stimuli

In the absence of looming cues, relative disparity resulted in the perception of MID but it was not always attributed to the stimulus component undergoing the change in disparity. When the dot underwent changes in disparity and the random-dot texture was held at zero disparity (stimulus condition 8) all observers reported that the texture was stationary and that the dot moved in depth in a direction corresponding to its changing disparity (9.86 ± 0.96 cm, mean ± SEM). On the other hand, when disparity changed for the texture and the dot had constant disparity (stimulus condition 9), the texture appeared stationary while the dot exhibited induced MID opposite to the direction of the disparity of the texture (10.02 ± 0.77 cm, mean ± SEM). This was despite the fact that when observers fixated the dot there was no vergence signaling motion in depth for it (see Table 1 and Fig. 3, fifth trace; on this trial the observer responded that the dot moved 8 cm and the texture was stationary). To summarize, in the two cases in which motion in depth was specified by changing relative disparity between the dot and the texture (with looming held constant) the MID was attributed solely to the dot with no significant difference in the magnitude of the reported MID of the dot between the two conditions (see Fig. 4, right hand section).

When only the random-dot texture underwent looming with disparity held constant for both it and the dot, the composite stimulus appeared to move as an ensemble in a similar manner to the looming random-dot texture, but this condition was not studied in detail.

3.5. Disparity and looming specifying MID for compound stimuli

With relative disparity between the dot and the random-dot texture changing there are several possible combinations of disparity and looming in the compound stimuli. We studied two of these: (a) When the dot had a disparity that corresponded to the simulated MID from the looming random-dot texture (stimulus condition 10), the apparent MID of both texture and dot were reported to be in the same direction and of similar magnitude (15.20 ± 0.74 cm and 16.4 ± 1.19 cm, respectively). This was an unexpected finding as there was a relative disparity between the dot and the texture. We asked two observers to judge the *relative* depth between the dot and the texture and found that they could perceive the changing relative depth between them; but, they confirmed that when making separate judgments of the MID of the two stimuli, they appeared to move a similar amount in depth. (b) When the dot had constant disparity and the random-dot texture underwent MID specified by both looming and disparity (stimulus condition 11), MID of the texture in the direction specified by the disparity and looming was reported by all observers (19.10 ± 0.78 cm, mean ± SEM). Induced MID opposite to the motion of the texture in the objectively stationary dot was reported by all observers except for one. This apparent induced motion of the dot was reported as significantly smaller than that of the texture (mean 5.23 ± 1.04 cm, mean ± SEM) by all observers save one who saw it as similar. Fig. 6 shows these effects with the addition of the data from Fig. 4 for comparison purposes.

It should be noted that the vergence gains produced by the compound stimuli were much smaller than those of the single stimuli (Table 1) suggesting that relative disparity was more salient than absolute disparity.

4. Discussion

Our results support our hypothesis that the findings of Regan et al. (1986) and Erkelens and Collewijn (1985) of a lack of perception of MID from disparity modulation are likely due to a cue conflict with the unchanging looming information. For the large random-dot texture conditions we replicated Regan et al.'s and Erkelens and Collewijn's findings of no percept of MID from oscillations of absolute disparity (target vergence). Furthermore, we also replicated their finding and that of Likova and Tyler (2003) that vergence eye movements have little effect on the perception of MID from changing disparity.

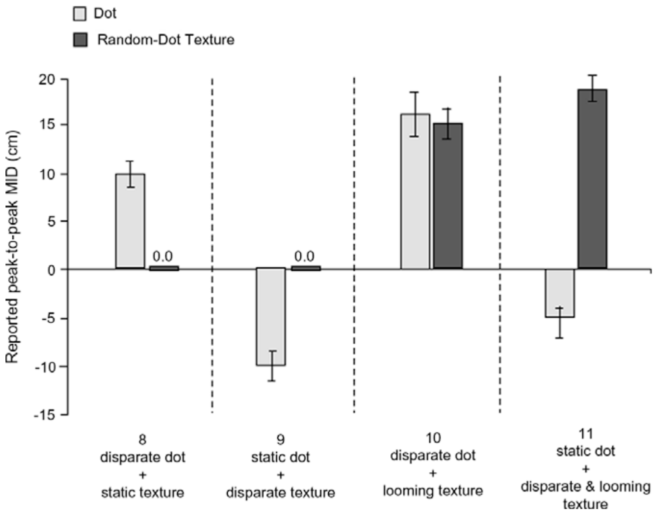

Fig. 6. Combinations of looming and disparity in compound stimuli. Positive values indicate that the perceived depth was in phase with the disparity oscillations; negative values indicate apparent depth in counter-phase with disparity. Errors are 95% CI.

Using stimuli that exhibit minimal or no looming, we showed that reliable MID is produced by modulations of disparity: specifically, for a small dot for which looming is minimal or sub-threshold (i.e., that would be treated by the visual system as a point), and for a radial grating for which looming does not change the proximal stimulus. More depth was produced with the dot than with the radial grating; however, since even a large stimulus such as the radial grating could produce small but significant depth without a reference mark, MID is more parsimoniously explained under the cue conflict hypothesis than by the lateral interactions between adjacent visual directions proposed by Regan et al. (1986), Erkelens and van Ee (1997), and Erkelens and Collewijn (1985). The present study shows that in the absence of conflicting looming information the sensation of motion in depth does not require changes in relative disparity amongst the different elements in the visual field. We replicated Howard's (2008) findings that changes in disparity do produce MID when conflicting looming information is either weak or absent.

The information regarding the exact magnitude of MID from looming or from relative disparity is inherently ambiguous; however, our observers were able to give consistent estimates of MID which suggests that some information regarding an absolute distance was used to calibrate the looming and the relative disparity we used. The estimates of the MID, although larger than zero, were significantly smaller than the depth simulated by the disparity and looming cues. This is a common finding in research using computer displays and stereoscopes where accommodation and the blur of the retinal image specify the depth of the display rather than that of the disparity-specified stimulus (Watt, Akeley, Ernst, & Banks, 2005).

We conclude that for the large random-dot texture, changing disparity as a cue for depth conflicts with its unchanging looming despite the large gain of the vergence eye movements produced. Similarly, Allison and Howard (2000) showed that conflicting (i.e., unchanging) motion perspective reduces the perception of motion in depth from the changing disparity that indicates changing slant; further, when perspective and disparity cues indicate an opposite slant, the monocular cues dominate. In the present study we found that looming in random-dot displays is stronger than changing disparity and that the perceived MID is always in the direction of the looming cue. In fact, MID from looming produces depth that is equivalent to the MID specified by looming and disparity combined even though no systematic vergence movements are made in response to the looming-only stimulus. We can conclude that the effect of the monocular cue of looming strongly dominates the percepts of MID in single stimuli.

When MID was specified by disparity in one or both elements of a compound stimulus, relative disparity was much more salient than absolute disparity; that is, with looming held constant, relative disparity produced robust changes in MID. When a dot and a random-dot texture display were presented together, the dot always appeared to move regardless of whether it or the random-dot texture had changing disparity. Motion induction appears to depend on the relative "strength" of the two signals with the stronger—in our case larger—stimulus appearing still. In cases of brightness differences, it is the dimmer stimulus that appears to move, whether or not it or the brighter one exhibits changes in disparity (Howard, 2008). Similar conclusions were reached from work on stereomotion (Howard, 2008; Nefs & Harris, 2008) and on motion induction in the frontal plane (Duncker, 1938; van Waters, 1934).

Our data show that when, in addition to disparity modulation, the random-dot texture had looming information indicating that it was moving in depth, the induced MID of the dot was much reduced. It appears that relative disparity is a more robust indicator of MID than absolute disparity, which can be nullified by conflicting looming information. Changes in relative disparity only signal relative motion and it is the relative strength of the stimulus elements that determines which one appears to move.

Regardless of the fact that they were given no special instructions, observers were able to attend to the two elements of the compound stimuli independently. Seemingly paradoxical results were obtained with a central disparate dot moving in depth and superimposed on a random-dot texture with identical MID specified by looming only (i.e., with zero disparity). Both the dot and the texture were reported to have a similar amount of MID. This is an unexpected result as it implies that the observers ignored the relative disparity between the dot and the texture and judged the component motions in depth independently. In fact, some observers anecdotally reported they were making separate perceptual judgements for the two stimuli while disregarding their relative depth. This was followed up with two observers who confirmed that they could attend and judge the relative MID between the two stimuli but, when making separate judgments of the MID of the dot and the texture, the two appeared to move a similar amount. Therefore, attention to relative disparity seems to change the nature of the perceptual response and make the relative depth salient. It seems paradoxical to be able to perceive identical motion in two objects while simultaneously being able to perceive changing depth between them if attention is drawn to it. Such paradoxes are well-known in perception and include dissociation between perceived position and motion in the motion after effect (Wohlgemuth, 1911), between vection and tilt in roll vection (Allison, Howard, & Zacher, 1999; Cheung, Howard, Nedzelski, & Landolt, 1989; Dichgans, Young, & Brandt, 1972), and between texture and stereomotion perception in stereoscopic motion standstill (Chia-huei, Gobell, Zhong-Lin, & Sperling, 2006; Julesz & Payne, 1968). Perceptual paradoxes are often interpreted as showing dissociation between systems or mechanism under conditions of conflict or performance limits. For instance, in the roll vection case, vision (vection) indicates continuous change in tilt while vestibular information indicates no change in tilt and the brain appears to resolve this conflict by generating a continuous vection concomitant with a paradoxical constant tilt. It is tempting to speculate that a similar dissociation—perhaps between absolute and relative disparity processing—underlies the current perceptual paradox.

To summarize, this study demonstrated: (a) that vergence (elicited by changing disparity) alone is an effective cue to motion in depth, (b) that previous reports finding it ineffective were likely due to cue conflict, (c) that change in relative disparity is an effective cue to motion in depth, even under conditions of strong cue conflict, and (d) that relative motion in depth from changing relative disparity is assigned based on interpretation of monocular looming cues. The first two findings extend those of Howard (2008) by considering the role of looming stimuli and vergence eye movements. We demonstrated the importance of looming cue interpretation by independently manipulating both the monocular and binocular cues. Vergence eye movements elicited by changes in absolute disparity did not result in MID unless the stimuli had weak or concordant looming cues. When looming and disparity were in conflict, looming was the stronger cue, which explains why vergence eye movements appear ineffective in eliciting MID for stimuli with cue conflicts. In contrast to the weak MID from changing vergence, robust relative MID was elicited by changing relative disparity; however, which stimulus element appeared to move was strongly influenced by looming cues. In our stimuli, cues were either concordant or in strong conflict (i.e., one cue specified motion in depth while another specified a stationary stimulus). Most modeling work on cue combination has considered unbiased cues with small conflicts where additive combination of depth from individual cues would be optimal (e.g., Domini, Caudek, & Tassinari, 2006; Landy, Maloney, Johnston, & Young, 1995). Under strong conflict, however, such linear combination is not ideal and nonlinear cue combination rules such as cue veto or cue promotion are to be expected (Bülthoff & Mallot, 1988; Knill, 2007; Landy et al., 1995; Zalevski, Henning, & Hill, 2007). In our stimuli with relative disparity cues, the relative MID from disparity was interpreted by the observers in the context of the available looming cues, which is essentially a form of cue promotion. For stimuli where target vergence was the only binocular cue to MID, looming cue dominance appears to be the case although further parametric study at multiple levels of cue conflict would be required to distinguish between down-weighting of the vergence cue and true cue veto.

Finally, our conclusion with respect to the historical context in which we introduced the aim of this study is that vergence is a useful cue for depth in certain viewing conditions. When a stimulus that lacks looming (i.e., an isotropic change in retinal image size) is replaced with a small dot, vergence eye movements become an effective depth cue. We concur with Howard's (2008) assertion that a small dot with unchanging retinal size is less likely to indicate a stationary stimulus than larger stimuli. In the present study the small dot, like the random-dot field, kept the same retinal image size. An explanation is thus needed as to why the large random-dot field was perceived as being fixed in space while the small dot was not. Our yet unpublished data provide a partial explanation: the discriminability of a difference in retinal size is a function of stimulus size, that of a small dot is poor compared to that of a large one (i.e., Weber's law fails at the extreme end of the stimulus size range). Whatever the eventual explanation, the findings of the studies reviewed in the introduction are consistent with our claim. Studies using small stimuli found that vergence is a cue to depth, whereas studies using large stimuli found that vergence is not.

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