[Invited Talk] The perceptual consequences of vergence eye movements

A brief review

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Abstract Vergence eye movements are a key factor in stereoscopic depth perception. In this brief review I will outline work at York University on select aspects of the relation between vergence and stereopsis, sensory fusion and depth constancy.

Key words Vergence, depth perception, distance perception, eye movements, depth constancy, fusion

1. Introduction

Of the classical five types of eye movements classified by Dodge (1903), four – saccadic, smooth pursuit, optokinetic and vestibulo-ocular eye movements—were conjunctive movements where both eyes moved in unison and in the same direction. In contrast, vergence eye movements are disjunctive eye movements where the two eyes move in opposite directions. In this review I concentrate on our work and to a limited extent on work of others exploring the consequences and uses of vergence for perception.

2. Types of Vergence

Vergence was traditionally thought of as an eye movement system independent from conjugate eye movements and rather slow. Research has shown the situation is more complex, for example saccadic and smooth pursuit eye movements can have adaptable disjunctive components (Maxwell & Schor, 1994; Schor, Gleason, & Horner, 1990), short latency vergence similar to short latency ocular following can be elicited with suitable conditions (Busettini, Fitzgibbon, & Miles, 2001), and vergence may influence the characteristics of the vestibular ocular reflex (Paige, Telford, Seidman, & Barnes, 1998). Vergence is also both influenced by and influences perception: in this review I am mainly concerned with disparity-evoked vergence eye movements and their relationship to binocular single vision.

The unqualified term 'vergence' usually refers to horizontal vergence where the eyes make oppositely directed lateral eye movements, for instance one eye rotating leftwards and the other rightwards. Nasal-ward movement of both eyes (left eye rightwards and right eye leftwards) it is known as convergence since the eyes become increasingly crossed; temporal-ward movement is known as divergence. Vergence can be driven by a number of stimuli including disparity, accommodation (blur), apparent depth/distance and this has led to various classifications of horizontal vergence such as fusional vergence, voluntary vergence, proximal vergence, accommodative convergence and so on (for review see Howard, 2012).

The eye does not just move laterally and is potentially capable of three degrees of freedom of rotation. Donders and Listing discovered in the 19th century that these degrees of freedom are

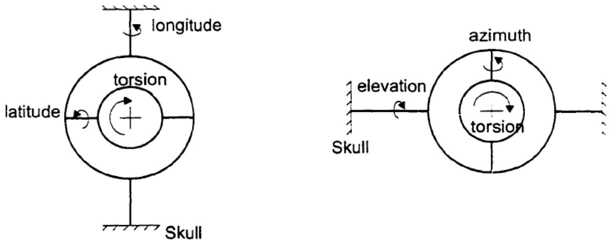

Figure 1- Vergence eye movements in terms of two common co-ordinate systems. In Fick's system (left-hand side), the eye is conceptually rotated first about a vertical axis first, then about the horizontal axis that moves with the eye in a gimballed fashion. In Helmholtz' system (right-hand side) the order is reversed with elevation rotation proceeding azimuth rotation. In both eye movement systems, the horizontal and vertical movements can be followed by a rotation about the resulting optic axis (torsion). Horizontal, vertical and torsional vergence result when the eyes make these respective movements differentially in the two eyes.

typically constrained so that the eye has a definite posture for a given gaze direction (Westheimer, 1981). Nevertheless these three degrees of freedom of movement of the eyes can be described as combinations of lateral, vertical and torsional eye movements in a suitable coordinate system (Figure 1) or by other standard ways of representing 3 degree-of-freedom rotation such as rotation matrices or quarternions (Westheimer, 1957). Disjunctive horizontal, vertical and torsional movements are known as horizontal vergence, vertical vergence and cyclovergence, respectively.

3. Motor Fusion

One of the primary functions of vergence is to support the attainment and maintenance of binocular single vision. To be seen singly, the images of an object in the two eyes must be brought into register (toward being formed on corresponding points on the two retinas) until they are within a limited range of disparities that can be perceptually fused (Panum's fusional area). Fusional vergence eye movements accomplish the task of reducing large disparities by re-aligning the eyes on targets of interest. Thus, horizontal vergence aids fusion of objects at various distances; on the other hand, vertical and cyclo-vergence maintain the overall relative alignment of the two eyes and compensate for phoria. Perhaps then it is not surprising that the dynamic responses of vertical vergence (Howard, Allison, & Zacher, 1997) and cyclovergence (Howard & Zacher, 1991) are relatively sluggish responding well to low frequency changes with gain falling and phase lag increasing after 0.5 Hz. While horizontal vergence tracking has similar dynamics, the response to steps or rapid ramps of disparity have a transient, fast component that brings vergence rapidly toward the target (Semmlow, Hung, & Ciuffreda, 1986). This difference in dynamics matches well to function: vertical vergence and cyclovergence act to maintain continuous alignment while horizontal vergence must change often to acquire and track objects of interest.

Similarly, given the primary roles of horizontal vergence for selecting targets in depth and that of vertical and cyclovergence in eye alignment, it is not surprising that we have found that the spatial integration area of horizontal vergence is much smaller than that of vertical and cyclovergence (Allison, Howard, & Fang, 2004; Howard, Fang, Allison, & Zacher, 2000). Vertical vergence seems to sum disparities over large portions of the visual field to produce an average vertical disparity signal that indicates eye misalignment. As a result of this spatial averaging, a small target with a disparity beyond the range of sensory fusion may be fusible in isolation but not when placed against a zero-disparity background (Allison, Howard, & Fang, 2000). In contrast, while horizontal vergence responds to peripheral stimuli (Howard et al., 2000), it is well-known that subjects can selectively converge on a target in the presence of objects with different disparity (for a recent example see Allison et al., 2004).

4. Distance Perception from Vergence

The vergence required to fixate an object binocularly is a simple function of the object's distance, D:

$$v = 2\arctan\left(\frac{a}{2D}\right)$$

for an observer with interocular separation of a. Scholars of vision have long realized that this relation could be inverted and distance obtained if vergence were known (for example, Descartes, 1897).

The signal or correlate for vergence could be based on eye muscle proprioception (Steinbach, 1987), efference copy, or retinal correlates such as vertical disparity (Gillam & Lawergren, 1983; Mayhew & Longuet-Higgins, 1982). Eye muscle proprioception is notoriously hard to demonstrate in humans and, like efference copy, likely to be of limited precision. The nonlinear relation between vergence and distance means that vergence changes very little beyond about 2 m and 70% of the total physiological range of vergence is within 1 m of the observer (Howard, 2012 pg. 481). In agreement with these geometrical considerations studies have generally found the influence of vergence on distance judgments to be limited to distances of less than 1-2 m (Tresilian, Mon-Williams, & Kelly, 1999).

Patterns of vertical disparity provide an alternative means to provide a distance correlate. Vertical disparity is only useful as a distance cue with a spatially extended stimuli and complements vergence for distance estimation at a near range (Bradshaw, Glennerster, & Rogers, 1996).

5. Depth Perception from Vergence

While distance perception from vergence has limited range and precision it is possible that vergence changes when fixating between different stimuli, or while tracking a moving stimulus, could signal relative depth. Historically this was the logic behind early oculomotor theories of stereopsis (Brücke, 1841) that were not tenable in the light of demonstrations of stereopsis with short duration stimuli, steady fixation and other experimental evidence. Nevertheless, while vergence is not necessary for stereopsis from fused disparate stimuli it could contribute.

Erkelens and colleagues (Erkelens & Regan, 1986; Regan, Erkelens, & Collewijn, 1986) presented compelling evidence against the use of vergence change in the perception of motion in depth. They oscillated a pattern (similar to that in left hand panel of Figure 2) back and forth in opposite directions in the two eyes to drive vergence. Surprisingly, they found that, despite large changes in vergence, their subjects perceived no motion in depth. We replicated and extended these experiments using the stimuli in Figure 2 (Gonzalez, Allison, Ono, & Vinnikov, 2010). Like Howard (2008), we found that stimuli designed to minimize conflict with unchanging size cues (looming) did produce motion in depth from changing disparity (Figure 3). Furthermore, this was true whether the eyes tracked the stimulus or not and that changing

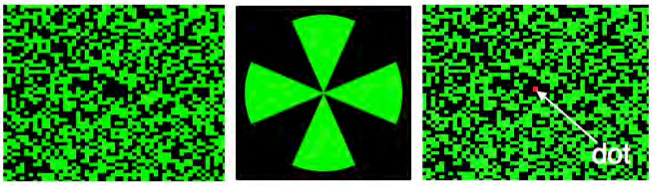

Figure 2 - Stimuli used by Gonzalez et al (2010). The patterns were presented dichoptically with nothing else in view. To simulate motion in depth they were oscillated back and forth in opposite directions in the two eyes and/ or made to expand and contract periodically. The random-dot texture (left) subtended 18.6º and contained features that supported both changing vergence and looming cues. The radial grating (middle) extended beyond the viewing aperture and thus did not appear to change when looming. Finally the dot was small and did not loom appreciably. The dot and random-dot pattern in some conditions were presented together (left) and their motion-in-depth cues independently varied. . Figure reproduced from Gonzalez et al. (2010).

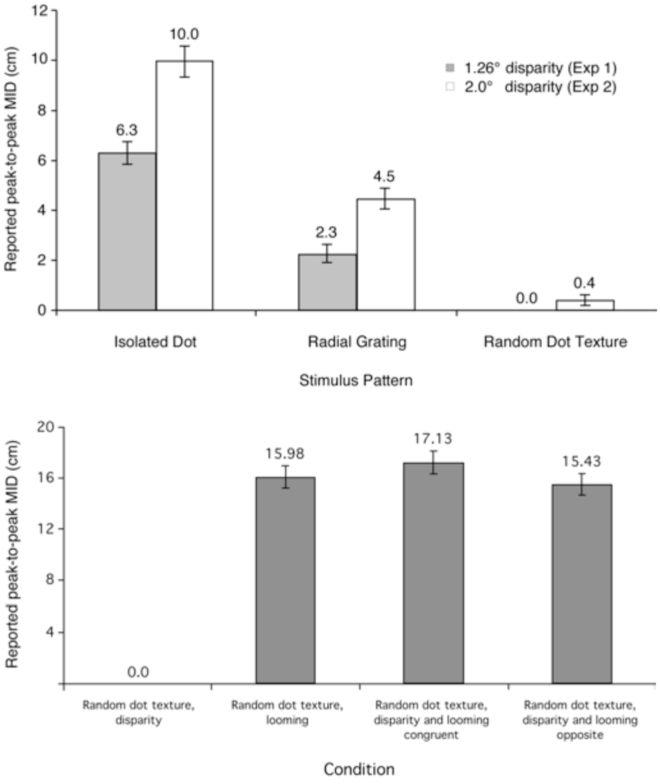

Figure 3 - Top shows perceived peak motion in depth for the patterns in Figure 2 when undergoing oscillating change in disparity. No motion in depth was perceived with the random-dot stimulus that had conflicting (unchanging) size cues while robust motion in depth was found for stimuli with size cues that were undefined (radial grating) or too small to perceive (isolated dot). Bottom shows perceived motion in depth for the random dot texture for different combinations of looming and disparity/vergence cues. Looming cues dominated the disparity cues with this stimulus. Note that motion in depth was in the direction of the looming rather than disparity cue when the two cues were opposed. Figure reproduced from Gonzalez et al. (2010).

disparity, not vergence per se, was the effective stimulus. When we combined changing size and changing vergence cues we found that the monocular cue of looming, when present, strongly dominates the percepts for motion in depth in isolated stimuli. When motion in depth was specified in one or both elements of a composite display containing both a dot and a textured pattern, relative disparity was much more salient than absolute disparity. It appears that relative disparity is a robust indicator of relative motion in depth. In contrast, absolute change in disparity appears to be a weak indicator of motion in depth of an isolated stimulus or when it can be discounted by conflicting looming.

Recently the late Prof. Howard built the dichoptiscope (Figure 4), a unique device that enables precise control of vergence demand and other cues to motion in depth. The device relies on real physical props as stimuli and precision mechanisms to provide dynamic cues. This allows users of the device to present all cues to motion-in-depth with high fidelity, while achieving independent control over each of the dynamic and static depth and motion-in-depth cues (Howard, Fukuda & Allison, submitted). This flexibility should allow for the study of many aspects of motion-in-depth perception that have not been previously investigated.

6. Is Vergence Required for Depth from Diplopia?

Ogle (1950) and others have noted that large disparities, beyond the range of sensory fusion, can still produce the perception of depth at least until an upper limit where stereopsis is lost. Recently we have investigated whether the perception of depth can be elicited by diplopic stimuli in the absence of vergence eye movements (Lugtigheid et al., submitted). In our basic manipulation we formed dichoptic afterimages on the retinas using a photographic flash. These allowed us to produce retinal disparity stimuli that persisted but did not change when the eyes moved. All our subjects were able to make quantitative estimates of depth from diplopic stimuli under these conditions leading us to conclude that vergence is not required to perceive depth from large diplopic disparity.

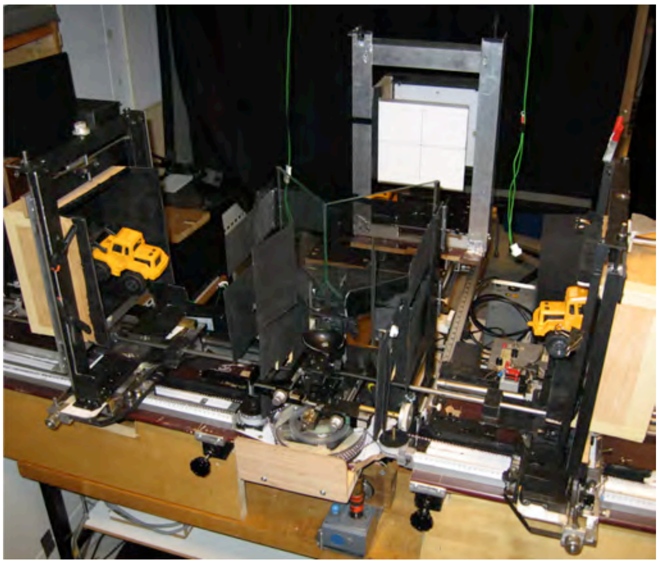

Figure 4 - The dichoptiscope, a unique apparatus for studying motion in depth designed by Prof. I. P. Howard. The device is unique in many respects including the ability to vary the disparity in stereoscopic views of real objects. In this case the object in question is a plastic model of a vehicle.

7. Depth Scaling

Assuming targets near the median plane of the head, an approximation for the retinal disparity produced by a given depth interval (d) between two targets at distance (D) is:

$$disparity = \frac{ad}{D^2}$$

therefore, for a constant depth, disparity decreases with distance squared.

Stereoscopic depth constancy refers to the ability to perceive a given depth interval as constant, despite large changes in disparity at different viewing distances. As such it implies compensation for this quadratic dependence on distance. Vergence and vertical disparity have long been thought to be sources of the distance information used for this scaling. However, our recent demonstration (Allison, Gillam, & Vecellio, 2009; Palmisano, Gillam, Govan, Allison, & Harris, 2010) of substantial stereoscopic depth constancy at distances of 10's of metres suggests that, in fact, vergence is not required for depth constancy although it likely plays an important role within reach space (Figure 5).

8. Conclusions

I have reviewed recent work in my lab (and that of my

Figure 5 – Recent studies of stereoscopic depth constancy with targets at distances of between 4.5 and 200+ m were performed in large spaces, including a long laboratory (left, image from Allison et al., 2009) and a converted railway tunnel (right, image from Palmisano et al, 2010). Careful control of the target configuration ensured that only disparity cues were available to signal relative depth between the two LED targets. These targets can be seen through a slit in the black drape on the left hand side (barely visible in the photo due to their small size). The right hand side shows an elevated view with drapes removed so that more of the LED targets can be seen (only a single pair would be visible to the subject through a narrow slit). By controlling lighting we could provide rich distance cues to the layout of the surrounding environment while still restricting depth cues between the targets to disparity alone. When such cues were provided, considerable but imperfect stereoscopic depth constancy was achieved for target configurations starting at up to 40 m and with depth separations of up to 248m, well beyond the range of vergence as a distance cue.

colleagues at York University) on a few aspects of the relation between perception and vergence; but have only touched on a portion of our work on these problems and given little attention to the important and exciting work of other labs. Furthermore important aspects of the relation between vergence and perception—including visual direction; the role of perception in driving vergence; interactions with other eye movement processes; adaptation, learning and development; cognitive influences; vergence and ambiguous stereoscopic stimuli; neurophysiological correlates; cue conflict and visual fatigue; and the general role of vergence in space perception—were left untouched. It is clear that while vergence is an important factor in stereopsis, depth and distance are not simply derived directly from vergence state. Vergence and retinal disparity are interpreted in concert in a flexible manner and these signals are interpreted in the light of other information about spatial layout.

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