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Vergence in reverspective: Percept-driven versus data-driven eye movement control

Michael Wagner [a], Walter H. Ehrenstein [b], Thomas V. Papathomas [c,*]

[a] Ariel University Center of Samaria, Ariel, and Smith Psychobiology Laboratory, The Hebrew University, Jerusalem, Israel
[b] Leibniz Research Center for Working Environment and Human Factors, University of Dortmund, Germany
[c] Rutgers University, Laboratory of Vision Research and Department of Biomedical Engineering, 152 Frelinghuysen Road, Piscataway, NJ 08854-8020, USA

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ABSTRACT

'Reverspectives' (by artist Patrick Hughes) consist of truncated pyramids with their small faces closer to the viewer, allowing realistic scenes to be painted on them. Because their pictorial perspective reverses the physical depth arrangement, reverspectives provide a bistable paradigm of two radically different, competing depth percepts, even when viewed binocularly: points that are physically further are perceived to be closer and vice versa. The key question addressed here is whether vergence is governed by the physical and/or the perceived depth of fixated targets. Vergence eye movements were recorded using the *EyeLink II* system under conditions optimized to obtain both the veridical and illusory depth percepts of a reverspective. Six gaze locations were signaled by LEDs placed at strategically selected depths on the stimulus surface. We obtained strong evidence that stable vergence fixations were governed by the percept: for the same LED position, eyes converged under veridical depth percepts and diverged under illusory percepts, thus rendering pictorial cues to be as effective as physical cues in vergence control. These results, obtained with *stable* fixations, do not disagree with earlier studies that found *rapid* fixational eye movements to be governed by physical depth cues. Together, these results allow us to speculate on the existence of at least two eye movement systems: an automatic, data-driven system for rapid successions of fixations; and a deliberate schema-driven vergence system that accounts for stable fixations based on the perceptual state of the observer.

Binocular vergence eye movements provide the mechanism of range-finding stereopsis. The eyes converge or diverge so that the two visual axes intersect on the point of interest and the retinal images of a fixated region approach zero disparity at all viewing distances. The images of an object outside the plane of fixation have a disparity with a sign that depends on whether the object is nearer or farther away than the fixated object. Vergence eye movements thus subserve proper binocular fixation and fusion. Traditionally binocular disparity and retinal image blur are considered the primary physical stimuli to the vergence and accommodation eye movement systems [13].

Few reports, however, show that vergence eye movements may be evoked by stimuli that give the impression of being nearer or further than the point of convergence, in the absence of disparity or accommodation cues. This type of vergence movements has been labeled "proximal vergence" (Howard [12], p. 386). For instance, Enright [8] found that subjects converged when an apparent near part of the drawing of a cube was monocularly fixated and diverged when an apparently far part was fixated. In this case the cue to depth was provided only by perspective. Vergence movements were also elicited in the closed eye when the gaze of the open eye changed from a part of a painting that depicted a near object to a part that depicted a far object, suggesting that vergence changes were "appropriate for the distance relationships implied in the illustration" [7]. Ringach et al. [19] used the kinetic depth effect (KDE) to study the same issue. They reported that, under monocular viewing, observers' vergence eye movements were governed by the perceived depth that was elicited by the KDE, rather than the veridical depth. Further evidence for proximal vergence was presented by Liu et al. [15] who were able to elicit vergence by horizontal phantom stereograms (relying on partial occlusion rather than on contrast-defined binocular corresponding features). Sheliga and Miles [21], using Ogle's "induced size effect" to dissociate depth and disparity (a flat surface in the frontal plane appears slanted about a vertical axis when the image in one eye is vertically compressed relative to the image in the other eye), found some vergence that depended on apparent depth, although this vergence was weaker than that due to disparity cues. A similarly weak effect

* Corresponding author. Tel.: +1 732 445 6533; fax: +1 732 445 6715.
E-mail address: papathom@rci.rutgers.edu (T.V. Papathomas).

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of vergence eye movements is elicited by a slanted plane "Werner illusion" [1]. In a visual exploration task, Ehrenstein and Wagner [6] compared vergence eye movements to targets presented on a frontoparallel surface with perspective cues that afforded ambiguous, coplanar, or depth, percepts with marked intersubject variability. Substantially smaller vergence changes were found for "coplanar" perceivers compared to "depth" perceivers, suggesting that vergence reflects perceived depth. Similarly, Hoffmann and Sebald [11] found vergence changes while observes fixated a hollow mask under different viewing conditions, taking this as evidence that eye vergence is susceptible to the hollow-face illusion. Conversely, Wade et al. [25] reported that fluctuations in perceived depth did not correlate with changes in vergence. Moreover, Wismeijer et al. [26], using a Wheatstone stereoscope and a rivalry slant stimulus [9] to further dissociate depth perception itself from both monocular and binocular cues that give rise to perceived depth [23], found that perspective cues, being congruent or incongruent with disparity, caused just a 14% difference in vergence change. They concluded that depth cues, rather than perceived depth, control vergence and further questioned Hoffmann and Sebald's conclusion [11] by pointing to the low-resolution of their eye posture measurements as well as to their insufficient control of the perceptual state of individual subjects that may not warrant a clear conclusion.

The present study uses reverspective stimuli in order to produce competing *physical* depth cues that elicit veridical depth percepts and *illusory* perspective cues that give rise to strong virtual, or illusory, depth percepts [17,24]. "Reverspectives" (by artist Patrick Hughes) consist of truncated pyramids with their smaller faces closer to the viewer such as to allow a realistic scene to be painted on them [24]. With their pictorial perspectives that reverse the physical depth arrangement, reverspectives provide a bistable paradigm of competing depth information [17,18]. The depicted scene contains perspective lines and foreshortening cues, including the streets' texture gradient.

An important reason of the present study is to substantiate our understanding of the two putative distinct pathways in the visual system [22]: namely, a dorsal pathway that is commonly referred to as the "where" pathway, projecting to the posterior parietal cortex (PPT), that is thought to process spatial and movement attributes; and a ventral ("what") pathway, projecting to the inferotemporal (IT) cortex, that presumably processes figural properties of objects and faces. These pathways were further proposed to specify two distinct systems: the primordial dorsal "vision for action" system performs rapid sensorimotor transformations to guide movements and actions for interacting with objects; the more recently developed ventral "vision for perception" system uses more cognitive processes to identify objects and processes their visual properties such as shape, color and brightness [2,16]. One source of evidence for such a putative dichotomy results from experiments in which subjects are asked to handle an object that is subject to an illusory distortion of size, shape, or spatial orientation, as a result of a visual illusion. Some studies report that humans handle the object veridically, i.e., the visual illusion plays no role in their handling task (e.g. Refs. [2,14,16]); they present this as evidence that the "vision for action" stream does not receive input from the "vision for perception" stream. However, other researchers have reported significant influences of visual illusions on grasping and handling tasks [10].

In most of the above studies, the magnitude of the illusory distortion is small (the studies by Hartung et al. [10] and Kroliczak et al. [14] are exceptions); thus, the illusory percept deviates only slightly from the veridical percept and this may account for the continuing debate. The advantage of our stimuli is that the illusory depth percept is drastically different from the veridical depth, thus enabling us to draw strong conclusions. Our research concentrated on the vergence eye motor system, asking the same fundamental

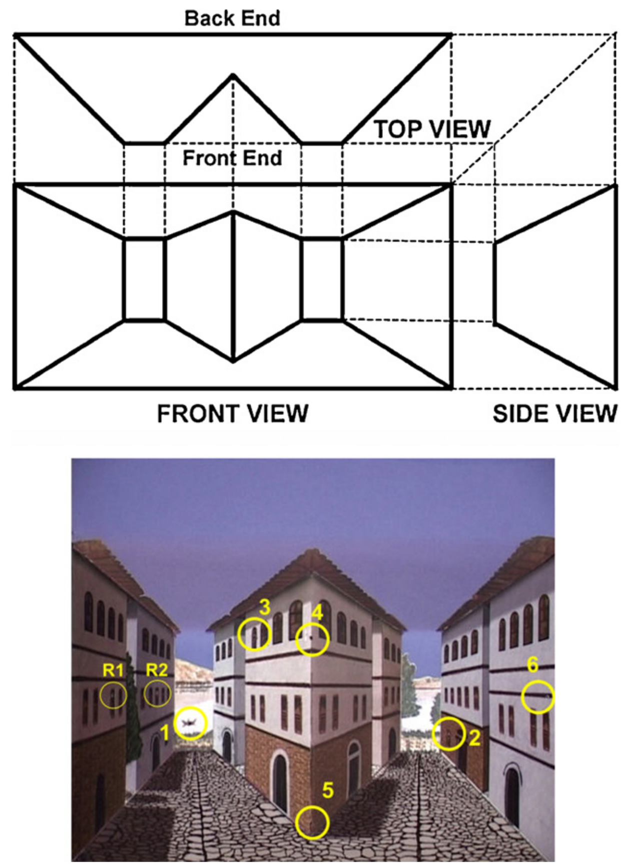

Fig. 1. (a) Front, side, and top orthographic projections of the reverspective stimulus employed in the experiment. (b) Subject's view of reverspective. The six fixation locations are signaled by embedded LED's within the center of the circles. Locations 1–6 are arranged in ascending order of real distance, whereas pictorial depth cues, as indicated in this 2D representation, suggest a reverse distance relation. Locations R1 and R2 served for testing the observer's depth percept, or mode (veridical versus illusory). With a "real" percept, R2 appeared closer than R1, whereas with an "illusory" percept R2 appeared to be more distant than R1.

question, namely whether this system is governed by the illusory or the veridical depth in ambiguous stimuli. We selected a three-dimensional (3D) bistable stimulus that offers a prime opportunity to study this question because it elicits two stable depth percepts that differ radically. Thus we have a case where observers that are presented the same physical stimulus can maintain one of two stable percepts for several seconds at a time, allowing us to measure precisely the vergence angles for strategically selected points on the stimulus surface.

The front, side, and top orthographic projections of our stimulus are shown in Fig. 1a; the frontal view of the actual stimulus "Kastoria 2005" is shown in Fig. 1b (reverspective).

The reverspective 3D model, constructed by cardboard, was attached to a 70 cm × 80 cm black background board. Target distances were measured between the subject's eyes and reverspective background board. The two model pyramids protruded 10 cm from the background board.

To obtain convincing evidence for the behavior of the vergence eye movement system, we used a series of strategically selected targets on the 3D surface (locations 1–6 and the two fixation references, R1 and R2; see Fig. 1b). Since the vergence angle for a point that is veridically fixated is negatively correlated to its distance from the observer (the more distant the point the smaller the vergence angle), a plot of the vergence angles will give a "signature" of the depth structure of the veridically fixated object. To examine the behavior of vergence eye movements under the virtual, or illusory, percept we planned to assess whether, and how, this signature changes when the viewer perceived the illusory depth. In this case points nearer the observer appear to be further than points that are physically further away so that convexities and concavities are transformed into concavities and convexities, respectively. Thus, if vergence movements are governed by the illusory percept, then the pattern of the signature plot is predicted to look like a mirror-reflection of its veridical version; if, on the other hand, these eye movements are only driven by the veridical depth, independently of the percept, then the pattern of the signature plot should remain the same.

The "reverspective" was mounted on holders that could slide along the middle path of a 2.3-m long table. A 120 cm × 80 cm black board was mounted at the table end nearest to the subject, with a 40 cm × 30 cm aperture at its center, containing the LCD calibration screen of the *EyeLink II* system. The screen could be flipped downwards to expose the stimuli, with their centers aligned to the subject's straight-ahead line of sight. A chin-rest was used to keep the subject's head stable. PL-C lamps (13 W) were used for ambient illumination in order to avoid shades and to provide similar brightness levels at all stimuli distances. Except for the ambient illumination the experimental room was dark, with walls covered by black curtains.

All of the observers were naïve in that they had never seen any of Hughes's reverspectives and did not know the scientific purpose of the study. Subjects (6 males and 1 female, aged between 22 and 30) had normal vision; they were screened for visual acuity (LogMAR), stereoscopic vision (recognition of RDS figures), binocular balance (PTIB, [20]) and eye preference (hole-in-the-card test [5]). Experiments were conducted in accordance with the Declaration of Helsinki; all procedures were carried out with the adequate understanding and written consent of the subjects.

Vergence eye movements were recorded at a sampling rate of 500 Hz by means of an *EyeLink II* system comparatively for binocular reverspective conditions (optimized to obtain either illusory or veridical depth percepts). The calibration screen resolution was 1280 pixels × 800 pixels. During binocular calibration, each eye was calibrated separately, including an additional corneal-reflection measure option, to enhance accuracy. Gaze locations were signaled by LEDs, inserted in 6 positions on the model. Following the standard calibration procedure performed at an eye-to-screen distance of 50 cm, the screen was flipped downwards revealing the "reverspective". In addition to this standard calibration, vergence measures were taken for each participant for an individual distance calibration across a range of 80–200 cm. In this case subjects had to fixate a fixation-cross presented for 7 s at 7 distances, i.e., within steps of 20 cm across the distance range twice (in an ascending and descending order). Individual measures were found to be fairly stable, especially in the experimental distance range (100–140 cm).

Each one of the 6 fixation locations was signaled twice in random order (10 s intervals introduced by an auditory warning beep of 400 ms); immediately afterwards, an LED was activated on one of six locations for 2 s and was turned off, followed by an interval of 5 s, during which Ss' were asked to further fixate at the signaled location and inspect the immediate neighborhood for texture details while maintaining fixation, until the next beep indicated the next location to be signaled.

Illusory or veridical percepts were reported verbally and, in addition, tested by using the LED pair R1–R2, for which subjects had to decide which location appeared closer (R2 is veridically perceived as closer, and illusorily as farther than R1).

All participants were first introduced to the "reverspective" at a distance of 160 cm. This distance is far beyond the critical distance at which illusory depth percepts might turn over to real depth percepts (see Papathomas [17]). Thus we ensured that subjects could obtain illusory depth percepts. The following 3 distances were introduced in a decreasing sequence: 140, 120, and 100 cm (distance measures are between observer's eyes and the reverspective background board). Participants were first introduced to the experimental room, performing chair, chin-rest, and EyeLink head-set adjustments. During the initial reverspective exposure at a distance of 160 cm, participants received instructions (to direct their gaze to scene locations signaled by the LED's), and were asked to describe orally the displayed scene, referring to relative depth of scene details. Then the screen was up-folded for EyeLink calibration and "drift correction" procedures and down-folded again to start a session. Drift corrections were performed at the beginning of each trial. Drift corrections are based on computing and applying a corrective offset to the raw eye-position data. These procedures were repeated before each experimental session (at distances of 140, 120, and 100 cm).

The data recorded by the *EyeLink II* system were analyzed off-line by a *MATLAB* program which selected the simultaneous binocular fixations ("dual fixations") corresponding to the various LED-signaling periods. Vergence measures were obtained from the Lx-Rx gaze data (in pixels), measured on the calibration screen surface during trials ("virtually", since the real screen was folded down during trials). Dual fixations of less than 15 ms durations were filtered out (mean number of fixations during pairs of LED signaling periods was 21.15; S.D. = 8.4).

Raw vergence data (in pixels) were transformed into gaze distance and vergence angles by linear interpolation, based on individual distance calibration charts. This calculation was based on the following parameters:

(A) physical distance measured between each of the 6 fixation positions on the Reverspective model and the observer's eyes (cyclopean eye location), in the 3 distance conditions (100, 120 and 140 cm.); (B) inter-pupil distance (IPD) for each observer; (C) accurate distance between the observer's eye and the calibration screen; (D) display screen parameters, based on the vergence angles obtained in the experiment.

These converted data were subjected to a 3 × 6 × 2 within participants multiple analysis of variance (MANOVA) with the following factors: viewing distance (100, 120, 140 cm), perceptual mode (real versus illusory depth) and fixation position (1 to 6). Viewing distance was the only significant main factor ($F(2, 40) = 22.4$, $p < 0.001$) and, among the interactions, perceptual mode × fixation position was highly significant ($F(5, 100) = 5.16$, $p < 0.001$). This interaction indicates that participants fixated to different depths, depending on their percept mode. Under the illusory percept, participants tended to fixate at a more distant location (at near LED locations 1 and 2), following the pictorial depth cues, instead of following real depth cues. At far LED locations (4–6) vergence curves reverse in that now participants fixated at a closer distance when their percepts were guided by pictorial rather than real cues with a crossing of curves at a middle LED distance (3). Fig. 2 shows the means and standard errors for the calculated vergence distances for *illusory* (*virtual*) versus *real* perceptual modes and the 3 distance conditions. Actual depth, depicted for reference, is slightly increasing with fixation position (their numbers are arranged in ascending order). Vergence measures indicate that, on average, participants directed their gaze at a shorter than actual distance for the 100 and 120 cm conditions, whereas they were pretty much in the range of actual distances for the 140 cm condition. Such errors in binocular fixation have been reported as common under natural viewing conditions [3]. Apart from this underestimation of distance for the 100 and 120 cm conditions, vergence profiles for the three experimental distances are quite similar in their reverse trends for real and illusory perceptual modes. This is also reflected by high negative

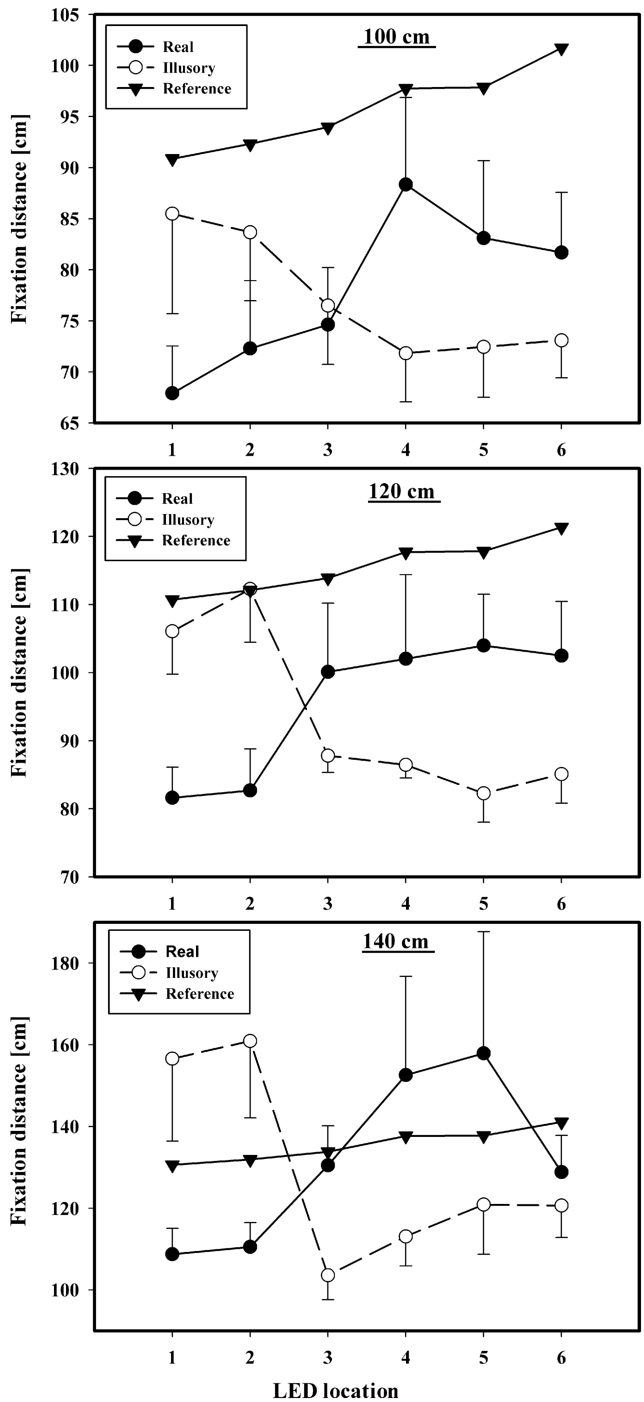

Fig. 2. : Mean calculated fixation distances for *illusory* versus *real* depth percepts (error bars indicate standard error), in the three distance conditions (a: 100 cm; b: 120 cm; c: 140 cm), for the six fixated LED locations on the reverspective. The actual eye-LED distances (arranged in ascending order) are given as *reference* (triangles). Note that depth is always physically the same for both real and illusory percept conditions. Vergence profiles for the three experimental distances are quite similar: the trend for vergence under the illusory percept is the reverse of that obtained under the real percept.

Pearson correlations: $r = -0.93$, $r = -0.98$, and $r = -0.74$ (for 100, 120, and 140 cm distances, respectively). As can be seen, vergence seems to follow either the real depth or, to almost the same extent, the illusory depth, depending on the percept obtained by the viewer.

Our results confirm and extend those of Hoffmann and Sebald [11]. Whereas they only used one vergence target, we strategically selected several targets on the 3D surface. Comparison of the pattern of results under the veridical and the illusory depth percepts enables us to obtain strong evidence for the behavior of vergence eye movements, when observers view identical stimuli, but obtain drastically different percepts. We recognize that a much better way to address this issue, as one reviewer suggested, would be to use an eye coil or a DPI system for tracking eye position. Nevertheless, the EyeLink system is very competitive for eye tracking [4]: 500-Hz sampling rate; three overlapping measurement modes (pupil, corneal-reflection, frontal LED tracker). EyeLink can assess individual eye positions, rather than just vergence angles. This can address, in future studies, the question of whether one eye, perhaps the dominant one, fixates accurately, while the other eye is misaligned or, alternatively, whether both eyes are misaligned.

Our findings are also in agreement with those of Sheliga and Miles [21] and Both et al. [1]. The former obtained evidence that the perceived depth influenced open-loop gaze shifts, despite the presence of binocular disparity signals; they estimated that, depending on conditions, the perceived depth accounted for 15–41% of the vergence. The latter showed that disparity signals were dominant in determining saccadic eye movements, but perceived slant also played a role.

At first sight, our results appear to disagree with those of Wade et al. [25], who failed to obtain correlations between vergence and perceived depth, and Wismeijer et al. [26], who reported that vergence responses slightly depended on perspective cues, but concluded that they are governed mostly by binocular disparity, irrespective of the perceived depth. However, on closer examination, the fact that our data exhibited a much stronger dependence on perceived depth than in their experiments may be attributed to the time scale used for monitoring eye movements. We analyzed fairly long, *stable fixation* times that could enable later processing stages in the eye movement control to develop their impact, whereas they monitored rapid successions of fixational vergence movements. Indeed, the preparation of a saccade lacks the constant feedback present during stable fixation.

On the issue of whether the “perception-for-action” system is fooled by visual illusions: it seems that, in our case, it is. Vergence eye movements appear to be a special case of motor control processes that are subject to inputs from cognitive processes, in contrast to reports on grasping movements that appear to be unaffected by such cognitive influences [2,9,16]. In fact, the results of our study, taken together with those in [25,26], allow us to propose two eye movement systems: an automatic, data-driven system that produces a rapid succession of fixations without much top–down influences; and a deliberate, slow, schema-driven vergence system that accounts for stable fixations based on the perceptual state of the observer.

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