Review: Binocular double vision in the presence of visual field loss

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Binocular double vision in strabismus is marked by diplopia (seeing the same object in two different directions) and visual confusion (seeing two different objects in the same direction). In strabismus with full visual field, the diplopia coexists with visual confusion across most of the binocular field. With visual field loss, or with use of partial prism segments for field expansion, the two phenomena may be separable. This separability is the focus of this review and offers new insights into binocular function. We show that confusion is necessary but is not sufficient for field expansion. Diplopia plays no role in field expansion but is necessary for clinical testing of strabismus, making such testing difficult in field loss conditions with confusion without diplopia. The roles of the three-dimensional structure of the real world and the dynamic of eye movements within that structure are considered as well. Suppression of one eye's partial view under binocular vision that develops in early-onset (childhood) strabismus is assumed to be a sensory adaption to diplopia. This assumption can be tested using the separation of diplopia and confusion.

Introduction

Double vision is the simultaneous perception of two different images of a single scene, overlapping but shifted relative to each other. Double vision occurs either monocularly because of optical distortion or disease in one eye (Lee & Volpe, 2001) or binocularly because of the misalignment of eyes. Only binocular double vision is addressed in this review.

Binocular double vision is composed of two phenomena – Binocular Diplopia and Visual Confusion (Pickwell, 1989; Pickwell, 1980; Schor, 1977; Stidwill & Fletcher, 2010; von Noorden & Campos, 2001). Diplopia refers to seeing/perceiving the same object in two different directions. This means seeing one copy of an object fixated by the dominant eye (seen centrally) and another copy seen in a different direction by the other, deviated eye (Stidwill & Fletcher, 2010). Binocular visual confusion is an equally important consequence of ocular misalignment, referring to seeing/perceiving two different objects in the same direction, superimposed on each other. Binocular diplopia occurs because images of an object fall on noncorresponding retinal loci in both eyes (Prieto-Diaz & Souza-Dias, 2000; Stidwill & Fletcher, 2010). Noncorresponding retinal loci are associated with different perceived directions. Binocular confusion occurs if, because of eye misalignment, images of two different (salient) objects fall on corresponding retinal loci in both eyes, those objects are then perceived in the same direction (overlapping or superimposed on each other). Binocular confusion is highly related but not identical to binocular rivalry. Confusion is the retinal imaging situation that may result in rivalry—a perceptual phenomenon or in suppression. The rivalry perception is elicited experimentally when images of two (salient) objects are placed on corresponding retinal loci. These can be the two foveas, two peripheral corresponding retinal loci, or an extended portion of the retinas. The two images are usually of similar contrast and typically static.

Having a binocular double vision in the periphery or even pericentrally of objects at distances from the observer sufficiently different from the distance of the fixated object (in the three-dimensional real world) is normal (Bishop, 1981). This physiological double vision takes place over most of the visual volume and does not require misalignment of the eyes; therefore it is a common occurrence. The physiological double vision can be easily demonstrated but is usually not noticed by observers. When looking at a flat scene displayed on a paper or a screen, binocular double vision within the central field is apparent when both eyes are not aligned due to strabismus (Economides, Adams, & Horton, 2012; von Noorden & Campos, 2001), or if a prism

Citation: Peli, E., & Jung, J.-H. (2024). Review: Binocular double vision in the presence of visual field loss. *Journal of Vision*, *24*(6):13, 1–33, https://doi.org/10.1167/jov.24.6.13.

https://doi.org/10.1167/jov.24.6.13 Received November 4, 2023; published June 20, 2024 ISSN 1534-7362 Copyright 2024 The Authors

(horizontally or vertically) is placed in front of one eye. Central double vision is easily noticed by the affected person and is annoying and bothersome, even though it exists across the whole binocularly overlapping visual field. Because of the lack of attention to the periphery, diplopia in the periphery might be less bothersome.

There are two types of misalignments of eyes: phoria and tropia. "Tropia" is a misalignment of the eye that is manifested even with both eyes open and causes binocular double vision (von Noorden & Campos, 2002). "Phoria" is a latent misalignment of the eyes that only appears when binocular vision is interrupted (i.e., by covering one eye) (von Noorden & Campos, 2002). Phorias are relative misalignment of both eyes, whereas tropia is allocated to the nonfixating eye. There are certain types of field loss that prevent binocular fusion, which may cause pre-existing phoria to manifest as a tropia (Kao, Liu, & Yang, 2017; Peli & Satgunam, 2014). The dynamics of vision, such as changes in fixation in lateral and depth directions, further interact with phoria and scotomas. This interaction sometimes results in diplopia only, visual confusion only, neither, or both in cases of misaligned eyes. These situations are the focus of this review. Tropias may be lateral, which are then classified as esotropia (convergent tropia) or exotropia (divergent tropia) (von Noorden & Campos, 2002). Crossed diplopia is experienced under exotropia (the left eye's image is seen to the right of the right eye's image) whereas esotropia causes uncrossed diplopia (Stidwill & Fletcher, 2010). Vertical eye misalignments/tropias are classified as right hypertropia if the right eye is deviating up, in which case the diplopic image of that eye is perceived below the image seen by the fixating left eye. The eye deviation may be rotational (around the visual axis) resulting in torsional strabismus. Further classifications of the strabismus such as alternating, intermittent, and concomitant versus non-concomitant are addressed below, as needed. There are various causes of strabismus. Mechanical strabismus (or paralytic strabismus) is the misalignment of the eye because of inability of the extraocular muscles to control the eye position within the orbit due to neuromuscular disease, surgical effect, or trauma. Uncorrected high hyperopia (farsightedness) may cause accommodative esotropia (turning inward) (Rutstein, 2008). Because the accommodation and convergence controls are linked (accommodation-convergence reflex) (Schor, 1986), when people with uncorrected hyperopia or high accommodation-to-convergence ratio activate accommodation to focus their view, the accommodative effort may cause excessive convergence (turning both eyes too far inward), which may break the fusion and result in strabismus (esotropia) and double vision.

Infantile (or congenital) esotropia and childhood exotropia may be constant or intermittent, and the fixating eye may be alternating. They are the most common, yet their causes are not generally known. These early childhood strabismus conditions are rarely associated with reports of double vision. Children are said to suppress the vision from the deviated eye to avoid double vision (Pratt-Johnson & Tillson, 1984). Suppressing the fovea of the deviated eye eliminates central confusion, whereas suppressing the relevant peripheral retinal location in the deviated eye eliminates central diplopia (Travers cited by Jampolsky, 1955). That extrafoveal point in the deviated eye receiving the image intended for the fovea (Stidwill & Fletcher, 2010) was named "zero-measure point" (Jampolsky, 1955). In exotropia, suppression of the temporal retina in the deviated eye eliminates the central diplopia. Because the fovea of the deviated eye remains perceptually active (Economides et al., 2012), the corresponding temporal retina of the fixating eye is also suppressed to eliminate the pericentral diplopia. Suppression of diplopia plays a key role in developmental strabismus because it eliminates the "error signal" that would normally stimulate vergence to bring the eyes back into alignment (Economides et al., 2012). Because the two eyes' views are angularly shifted relative to each other, the double vision affects every point in the visual field.

Figure 1 illustrates how, generally, binocular diplopia always coexists with binocular visual confusion, and each view of a diplopic object is also confused with other objects. As it may appear in Figure 1, diplopia affects each and every object within the field of view (except near the edges of the images where the view may be monocular). Although it may be less apparent, confusion similarly affects each and every object and point in view.

A typical illustration of the double vision, using the transparency function in image processing software, results in reduced contrast (Figure 1A). However, the actual perception of contrast in binocular double vision is not reduced. Both copies are perceived in full contrast. This can be demonstrated easily by holding a vertical prism in front of one eye causing double vision. To illustrate the binocular double vision with no contrast reduction in print, we mostly use cartoon-like illustrations of the percept diagram in this article (Figure 1B). In the cartoon image, each local line segment is observed on the white blank background in full contrast while cartoon objects (formed by those connected lines) are superimposed and illustrate double vision. The cartoon images also work well to illustrate visual field loss, making them particularly useful in this article. Several conditions will be shown below in which, because of the interaction of double vision with visual field loss, the percept diagram can be simulated at full contrast without resorting to the cartoon presentation.

Although almost all objects in Figure 1 appear to be diplopic (except near the edges of the images), objects

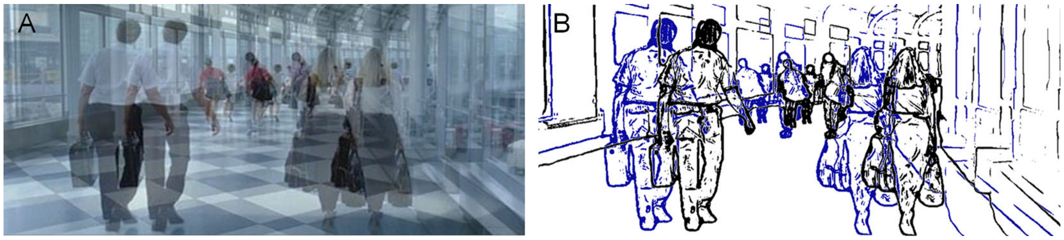

Figure 1. Illustration (percept diagram) of double vision with lateral misalignment of eyes. (**A**) Typical "simulation" of double vision using transparency functions (50%) in imaging applications. The low-contrast appearance of both eyes views is not representative of patient's perception, where both views are perceived in full contrast in binocular viewing. (**B**) Illustration of double vision using cartoons. The cartoons maintain the full contrast of both images. The two colors are not representative of the real views; the blue lines mark the left eye's view. In this illustration, the left eye is deviating to the right (esotropia); hence, the blue scene is shifted leftward (uncrossed diplopia). Binocular visual confusion is also illustrated in both **A** and **B**, where images of two different objects are superimposed, representing them to be perceived in the same direction.

in one or even both copies do not always appear to explicitly be confused (i.e., superimposed) with another object. This may be merely a result of the incidental locations of objects in the image (i.e., overlapping with empty or blank space). As emphasized in the cartoon presentation (Figure 1B), the visual confusion is frequently with part of the white background. This may happen in a natural (non-cartoon) image as well if a salient object is confused with a blank wall or other low-contrast surface. This difference in the prevalence of diplopia and confusion across natural scenes may account for the fact that diplopia rather than confusion is frequently reported spontaneously. It is also likely that the difference in spontaneous reporting is a result of the fact that every attended (fixated) object is always diplopic when the eyes are misaligned. Importantly, fixation is usually at a salient object. However, an attended object may frequently not be confused (because of the visual confusion being with a blank or low-contrast low-salient content). For example, the feet of the diplopic man on the left that seems not to be confused with anything. In fact, if the floor tiles were reproduced in the cartoon diagram, the diplopic man's feet would be confused with these patterns. Note that although resolution and contrast sensitivity decrease with increasing retinal eccentricity, and we have simulated these effects as the perceptual view (Peli, 2002a), to simplify the discussion of double vision, we will not apply them to the illustrations in this paper.

Despite the caveat above, diplopia generally coexists with confusion everywhere in the field of view (Figure 1). However, with visual field loss, there are cases that result in either only binocular visual confusion or only diplopia. Examples of these and the consequences of these effects will be discussed in this review.

Even with normal intact visual fields and without misalignment, both eyes fields of view do not fully overlap. The binocular overlap area may shrink or expand when the eyes are misaligned in exotropia (Figure 2A) or esotropia (not shown), respectively. We distinguish field of view (the portions of the scene that fall on the functioning retina) from visual field (the functional portions of the retina). Although the field of view and the visual field are the same in normal binocular vision, the sizes of the field of view and the visual fields are different in strabismus (i.e., larger field of view in exotropia and smaller field of view in esotropia). Figure 2B is a percept diagram (Apfelbaum, Ross, Bowers, & Peli, 2013) representing the view seen by the patient whose visual fields are presented in the field diagram (Figure 2A). The separation of diplopia from confusion can occur more often with visual field loss or with the use of partial prism. (Partial prism is a prism applied to the spectacle lens and covers only part of that lens so that vision is available within and outside of that prism). The relevance of such separation and its importance will become clearer below. Note that we will use both the field diagram (Figure 2A) and the percept diagram (Figure 2B) to describe double vision perceptions in this article. Field diagrams can show diplopia if it is explicitly measured (e.g., asking the subject to report the appearance of two targets) but do not show confusion because the blank perimeter background does not provide any images of salient objects to be superimposed on the test target. Percept diagrams (Figure 2B) illustrate both confusion (superposition) and diplopia, although noting the diplopia requires searching.

The analysis so far was limited to lateral eye deviations; there are, however, vertical deviations both latent and manifest. We will address these where they make a distinct difference from the lateral deviation conditions. Patients frequently present with combination of lateral and vertical deviation resulting in oblique deviation. Eye deviations may be induced with full prisms in the spectacle lens. High-powered

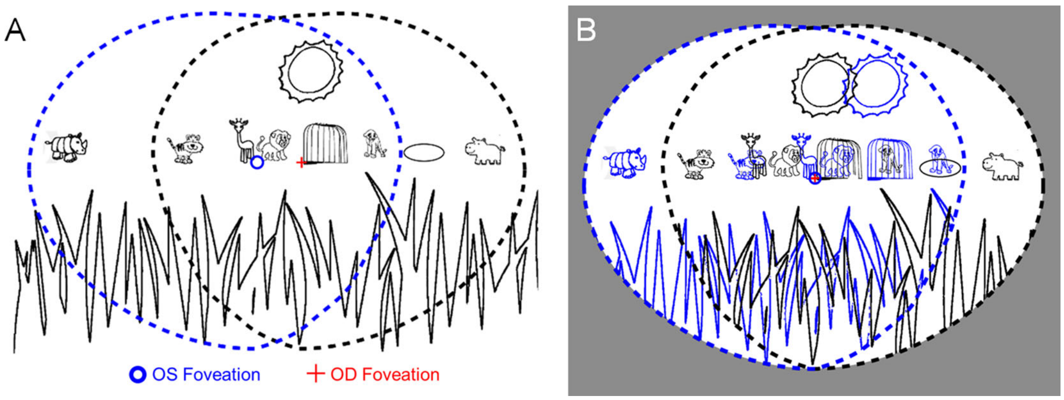

Figure 2. A cartoon of a savannah scene as seen by a patient with 20° (∼40Δ) left exotropia (left eye deviated to left). (**A**) The visual fields of both eyes (field diagram): the left eye's field in blue and the right, fixating eye, in black. The fixation point of the right eye is marked with a + symbol. The foveal direction of the deviated left eye is marked with an o symbol. (**B**) A perception diagram (Apfelbaum et al., 2013) as seen with double vision by that patient. Objects seen by the left eye are shown in blue. Many of the animals are seen twice (diplopia) as they fall on non-corresponding retinal loci. Many of them appear superimposed on others (visual confusion), as different animals fall on corresponding loci in both eyes. The rhinoceros on the left and the hippopotamus on the right are neither seen as diplopic nor visual confusion as each is seen by only one eye, because their images fall on the monocular peripheral crescent fields that have no corresponding retinal loci in the other eye. The elliptical pond is seen only by the right eye, its' image falls on a retina that has corresponding locus in the other eye (where the blue cub is imaged in the left eye), and thus, they appear superimposed. While the cub is also diplopic, the pond is seen only once (no diplopia). The tiger seen by the right eye is also seen by the left eye (diplopic), but the right eye copy appears not to be confused. This is not the case; it is indeed confused with an area of the plain background seen by the left eye, but that confusion is not apparent in the cartoon illustration (blank area).

base-out prisms induce exodeviation, whereas base-in prisms induce esodeviation, and vertical prisms induce vertical deviations. Prism lenses in the spectacles are sometimes used to treat (compensate for) lateral and vertical deviations, or their combination, and their symptoms.

Double vision with severe concentric peripheral field loss (visual confusion only)

If or when the two eyes are misaligned, the diplopia serves as the stimulus for vergence leading to fusion. The eyes could be misaligned when they go into the phoria posture. This can happen when one eye is covered or following change of fixation to an object at a different distance (Peli & McCormack, 1983; Peli & McCormack, 1986). If diplopia is absent because of visual field loss (one of the images falls within a scotomatous area), the eyes have no feedback for alignment and are likely to remain misaligned as a manifest tropia. Such a situation may arise in "tunnel vision," a severely reduced peripheral visual field of both eyes, most commonly occurring in advanced retinitis pigmentosa (RP) and glaucoma.

With sufficiently small residual central fields (frequently referred to as *tunnel vision*), if the two eyes become misaligned and the deviation is large enough (i.e., deviation > diameter of residual field) so that the two eyes' residual fields are not (or just barely) overlapping, the patient is faced with binocular confusion but no diplopia because no object may be seen by both eyes simultaneously (Figure 3). Patients with tunnel vision would manifest tropias under this situation even though they might have been phoric before the field loss. The narrow central residual fields have corresponding retinal loci, but the large deviation makes each eye sees different part of the scene (Figure 3A). Therefore, no objects are seen by both eyes, and thus diplopia (the visual signal for vergence) is missing.

The binocular visual confusion occurring with tunnel vision is central and thus likely to be noticed. Although binocular rivalry may disrupt perception, central to our interest here is that strabismus may result in expansion of the field of view. When the patient may be searching using scanning eye movements with the dominant/fixating eye, other objects of interest may fall into the residual field of the deviating eye and be detected.

As illustrated in Figures 3B through 3E, this effect may help walking patients detect possible collisions with objects near their walking path. At the instance illustrated in Figures 3B and 3C, the largely blank right wall of the terminal seen by the left eye is confused with the salient three people seen ahead by the right eye, but the impact of that binocular confusion on the patient perception is minimal. When the patient gets closer to the people ahead, a few seconds later (Figures 3D and 3E), the proximity "magnified" scene brings the woman's head into the left eye's residual field, making it possible for the patient to detect her presence. Once detected, the patient is expected to scan the scene to examine the detected head with the nondeviating eye. This illustrates the potential utility of the field expansion nature of the visual confusion. The illustrated situation may result in suppression of the deviated eye's fovea; see further discussion of suppression below. The percept diagram in Figure 3E illustrates that, at this later time, the central confusion is highly noticeable and may be disturbing despite the potential usefulness. Calling attention to the important differences between binocular function in the three-dimensional real world compared to the common testing and illustrations that are typically limited to two-dimensional screen or paper images. Additional examples of this distinction with fixation changes in three-dimensional space are presented below.

The eyes of a patient with tunnel vision are likely to frequently dissociate into their phoria posture (i.e., by covering one or both eyes or during a blink) (Peli & McCormack, 1986; Riggs, Kelly, Manning, & Moore, 1987; Stella, 1968). Once the eyes are in the phoria position, if the phoria is large enough relative to the residual fields, the two residual fields may not overlap, making realignment difficult. One such dissociating factor is shown in Figure 4, where fixation is changed from one target to another at a different distance and eccentricity. Such a common change in fixation in the three-dimensional space requires both saccadic and vergence movements and frequently results in one eye not foveating the next target at least for an instant (Alpern & Ellen, 1956; Bahill, Ciuffreda, Kenyon, & Stark, 1976; Kenyon, Ciuffreda, & Stark, 1980). In Figure 4A, the patient with tunnel vision is shown fixating binocularly at the head of the closer person, the woman. One of the three people farther away is also visible within the narrow residual right eye field. When the patient is changing fixation to that farther man, the patient first performs a saccade that shifts the right (dominant) eye's fovea to the farther man. If the patient has full normal visual field, the fixated farther man will be seen diplopically because the patient's eyes are still converging to the closer distance of the woman until the divergence is affected consistent with Hering's law of equal innervation. However, in the presence of tunnel vision, shown in Figure 4B, the fleeting dissociation and deviation after the saccade eliminates said diplopia because the left eye's residual field does not include that right farther man, resulting in manifested tropia. Such events may occur frequently for gaze shifts from

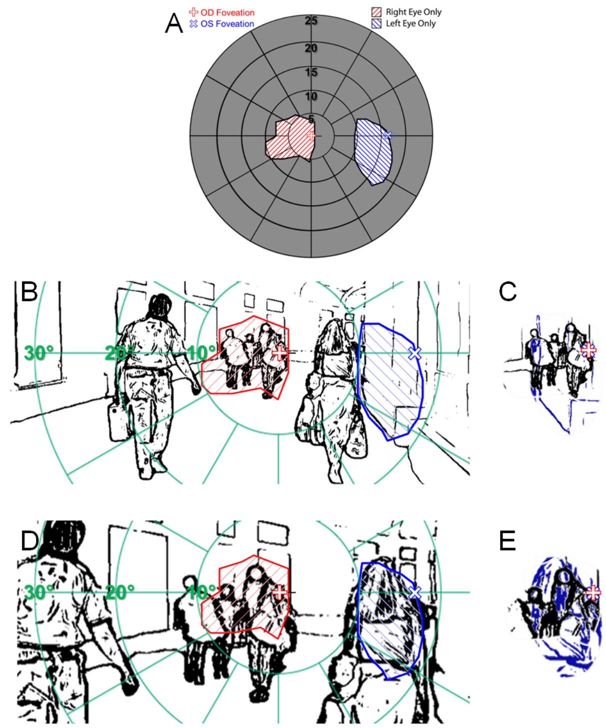

Figure 3. Binocular visual confusion only (without diplopia) in peripheral field loss with strabismus. (**A**) Dichoptic binocular visual field of a patient with peripheral field loss and left manifested esotropia (15°) obtained with a dichoptic perimeter (Woods, Apfelbaum, & Peli, 2010). Because the two eyes' residual central fields have corresponding retinal loci (central field in both eyes) but are not overlapping due to the eye deviation, the patient perceives only the visual confusion without diplopia. Therefore, the field of view with bilateral tunnel vision and tropia is wider than without tropia. (**B**) The dichoptic field diagram depicted in **A** is superimposed over the terminal scene. At that instant, the patient is fixating the group of three pedestrians ahead with his dominant right eye (red outlined) and may not be aware of either the closer man or the woman. (**C**) The percept diagram (patient's view) at that instance. The three passengers seen with the right eye (red edges) are superimposed over the terminal right blank wall and columns (blue edges) seen by the left eye (visual confusion). The lack of details on the blank wall makes this confusion inconsequential. (**D**) The terminal scene a few seconds later with the patient walking forward faster than the other people in the terminal do. The patient will be closer to the people ahead, and the "magnified" scene will move the woman into the left eye residual field. (**E**) The percept diagram at that later instance. Since each eye sees different and salient parts of the scene (two pedestrians and the woman, respectively), the visual confusion gives rise to the potentially beneficial field expansion effect. This, however, will also result in a much more noticeable/disturbing central confusion.

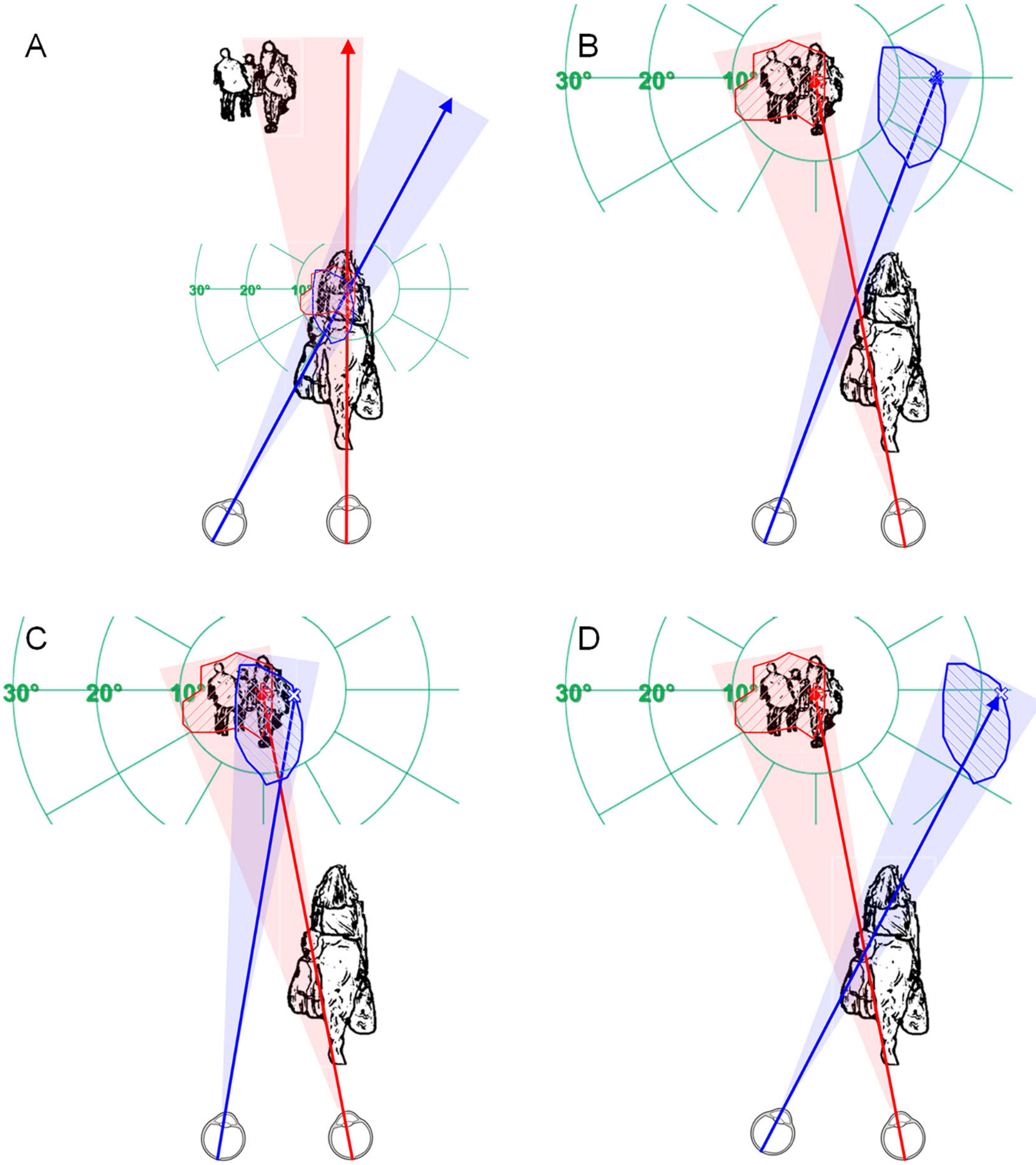

Figure 4. Schematic illustration of a mechanism for the dissociation of the two eyes in tunnel vision because of change of fixation in three-dimensional space. (**A**) Starting from a fixation on the closer woman's head with both eyes fused and with the limited field of view includes both the woman and one of the group of men farther away within the fixating right eye's residual field. (**B**) As the patient changes fixation to the distant man, first saccading with the fixating right eye before any divergence movement may be completed. Under this fleeting situation with tunnel vision, there is no diplopic image of the man in the left eye and the esophoric deviation manifests as a tropia. (**C**) If the patient has a pre-existing exophoria, the left eye will diverge toward the exophoria posture. When the fields of view of both eyes overlap enough to result in diplopia of the right distant man, the binocular divergence will ensue ending with fusion of that farther man. (**D**) The slower divergence movement that should follow to reestablish binocular fixation does not take place if the patient had a preexisting esophoria. If the patient has a preexisting esophoria, the left eye may be drifting to the right or the left, depending on the magnitude of the phoria. The esophoria shifts the left eye farther right and resulting in the confusion only illustrated here and in Figures 3D and 3E.

both near-to-far and from far-to-near. If the patient illustrated in Figure 4 has pre-existing exophoria, the left dissociated eye in Figure 4B will drift to the left toward the phoria posture. On its way, the field of the left eye will overlap the field of the right eye, resulting in diplopia of the group of persons, which triggers binocular fusion at the farther men correctly. If, however, the patient's pre-existing phoria is esophoric of large enough magnitude to keep the two residual fields separated, the manifest tropia will be maintained

(Figure 4D). A similar sequence of events could result in fusion for a patient with pre-existing exophoria on shifting fixation from a far to a near target (Figure 4C).

Once such tropia manifests after a fixation shift, the tropia results in confusion without diplopia, as described in Figure 3 and provides the same field expansion effect illustrated there. However, for exophoric patients, the manifest tropia with the field expansion effect is temporary and may be replaced with binocular fusion, once the eye movements bring the two residual field into apposition triggering diplopia and vergence.

Prevalence of strabismus with tunnel vision

We review the prevalence of strabismus in various field loss conditions where we think that it points to possible causal relationship between the field loss and the manifestation of strabismus in these conditions. The prevalence of lateral strabismus in the USA in the general children population was found to be 4.2% (Chew et al., 1994). In more than 1750 school children (mostly six years old from Sydney, Australia), 2.8% were found to have strabismus (Robaei et al., 2006). In more than 9000 Chinese school children, strabismus was detected in 3.5% of the overall group (Pan et al., 2017). The tropia prevalence in Iranian college students was found to be much lower at 1.5% (Hashemi et al., 2020). Similar prevalence of strabismus would be expected in children with RP before they manifest the field loss of the disease that usually starts in adulthood. The lifetime risk for developing adult-onset strabismus (in Minnesota, USA) was found to be under 4% (Martinez-Thompson, Diehl, Holmes, & Mohney, 2014). Yet, strabismus is highly prevalent in advanced RP (30%, Miyata et al., 2018).

High prevalence of diplopia was also reported in tunnel vision with advanced glaucoma (Sun, Leske, Holmes, & Khanna, 2017). The prevalence of diplopia in those treated medically (11%) was much larger than the prevalence of strabismus in the general population. The prevalence of strabismus was even higher for glaucoma patients treated surgically (21%), suggesting that the post-surgery strabismus was, at least in part, due to mechanical effects. A few case reports articles suggest an association between tunnel vision and strabismus, though they describe the symptoms as diplopia (Gobeille, Patel, Meltzer, & Fischer, 2020; Kao et al., 2017; Khanna & Holmes, 2017). We have shown above that diplopia with tunnel vision is unlikely, although it is not impossible. The use of the term diplopia in some articles may be a result of failing to distinguish the term *double vision* from *diplopia*, although the symptom is mainly visual confusion (where double vision includes diplopia and binocular confusion). A possible mechanism by which severe tunnel vision may lead to manifest tropia in the presence of phoria has been described above (see Figure 4).The high prevalence of strabismus with advance peripheral field loss in RP and glaucoma suggests that the field loss may be the cause of the strabismus development.

Magnitude of strabismus with tunnel vision

In the study by Miyata et al. (2018) of 119 consecutive cases of RP, the mean deviation of strabismus was in advanced RP patients (~7Δ and 14Δ, at far and at near, respectively). The normal population mean distance phoria is substantially smaller, varying from 0.6Δ to 0.3Δ exophoria but is 0.2Δ esophoria for people over 70 years (Palomo Álvarez, Puell, Sánchez-Ramos, & Villena, 2006). This difference between typical magnitude of phoria and strabismus in RP suggests that the magnitude of deviation (in tropia and phoria may be further affected by the (intermittent) lack of fields overlap and fusion.

Following complete continuous occlusion of one eye for about one week, adult patients had substantially increased phorias (Marlow, 1921). Smaller effects were also noticed in cases where the occlusion was occasionally interrupted. After four hours of complete occlusion of one eye, two of the three normally-sighted subjects had a measurable change in their phoria (Peli, 1990). Sethi (1986) reported large changes in horizontal phoria position after only four hours of monocular occlusion for normal observers. When binocular vision was restored, recovery was very fast, at about one minute.

Ellerbrock and Loran (1995) reported significant changes in vertical phoria after less than two hours of occlusion and measurable changes in less than half an hour. In another study, after eight days of continuous occlusion, all subjects developed large phorias (both horizontal and vertical), reported severe diplopia, and failed all tests of stereopsis (Brown, Berkley, & Jones, 1978). These effects all persisted for several hours, but all capacities returned to normal within 24 hours. The disruption of binocular vision, as may occur in severe field loss with RP in glaucoma, unlike in the various studies discussed here, is continuous and persistent and as such may be the cause for the large magnitude deviations cited above.

Measuring lateral eye deviations with tunnel vision

Most clinical tests for distinguishing tropia and phoria and for measuring their respective magnitudes of deviation largely rely on the presence of diplopia (Appendix 1). Of course, in cases of confusion without diplopia, as discussed here for tunnel vision, the lack of diplopia hinders this testing. If the patient with tunnel vision is orthophoric or has a small magnitude of phoria so that binocular fusion (and normal stereopsis) is maintained, using standard clinical tests for binocular vision will work fine. However, if the patient phoria is large enough to prevent both eyes' residual fields from overlapping once fusion is broken (i.e., by covering one eye), the phoria will manifest as tropia. Under cover–uncover testing, the one eye will maintain fixation, and the covered eye will deviate to the phoria position and upon uncovering the fixation target will not be visible to the deviated eye. Without the diplopic image, there is no trigger for the deviated eye to attempt to verge, and the uncovered eye remains at its deviated posture (manifest tropia). When testing the other eye, the same result is expected. Thus, such a patient may appear to have alternating strabismus under this testing, even though he or she may have normal binocular fusion when the two eyes are aligned or almost aligned. Similarly, under alternating cover test, once the fusion is broken when the eye that was under the cover is uncovered, it will not see the fixation target (nor will the other eye, which is now covered), and that may trigger random search movements. Once that uncovered eye gains fixation uncovering the other eye results in the same invisibility of the fixation target and inability to measure the magnitude of deviation. The test can be modified to enable measuring the magnitude of the deviation. Using an estimate of the deviation obtained with the less accurate Hirschberg test (requiring the patient to look at a bright light while the examiner observes the alignment of the light reflection to the pupils of both eyes), an approximate prism power may be used to bring the two residual fields into a sufficient partial overlap. This reestablishes diplopia within the residual fields and enables refining the measurement with the standard techniques. This approach may work with any of the phoria magnitude measurement tests. The same considerations apply to measuring vertical deviations.

Double vision with bitemporal hemianopia (diplopia only)

Bitemporal hemianopia (BTH) occurs due to injury to the optic chiasm, where the two optic nerves decussate (Figure 5A). In the chiasm, the fibers from the nasal hemi-retinas cross over to the contralateral side of the brain (from the left eye to the right side of the brain), while the fibers from the temporal hemi retinas proceed to the ipsilateral side of the brain. If the crossing fibers at the chiasm are broken or injured, both temporal hemifields are blinded. As a result, there is no binocular overlapping fields (left eye sees only the right hemifield and right eye sees only the left hemifield). BTH is most commonly due to tumors of the pituitary gland, that is situated above the chiasm (McIlwaine, Carrim, Lueck, & Chrisp, 2005), or surgery to remove the tumor (McIlwaine et al., 2005; Tieger et al., 2017). Violent shaking of the head, whiplash injury, as occurs in car crashes and other trauma may result in severing of the chiasm and results in BTH (Chirapapaisan & Sadun, 2005; Fisher, Jampolsky, & Flom, 1968; Kawai et al., 1998; Laursen, 1971). Complete BTH is very rare but is interesting for its ability to produce diplopia without confusion in patients with exophoria and central strip scotoma in patients with esophoria. BTH also results in the field loss of the temporal crescents on both sides (110°–120° of binocular field of view remains); a field that is considered large enough to function normally and to qualify for a driving license in most states in the USA and other countries (Krzizok & Schwerdtfeger, 2006). Therefore, BTH, although named for the visual field loss, may represent only modest peripheral binocular field of view loss (Figure 5A).

Diplopia without confusion may and does occur in cases of complete BTH (Peli & Satgunam, 2014; Shainberg, Roper-Hall, & Chung, 1995). If a patient with BTH had a pre-existing exophoria, it will manifest as exotropia as shown in Figure 5C. The manifest exotropia results in diplopia (Figure 5D). Because there are no corresponding points in the two eyes' retinas, there is no way for any (con)vergence movements to null the diplopia through fusion, the persistent misalignment of the eyes (manifest tropia) results in true binocular diplopia, but without binocular visual confusion (Figure 5D). We, therefore, call this case pure diplopia. The diplopia in this case is limited to a relatively narrow vertical stripe of the field of view. The width of the diplopic section is equal to the angular magnitude of the phoria/tropia (shown in Figure 5D), which is also the angular separation between every pair of diplopic objects. Unlike the diplopia experienced with normal visual fields, where most if not all the diplopic pairs of images end up in one cortical hemisphere or the other, the two diplopic images in BTH are always represented in separate cortical hemispheres. Note that the percept diagram in this diplopia-only situation can be illustrated in full color and contrast because there is no visual confusion (Figure 5D).

If the patient with BTH and exotropia notices the diplopia (Figure 5D), a convergence effort may be ensued to reduce the magnitude of the separation of the diplopic images, but single binocularly fused vision cannot be achieved (not possible because of the lack of corresponding points). We do not know of any reports that the patients converge to reduce the magnitude of the diplopia in BTH. Central to our interest is the fact that the central diplopia has no impact on the total extent of binocular field of view, while the

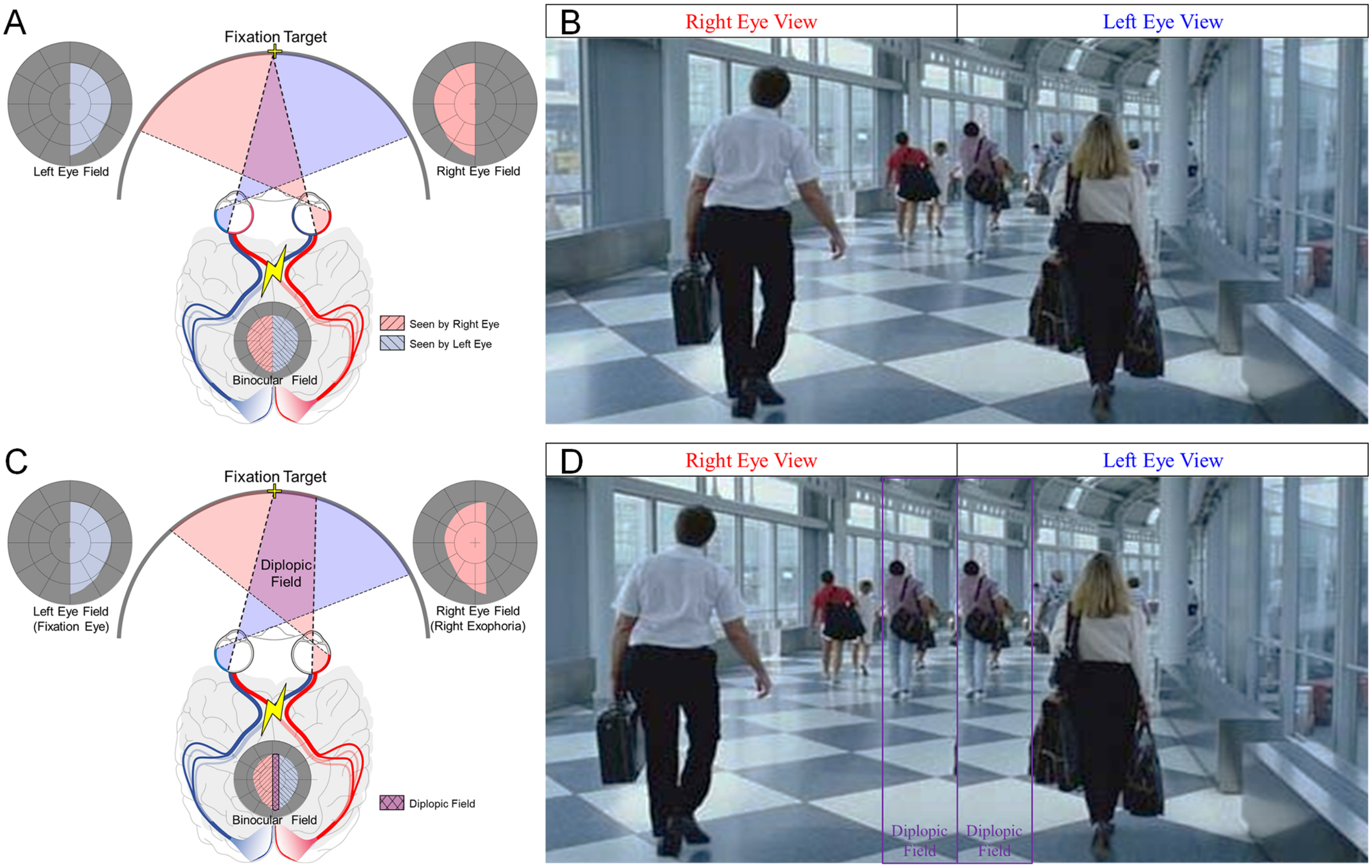

Figure 5. BTH. (**A**) An illustration of the optical neural pathway with the chiasm severed, resulting in both eyes losing the temporal fields. Left eye sees the right hemifield, and right eye sees the left hemifield without any binocular overlapping field of view. This is the case if the patient was orthophoric before the injury to the chiasm. (**B**) The percept diagram of the airport scene as seen by a patient with BTH and no phoria shown in **A**. (**C**) If a patient had exophoria prior to the damage to the chiasm, it becomes manifested as (right) exotropia with crossed diplopia. Vertical stripes areas of the field of view of both retinas, as wide as the angular magnitude of the tropia, are overlapping and thus pointing to the same objects that are perceived in diplopia (see crosshatched area in the inset). (**D**) The percept diagram, the airport as seen by the patient in **C** who fixating with left eye. The right eye nasal (left) hemifield sees further into the right hemifield (the strip includes the tall man with a shoulder bag) and thus duplicates a section of the same view seen by the nasal field of the left eye right hemifield). Every object within that strip (i.e., floor tiles and windows) is seen in crossed diplopia, but there is no visual confusion anywhere in the field of view of the patient (pure diplopia). Because of the right exotropia, the part of the far-left field seen by right eye (the left-most window seen in **B**) is missing from **D**. The diplopic areas here are limited in lateral extent and are only as wide as the angular magnitude of the strabismus. Note that here the diplopic images are seen at full contrast due to no visual confusion unlike the low contrast depicted in Figure 1A.

field of view is slightly reduced (compare the left side of Figures 5B and 5D). The peripheral field is reduced by the exophoria by about 10° whereas the loss of the bilateral peripheral crescents amounts to about 60°.

Bitemporal hemianopia with esotropia (neither diplopia nor confusion)

If a patient with BTH had preexisting esophoria before acquiring BTH, the deviated nasal hemifield is shifted away from the fixating eye hemifield resulting in a manifested esotropia and a vertical strip scotoma in the field of view between the two hemifields (Figure 6A). The percept diagram of the airport scene by the patient whose fields are shown in Figure 6A is simulated in Figure 6B. The vertical scotoma between the two hemifields eliminates content falling into it from the patient perception (two front people in this image). The scotoma is not visible to the patient, though its presence may be revealed by careful observation of the scene and through eye movements or if an object of interest is only partially obscured by the scotoma (Peli, Goldstein, & Jung, 2023).

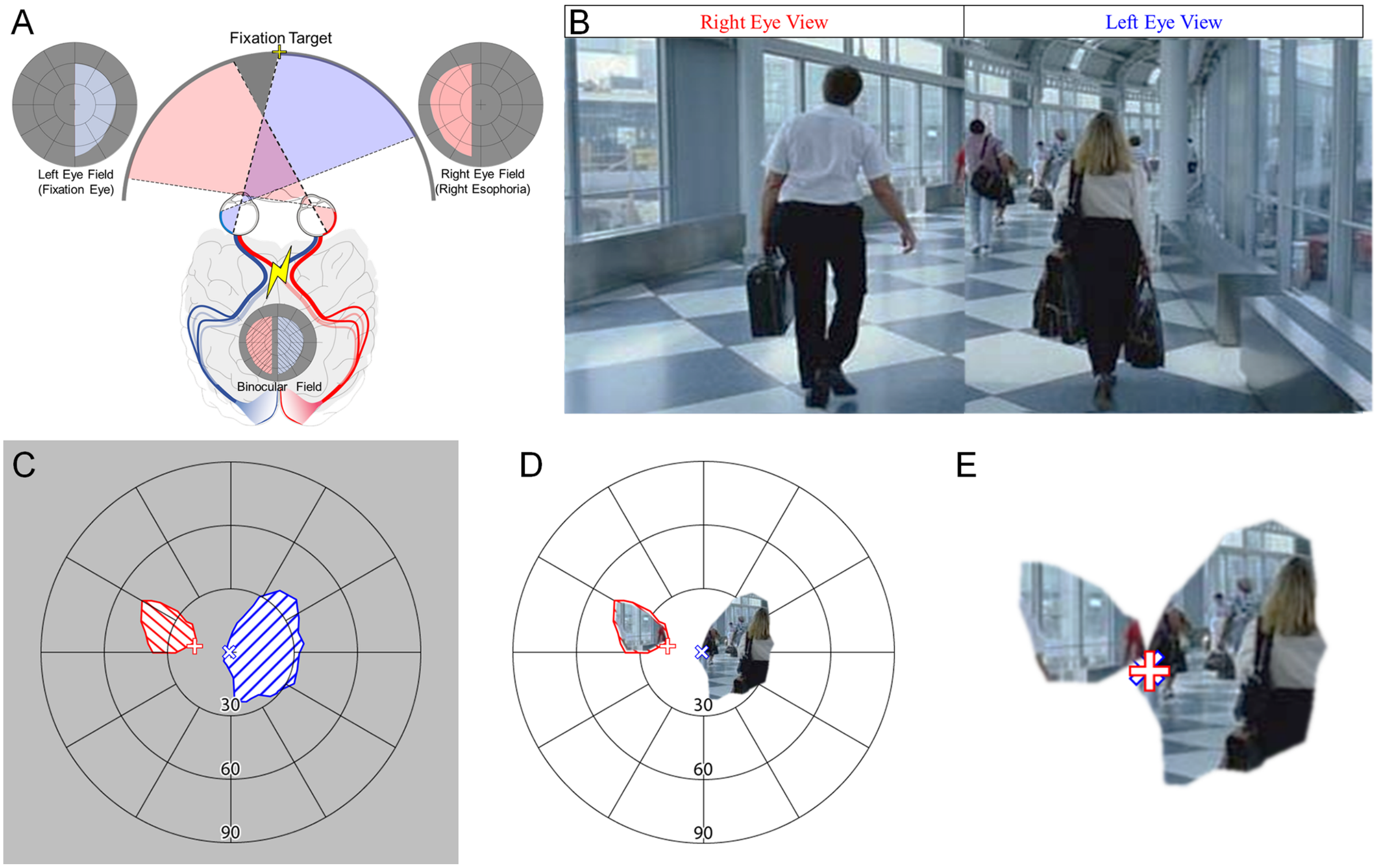

Figure 6. BTH with right esotropia. (**A**) An illustration of the primary visual pathway with the chiasm severed, resulting in loss of the temporal fields in each eye. If a patient had esophoria prior to the damage to the chiasm, it becomes manifested as (right) esotropia. A vertical strip (gap) between the fields of view of both eyes, as wide as the angular magnitude of the phoria/tropia, is not visible to either eye (see grey vertical strip scotoma in the binocular field inset). (**B**) Percept diagram, the airport scene as seen by the patient in (A) who is fixating with left eye. The right eye nasal (left) hemifield sees further to the left (a strip in the scene including the smaller two men images) is not visible to either eye. The missing content at the center (to the left of the man with the shoulder bag) is not noticeable without careful examination of contents continuity. There is no diplopia or confusion. (**C**) The visual fields of another patient with BTH because of a chiasmal tumor, resulting in severe peripheral nasal fields' reduction in addition to the complete BTH and in this case also right esotropia. The left shift of the right eye residual nasal field causes the 15° gap in the binocular field of view between the two eyes. Despite the similarity of this visual field diagram to that depicted in Figure 3A, there is neither confusion nor diplopia here. (**D**) The same field diagram, as in **C** that also shows the portions of the terminal scene seen with the residual fields shown in **C**. (**E**) The percept diagram of the patient with the field shown in **C** in the terminal with the same fixation of the left dominant eye as in **B** presented enlarged. The two foveae directions coincide in the perception diagram. Note that here too, because there is no confusion, the image can be presented with full contrast.

Specifically relevant to this article is the fact that here we have a strabismus with neither diplopia nor binocular confusion (no double vision). Also relevant here is the fact that the esotropia does not change the total extent of the binocular field of view, although far peripheral field of view of the deviated right eye is extended farther. However, for the patient, the positive value of the expansion of the far field of view (compare the left side of Figure 6B to that shown in Figure 5B) is much less than the negative impact of the important central field of view loss.

Figure 6C presents the field diagram of a patient with BTH caused by a tumor at the Chiasm combined with right esotropia. This unusual case with additional severe restriction of the residual nasal fields does not result in either diplopia or confusion despite the manifest strabismus. As a result, the percept diagram here too can be displayed in full contrast without visual confusion (Figure 6E) and there is no need for the cartoon illustration. Despite the field diagram in Figure 6C is very similar to the one shown in Figure 3A, the percept diagram in Figure 6E is very different than that shown in Figure 3E. Note that we added a foveation marker on the field diagram in Figures 3 and 6 for convenience, but the usual field diagrams in these conditions do not have them (i.e., the physiological blind spots cannot be measured in BTH and the tunnel vision smaller than 15° radius). This makes it very difficult to interpret totally different perception (i.e., visual confusion only in Figure 3A versus no double vision in Figure 6C) from the similar field diagrams.

Measuring lateral eye deviation with BTH

If the patient with complete BTH had a preexisting lateral phoria, it will manifest as a lateral tropia, as described above. If the BTH is not complete, there may be sufficient overlap supporting fusion. We will not consider this case because the shape and magnitude of the residual overlap may vary between patients making general rules impossible.

Correcting the tropia with prism can eliminate or largely reduce the tropia magnitude. This might be helpful for the patient, especially for reading, which is impacted negatively by either the central diplopia or the central scotoma (Peli & Satgunam, 2014). Measurement of the deviation is necessary to understand the possible diplopia or scotoma and thus determine the power of the correcting prism that may need to be applied separately for far and near corrections. In the case of exotropia, there will be diplopia that supports any of the clinical measurement methods. In the case of esotropia, with neither diplopia nor confusion, the patient needs to be shifted into the diplopia domain to be able to measure the magnitude of the deviation. To ensure being within the diplopia domain, the examiner should introduce base-out prism in sufficient power to elicit a cross diplopia response, as may be needed in the selected test. Once in that domain, the measurement is possible and once the diplopia is eliminated, the total prism power needed to neutralize the phoria may be calculated. The difficulty here is that the diplopic image deviation then needs to be reduced slowly to avoid falling into the scotoma (esotropia) domain if the total prism power exceeds the magnitude of the exotropia.

Vertical eyes misalignment with BTH (split diplopia without confusion)

If complete BTH is combined with a pre-existing *vertical* heterophoria, the effect is different (Shainberg et al., 1995). Here too the lack of corresponding points in BTH makes it impossible to overcome the phoria, and thus a vertical tropia is manifested (Figure 7B). However, the perceptual effect of the vertical hemifield slide is different from the effects of lateral tropias. The lack of corresponding points between the two eyes results in lack of visual confusion despite the vertical misalignment of the eyes. There is also *no* pure diplopia present, because no object is seen by both eyes and perceived twice in two different directions. This is another case where there is neither diplopia nor confusion. Instead, the views of both eyes are displaced vertically from each other (Figure 7C).

With this displacement, different *parts* of the same object may be seen at vertically different directions (e.g., right and left half of the lips and nose in Figure 7C). Because two parts of the same object are seen at two different vertical directions, the situation is conceptually similar (but not identical) to the perception of diplopia. We call this percept vertical "Split Diplopia." Although there is no binocular confusion in this situation, one can define "Split Confusion" in a similar way, where portions of different objects seen with different hemifields are perceived at the same vertical direction (cf., the left lower lip is at the same vertical direction as the right upper chin in Figure 7C). Vertical split confusion, although it exists there, is not easily noted. The simulation of split diplopia also can be done in full contrast and does not require the cartoon illustration approach because there is no pure visual confusion.

Measuring vertical eyes deviation with BTH

The vertical hemi-slide caused by vertical heterophoria before the BTH-causing lesion results in vertical split diplopia. With that split diplopia, many binocular tests to determine the magnitude of the vertical deviation (Appendix 1) should work. The description of the visible stimuli given to the patient may need to be modified because the Maddox Rod line does not extend across the vertical midline, but that should not make the task any more difficult for the patient in any of the clinical tests.

BTH with combined vertical and lateral tropia (oblique pure diplopia without confusion)

Patients with vertical eyes deviation with no lateral deviations are not common. Usually, the lateral deviation is larger in magnitude than the vertical deviation for both tropias and phorias. It is therefore not uncommon to find in patients with BTH a combination of lateral and vertical deviation, as illustrated in Figure 8. Figure 8A illustrates the field of view of a patient with BTH and with right hypertropia combined with right exotropia. These tropia may be a manifestation of preexisting right hyperphoria and exophoria. The field of view is characterized by the left

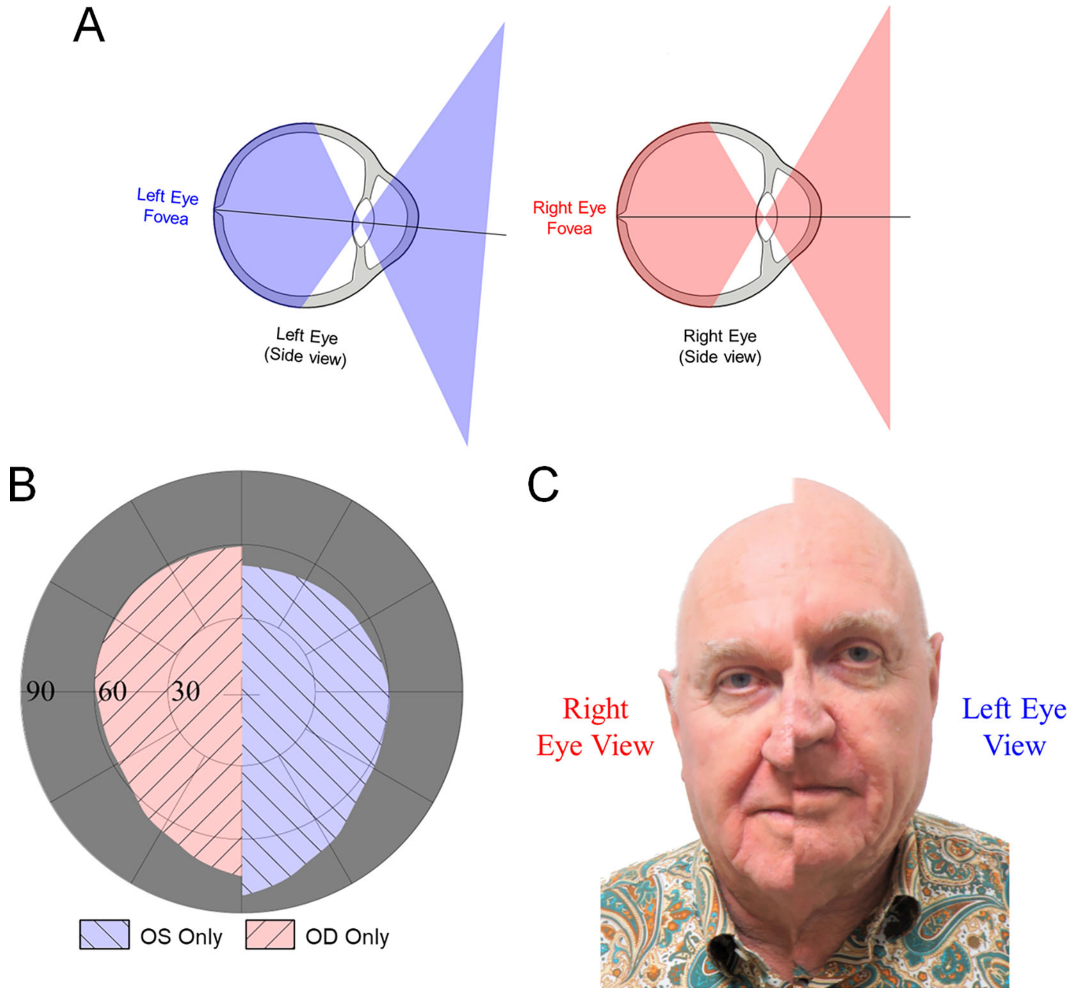

Figure 7. Split diplopia in BTH with vertical hemi-retinal slide. (**A**) Vertical hemi-retinal slide resulting when BTH is combined with preexisting vertical heterophoria (left hypophoria). (**B**) Field diagram. Left hypophoria manifests as left hypotropia results in vertical hemifield slide (right hemifield, seen by left eye, is shifted lower). (**C**) A percept diagram with face seen by a patient with BTH and left hypotropia without pure diplopia or confusion. No object is seen twice, but different parts of the same objects (i.e., nose or mouth) are seen at different vertical directions, creating an impression of vertical diplopia over the whole field. This is not pure diplopia, and we call it vertical "split diplopia."

hemifield (nasal field of the right eye) seen elevated and at the same time shifted rightward and as a result overlapping with the right hemifield (nasal field of the left eye). Figure 8C illustrates the field of view of a patient that had preexisting esophoria instead of exophoria. Here the left hemifield (seen by the right eye) is shifted to the left leaving a gap in the binocular field of view between that nasal field of the right eye and the nasal field of the fixating left eye. In Figures 8A and 8C, the nasal field of the right eye seen on the left is elevated relative to the nasal hemifield of the left fixating eye. Note that even though the relative positions of the right and left eyes' fields are the same as in Figure 7B, the absolute position is not the same because the right eye is fixating in Figure 7B, whereas the left eye is fixating in Figures 8A and 8C. The perception of the airport scene by the two patients with BTH are simulated in Figures 8B and 8D, respectively. In both cases, the right side of the scene seen by the left eyes appears to be deviated up relative to the left side of the scene. In Figure 8B, the result of that vertical shift combined with the right exotropic shift results in oblique pure diplopia with no confusion (thus no need to use the cartoon illustration) and no reduction in contrast. In Figure 8D, the (invisible (Peli et al., 2023)) vertical strip scotoma, because of the esotropia, eliminates the image content in that gap in the binocular field of view. As a consequence of the vertical deviation, the simulated view results in split vertical diplopia of similar (although not identical) appearance to the split diplopia seen with no lateral deviation. In both conditions, there is no binocular

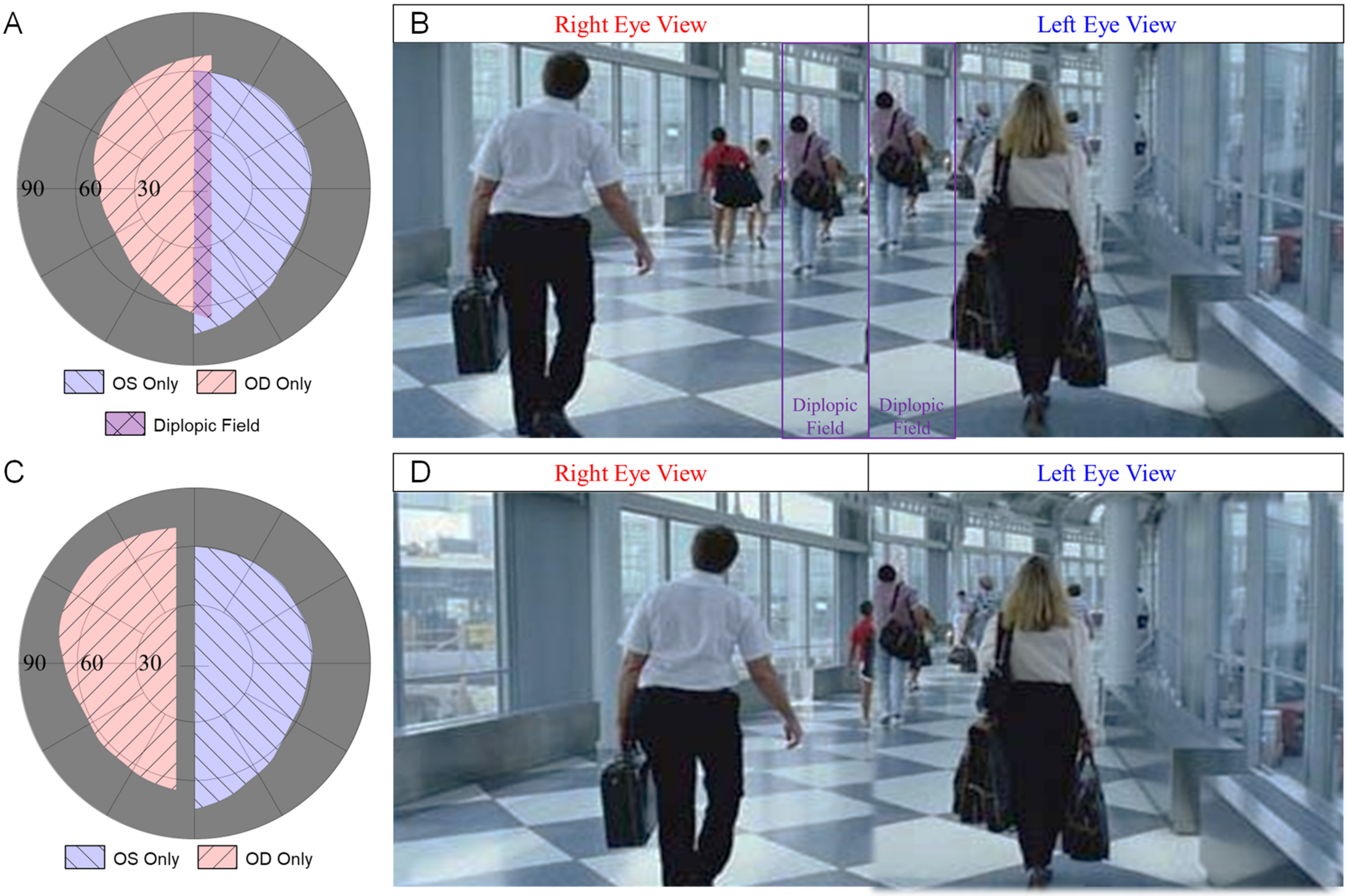

Figure 8. Visual fields and perception of patients with BTH with vertical hemifield slide due to pre-existing right Hyperphoria combined with right horizontal phorias. (**A**) Dichoptic visual field of a patient with BTH and preexisting right hyperphoria combined with (right) exophoria manifesting as right hypertropia and exotropia resulting in a strip of diplopic field of view. (**B**) Percept diagram of the view of the airport terminal as seen by the patient in **A**. Oblique pure diplopia over a central area of the scene is seen without confusion. (**C**) Dichoptic visual field of a patient with BTH and preexisting right hyperphoria combined with (right) esophoria manifesting as right hypertropia and esotropia resulting in a vertical central scotoma. (**D**) Percept diagram of the view of the airport terminal as seen by the patient in **C**. One pedestrian and half of another are missing from the view, although it is not obvious without careful examination. There is no diplopia and no confusion in this situation. Split diplopia may be noticed over the upper windows. At the same time, split confusion can be discerned on the floor by comparing to the vertical misalignments of the tiles in **D**. In both lateral phoria cases, full contrast is maintained. Note here that the right hyperphoria resulted in right hypertropia whereas in Figure 7 the equivalent left hypophoria resulted in left hypotropia that is different than right hypertropia.

confusion (although in Figure 8D split confusion effects may be noted), so there is no loss of contrast in these simulations.

Horizontal hemifield slide in asymmetric altitudinal binocular hemianopia

In addition to the horizontal pure diplopia and split vertical diplopia (both without confusion), as well as the vertical strip scotoma without diplopia found in the BTH (Peli & Satgunam, 2014), equivalent conditions just rotated by 90° occur in cases of asymmetric altitudinal hemianopia (AAH) (Figure 9). Vertical pure diplopia and split horizontal diplopia (both without confusion), as well as the horizontal strip scotoma without diplopia or confusion are found in some cases of optic neuropathy or glaucoma (Borchert, Lessell, & Hoyt, 1996; Sun et al., 2017) (where one eye sees only the upper hemifield and the other only the lower hemifield) and if it is combined with pre-existing lateral heterophoria (Figure 9).

Although the prevalence of AAH caused by optic neuropathy is not known and is probably quite low, the prevalence of this condition is moderately high in glaucoma. The asymmetry of field loss in glaucoma

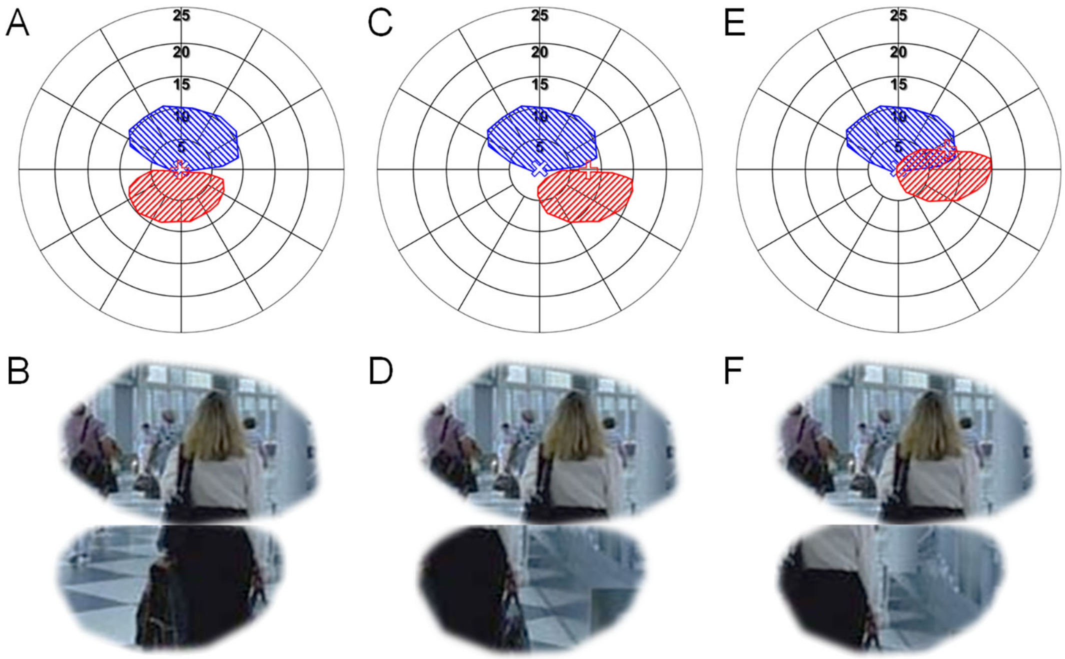

Figure 9. Horizontal hemifield slide with AAH in glaucoma. (**A**) Residual dichoptic visual fields of a patient with advanced glaucoma and orthophoria where the left eye maintained a central upper residual altitudinal hemianopia while the right eye residual field is limited to a lower central residual altitudinal. (**B**) Percept diagram of the patient in **A** when viewing the airport scene. (**C**) The field of view of the patient depicted in **A** if manifesting horizontal right exotropia because of pre-existing exophoria showing lateral expansion of the lower field of view to the right. (**D**) Percept diagram of the patient in **C** when viewing the airport scene exhibiting a left shift of the lower hemifield content, seen by right eye (crossed split diplopia and split confusion) manifested as lateral field expansion. (**E**) Residual fields of the patient shown in **C** but with the addition of preexisting right hyperphoria, manifested as right hypertropia and right exotropia. (**F**) Percept diagram of the patient in **E** when viewing the airport scene exhibiting an oblique pure diplopia (the woman's shirt is seen diplopically in the lower field shifted to the left and down by right eye) without confusion and with just a hint of horizontal split diplopia. In all cases, the full contrast is maintained in these simulations, so there is no need to use the cartoon images. Note that the upper and lower residual fields are shifted in the field diagrams but remain aligned in the percept diagrams. Only the content of the residual fields is shifted within the percept diagrams.

is common, and it is not rare to find cases where the residual field under the arcuate scotoma is under the upper scotoma in one eye and above the lower arcuate scotoma in the other eye (Khanna & Holmes, 2017; Sun et al., 2017). The hemifield slide in BTH usually does not affect the field extent meaningfully, because the vertical field usually remains full in BTH (although see Figure 6C), and the vertical phoria is usually of small magnitude of 1°or 2°. However, in the AAH especially in glaucoma, the horizontal extent of the residual hemifields is quite limited. As a result, the horizontal hemifields slide in these cases do expand the horizontal field of view, as seen in Figures 9A vs. 9B. In addition, the magnitude of lateral heterophoria is usually substantially larger than that of vertical phorias. Therefore, lateral field expansion is possible in these cases because of the split confusion (e.g., different objects across the same vertical meridian), and that field expansion can be illustrated without reducing the contrast.

Double vision in homonymous hemianopia

Homonymous hemianopia (HH), the loss of half the visual field on the same side in both eyes, is a frequent consequence of a lesion involving the visual pathway posterior to the chiasm, as brain damage from stroke, head injury, or surgery to remove brain tumors (Zhang, Kedar, Lynn, Newman, & Biousse, 2006). With hemianopic field loss, the interaction with various types of tropias results in different types of double vision and effects on the field of views, as illustrated in Figure 10. Tropia is a frequent sequela of stroke or other brain injuries that also result in HH. The double vision illustrations in Figure 10 present the situations with late onset tropias without the sensorial adaptations that take place with early childhood onset of strabismus, which are addressed later. Several case reports indicate that HH frequently manifests ipsilateral (the eye on the side of the hemianopic field loss) exotropia, presumably as a field expansion compensating mechanism (Donahue & Haun, 2007; Herzau, Bleher, & Joos-Kratsch, 1988; Koenraads et al., 2014). In such HH with ipsilateral exotropia, the hemifield of the deviating eye points farther into the blind side by as much as the exotropic deviation, resulting in field expansion (Figures 10C and 10D). The beneficial field expansion is achieved because of binocular visual confusion and is accompanied by peri-central double vision over the binocular overlapping parts of the fields. The diplopia within this area provides no field expansion, as illustrated in Figure 10D. For patients who develop the exotropia at a young age, the diplopia is said to be eliminated by the suppression (Economides et al., 2012; Economides & Horton, 2021), as discussed further below.

Similar field expansion also occurs with contralateral esotropia (the eye on the opposite side of the field loss) (Figures 10E and 10F), though in that case the same magnitude of field-of-view is being lost in the contralateral far peripheral field (Apfelbaum et al., 2013). The expansion in the central field is much more valuable to the patient than the similar size field loss in the far periphery. In both ipsilateral exotropia and contralateral esotropia, the nonexpanded field of view includes both confusion and diplopia everywhere and of all objects, except for the monocular temporal crescent. Here too the development of suppression in childhood strabismus largely eliminates the double vision as described below.

While the field expansion from ipsilateral exotropia and contralateral esotropia with HH is arguably helpful, there are two other syndromes that do not provide any useful field expansion: HH with contralateral exotropia (Figures 10G and 10H) and HH with ipsilateral esotropia (Figures 10I and 10J). Contralateral exotropia (Figures 10G and 10H) does provide field expansion,

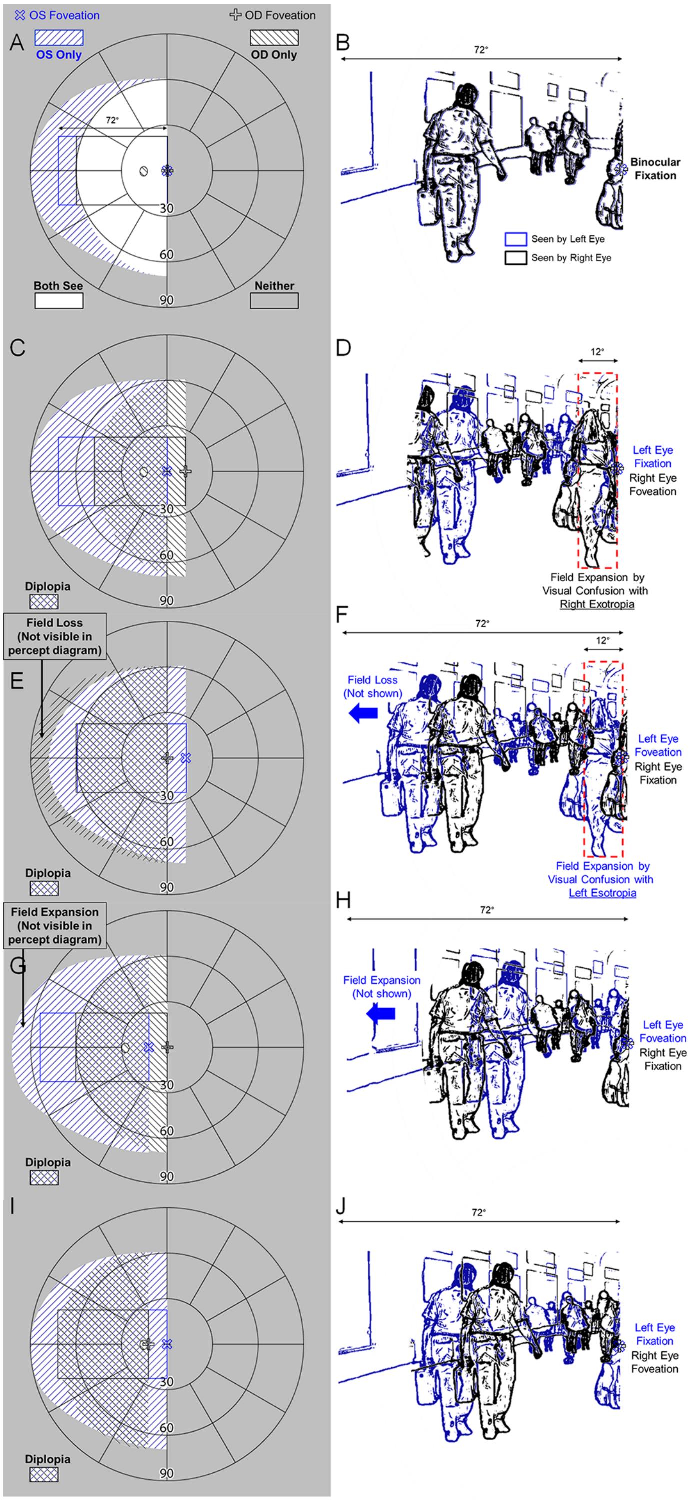

Figure 10. Double vision in right HH combined with various types of **adult** onset strabismus. (**A**) Field diagram and (**B**) percept diagram of right HH with no strabismus (orthotropia). The left eye view (spanning 72°) is shown in blue, and right eye view is in black. The left eye and right eye fixation points are marked with the open blue x mark and black cross mark, respectively. The blue and black rectangles in **A** mark the angular extent of the left (72°) and right (60°) eyes percepts shown in **B**, respectively. (**C**) Field diagram and (**D**) percept diagram of right HH with ipsilateral adult onset (right) exotropia. The right eye view (black) in the section highlighted by red dashed lines represents the field expansion achieved via confusion (e.g., the woman visible only by the right exotropic eye). (**E**) Field diagram and (**F**) percept diagram with right HH and contralateral (left) esotropia. While the same field expansion is achieved centrally (the woman) as in **C**, the farthest left periphery is missing. (**G**) Field diagram and (**H**) percept diagram of contralateral exotropia. The field expansion here is achieved in the farthest periphery, it is of minimal benefit and thus inconsequential. (**I**) Field diagram and (**J**) percept diagram of ipsilateral esotropia. In this case, the confusion does not provide any field expansion, because all objects seen by the esotropic right eye are already seen by the fixating left eye.

but the field expansion is at the far periphery (Cooper & Feldman, 1979; Good, Fogt, Daum, & Mitchell, 2005) and thus largely inconsequential. Ipsilateral esotropia (Figures 10I and 10J) does not provide any field expansion although it results in double vision over most of the functional overlapping field of view. Therefore, both conditions are not beneficial.

The double vision within the overlapping residual fields is annoying, and adult patients who develop this syndrome frequently feel that the field expansion is an insufficient benefit to compensate for the annoyance of the double vision and the poor cosmetics of the visible strabismus (Donahue & Haun, 2007; Economides & Horton, 2021). They then seek some way of eliminating the double vision and visible eye deviation: via surgery, prism correction, or by occluding the deviating eye, all of which eliminate the field expansion benefit. Although double vision is what is mentioned by these patients, it is not clear that the central diplopia is more bothersome than the central confusion in these cases. Most lay people are not familiar with the terms diplopia or confusion, and they use the term “double vision,” which is interpreted for them to be diplopia by clinicians, many of whom also do not distinguish the two terms. It is just as likely that the patients refer to the confusion they experience as “double vision.”

The pericentral diplopia is constant and therefore may be more noticeable (e.g., Figure 5D), whereas the confusion is intermittent and depends on the scene (e.g., Figures 3C and 3E), and therefore may be less bothersome. However, central confusion may be very bothersome because it affects the visibility of the fixated object of interest and may rival, while diplopia only adds a copy of it at peripheral eccentricity. Patients who develop strabismus in early childhood are free from diplopia and confusion and may benefit from the expanded field of view by meeting the visual requirement for driving (Peli, 2002b; Peli, 2009; Peli & Moharrer, 2022).

These observations of various types of field expansion in HH with strabismus highlight the fact that while confusion is necessary for field expansion, confusion is not sufficient on its own to expand the field and varies with the direction of deviation. In fact, the peri-central confusion occurring in HH with ipsilateral esotropia (Figures 10I and 10J) offers no apparent field expansion benefit and only the potential for annoyance. Unlike diplopia, which is apparent for any fixated (salient) object in the field expanding variants of the syndrome, the confusion may not always be manifested. When the patient is fixating a salient object, the fovea of the deviating eye may fall on a blank or low salience area of the scene resulting in no apparent confusion (cf., the tiger in Figure 2B and the wall on the right in Figure 3C). This is highly dependent on the image statistics and eye movements, which may make it more difficult to notice the existence of the confusion. The pericentral diplopia that occurs in these conditions is related to the nonfixated unattended objects and the more central copy of the two is seen by the deviating eye, with all of these making it less noticeable.

HH, strabismus, and suppression

Children with strabismus develop suppression as a sensory adaptation (Cooper & Record, 1986; Daw, 1995; Economides et al., 2012; Economides & Horton, 2021; Jampolsky, 1955; Pickwell, 1989; Pickwell, 1980; Pratt-Johnson & Tillson, 1984; Pratt, Stevenson, & Bedell, 2017; Verma, 2007). Although the mechanism and purposes of suppression are not known (Pickwell, 1980), it is generally stated that the (peripheral) suppression of the deviating eye is an active act of adaptation meant to avoid diplopia (Awaya, 1975; Jampolsky, 1955; J. Pratt-Johnson & Wee, 1969; Pratt-Johnson, Wee, & Ellis, 1967; Schor, 1977) (though some also mention avoiding confusion(Awaya, Nozaki, Itoh, Kikuko, 1975; Holopigian, Blake, & Greenwald, 1988; Pratt-Johnson & Tillson, 1984; Schor, 1977)). Suppression of vision in the deviating eye may exist only under binocular vision and under natural vision conditions (Awaya et al, 1975; Jampolsky, 1955). However, there is some uncertainty about this because many of the tests used to document suppression in children have not used dichoptic perimetry (Woods, Apfelbaum, & Peli, 2010). Jampolsky (1955) argued that the high sensitivity to any deviation from the natural viewing condition suggested that anaglyphic (color separation) dichoptic techniques are unlikely to support documentation of suppression. Indeed, using anaglyph and a dark background, diplopic target only with no confusion (i.e., confusion with blank) resulted in no suppression measured in five of six patients with intermittent exotropia (Cooper & Record, 1986). However, with a different anaglyphic technique that included dim colored background (i.e., diplopic target with possible visual confusion with background pattern), Economides et al. (Economides et al., 2012; Economides & Horton, 2021) documented suppression in the deviating eye of 14 patients with alternating intermittent exotropia.

Suppression is partial, affecting only part of the retina/field (Jampolsky, 1955; Pratt-Johnson, Wee, & Ellis, 1967). Discrepancies in the measurements of the spatial extent of the suppression areas are common, as reviewed by Awaya et al. (1975) and by Cooper and Record (1986) presumably because of the differences in testing methods and the fleeting nature of suppression if testing conditions do not replicate natural binocular conditions (Awaya et al., 1975; Griffin, 1984; Jampolsky, 1955). Economides et al. (2012) found that the suppression of the deviating eye in alternating exotropia extends laterally beyond the temporal hemifield into the nasal hemifield and up to the vertical meridian midway between the two foveal directions. This finding conflicts with the description of Jampolsky (1955) that insists that, for both exotropia and esotropia, the suppression area is limited to one hemifield and does not cross over the vertical midline. Similar hemifield-only suppression was reported in intermittent exotropic patients when their eyes were aligned (Serrano-Pedraza, Manjunath, Osunkunle, Clarke, & Read, 2011). Much smaller localized suppression scotomas were measured at the diplopia point and near the fovea of the deviating eye in both esotropia and exotropia (Pratt-Johnson & Wee, 1969; Pratt-Johnson et al., 1967). In contrast, suppression of the whole binocularly overlapping field of the deviating eye was reported by the same group using a different testing paradigm (Pratt-Johnson & Tillson, 1984; Pratt-Johnson, Tillson, & Pop, 1983).

Relevant to our interest, many of these differences disappear in cases of HH, where for both exotropia and esotropia, the suppression cannot cross the vertical meridian regardless of the model and testing used (Figure 11). The lateral extent of the suppression in the deviated eye's field includes the peripheral locus in the deviating eye aiming in the same direction as the fovea of the fixating eye (the zero-measure point) (Economides & Horton, 2021; Jampolsky, 1955; Pratt-Johnson et al., 1967; Rutstein & Daum, 1998). Suppressing the zero-measure point and its immediate surrounds prevents the central diplopia (diplopia of the fixated object). The lateral extent of suppression extends (according to some reports) from around the zero-measure point to around the fovea of the deviating eye (where it is eliminating the central confusion). In one report, the suppression around the fovea of the deviating eye is localized to just that area (Pratt-Johnson et al., 1967).

The vertical extent of the suppression is also limited and variedly reported. Jampolsky (1955) described various ways to measure the vertical extent and in his Figure 1 illustrated vertical span of about 30°. Economides and colleagues' measurements were also limited to a vertical extent of 30°, though they illustrated the result to extend to the full vertical visual field extent (Economides et al., 2012; Economides & Horton, 2021). We, therefore, illustrate a suppression area as an ellipse of 30°V × 60°H (30°H only in the seeing side of HH) centered at the deviated eye fovea (Figure 11). Although at least one group results limit the vertical extent to just 2° in esotropia (Pratt-Johnson et al., 1967) and in exotropia (Pratt-Johnson & Wee, 1969), which is 15 times smaller than the scotoma suppression we illustrate based on other reports.

Here the suppression of the left eye in the expansion zone and the suppression of the right eye in the surviving left hemifield (Economides & Horton, 2021) result in the elimination of the double vision in

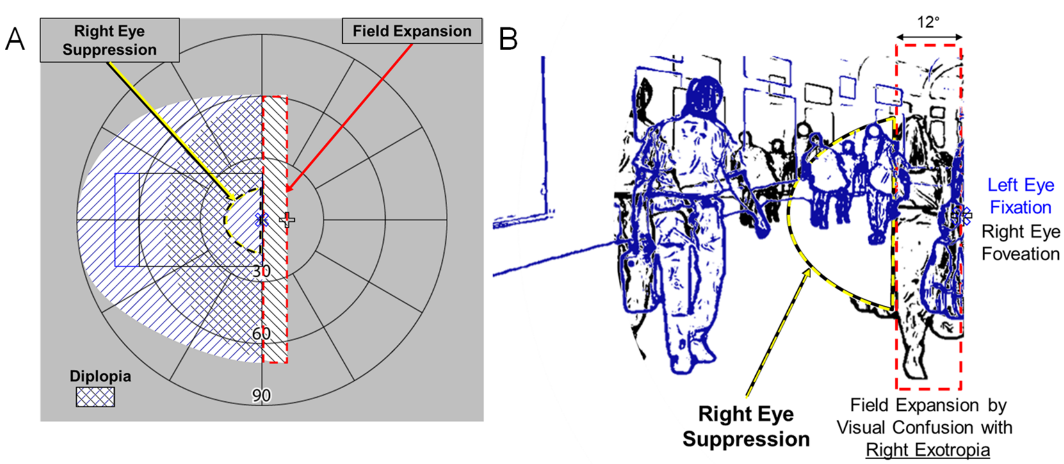

Figure 11. The interaction of HH with suppression in patients with **childhood** strabismus. Here a patient with right HH with childhood onset ipsilateral (right) exotropia is illustrated. (**A**) The field diagram illustrates half elliptics suppression of the right eye (adapted from Jampolsky (1955)). The vertical strip of the right eye field of view, which is not overlapping with the left eye's view (no diplopia but visual confusion only), is not suppressed, as described by Economides and Horton (2021). The blue and black thin lines rectangles represent the areas seen by the left and right eyes, respectively, in the percept diagram in **B**. (**B**) In the percept diagram, the unsuppressed right eye view (woman in black) in the section highlighted by red dashed lines represents the field expansion as a consequence of peripheral confusion (is visible only by the right exotropic eye). The pericentral part of the deviated right eye's retina is suppressed and prevents diplopia within the central part of the fixated left eye (i.e., the bag held in the woman's left hand and the leg of the guy in far). As a result, the three people in blue in the left eye's field of view are seen in diplopia but not in confusion. Outside of the suppressed area, within the overlapping field-of-view (crossed hatched in **A**), both diplopia and confusion are notable.

the residual overlapping pericentral field, except for the upper and lower segments of the field (compare with Figures 10C and 10D).

Figure 11 illustrates the effect of suppression developed with childhood strabismus (right exotropia) on the perception with adult onset of right HH in the field expansion situation of Figures 10C and 10D. The field diagram of Figure 11A includes a suppression of the right eye depicted as an ellipse of 30°V × 60°H (30°H only in the seeing side of HH) centered at the deviated right eye fovea. Because of the 12° right exotropia, the same width vertical strip of the right eye's field of view in the blind side (field expansion) is not overlapping with the fixated left eye's field of view (no diplopia but only confusion) and, therefore, is not suppressed within the potential suppression area (Economides et al., 2012). However, the deviated right eye is suppressed to the left of the fovea as seen in the percept diagram Figure 11B. The field expansion is manifest as the visibility of the woman seen by the right eye (illustrated in black). The suppression of diplopia within the suppressed area of the right retina is notable as the suppression of most of the bag held in the woman's left hand. Only the very bottom of the bag (illustrated in black) is visible to the patient's right eye.

Prevalence of strabismus with HH

The prevalence of HH in the adult population over 49 years of age is almost 1% (Gilhotra, Mitchell, Healey, Cumming, & Currie, 2002). As many as one-third of stroke survivors in rehabilitation have HH (Rossi, Kheyfets, & Reding, 1990; Townend et al., 2007). The prevalence of strabismus in adults with HH is much higher than in the general population. Fowler (1996) found strabismus in 37% of adults with a history of brain injury from various causes. Rowe (2010) reported that 16.5% of adults developed strabismus after strokes.

There are fewer children with exotropia than esotropia in the general population (1.5%/5%) (Chew et al., 1994). Similar ratio of exotropia/esotropia (19/75) was also found in study of 100 strabismics (Pratt-Johnson & MacDonald, 1976). In pediatric population with HH, both exotropia and esotropia occur substantially more often, 23.6% and 8.8%, respectively (Bronstad, Peli, Liu, Doherty, & Fulton, 2018). Note that the ratio of exotropia/esotropia (23.6/8.8) is reversed with HH, many more with exotropia than esotropia. In the 16.5% of adults that developed strabismus after strokes and HH, the ratio of exotropia/esotropia (72/28) was also reversed (Rowe, 2010). Exotropia often follows hemispherectomy, which results in HH in all cases (Handley, Vargha-Khadem, Bowman, & Liasis, 2017; Koenraads et al., 2014).

In the retrospective review of charts at Boston Children's Hospital, we identified 103 patient records with both HH and strabismus (Bronstad et al., 2018). Of the 75 with exotropia, 53 (70%) had an ipsilateral exotropia that potentially expanded the field (Figures 6C and 6D), whereas from the 28 with esotropia only nine (32%) had the field expanding deviation (Figures 6E and 6F). It is important to note that the field expansion effect of the horizontal strabismic deviation is effective at any position of gaze in comitant strabismus. The diagnosis of strabismus, as well as the measurement of the magnitude of the strabismus, is impeded by the hemianopic field loss (Appendix 2).

Torsional eye deviations

Torsion or cyclorotation is the rotation of the eye around its visual axis (Guyton, 2008b; Holgado, Enyedi, Toth, & Freedman, 2006; Philips & Hunter, 1999; Sullivan & Kertesz, 1978). Torsion without a known pathological cause is called anatomic torsion (Guyton, 1983). Detection of anatomic torsion is based on objective measurement by indirect ophthalmoscopy, fundus photography, or perimetry. In all these techniques, the relative rotational angle between the optical nerve head and the fovea provides the measurement (Guyton, 1983; Morton, Lucchese, & Kushner, 1983; Philips & Hunter, 1999). Torsional deviations below 9° are considered phoria; above 9° strabismic. To our knowledge, this threshold is arbitrary. Torsional strabismus should be suspected when there are both horizontal and vertical strabismus (Kushner & Hariharan, 2009; Philips & Hunter, 1999). The torsional strabismus may be incyclotorsional if the tops of the eyes turn nasally or excyclotorsional when the tops of the eyes turn temporally. Torsional strabismus frequently goes unnoticed by the patient, especially when congenital. Patients rarely report symptoms (torsional diplopia or confusion) presumably because of sensory-motor adaptations (Philips & Hunter, 1999). With fundus imaging and conventional perimeters, torsion can only be measured for one eye at a time. As these measurements are conducted monocularly, they may represent cyclophoria. The Double Maddox Rods test (Liebermann, Leske, Hatt, & Holmes, 2017) measures the rotation under binocular but dissociated condition, so it too cannot distinguish if the condition is a phoria or a manifested tropia. A dichoptic perimeter (Woods et al., 2010) is needed to measure the torsional deviation under binocular viewing, enabling an actual distinction between cyclophoria and torsional strabismus (Satgunam & Peli, 2012). In torsional strabismus or cyclotropia, the eyes will remain counter

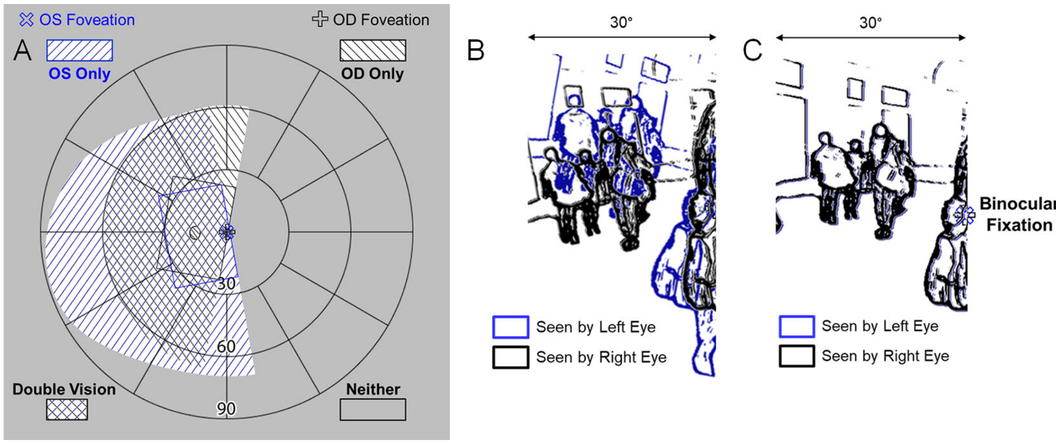

Figure 12. Visual field expansion in right homonymous hemianopia (HH) when combined with 9° intorsional strabismus. (**A**) Schematic dichoptic binocular visual field diagrams illustrating field of view expansion, evident to the right of the vertical midline both above and below. The field expansion is of larger lateral magnitude the farther vertically it is from the fovea. The crosshatched area is seen in torsional double vision. The lateral and vertical magnitude of the diplopia and confusion in this area is minimal centrally and increases gradually with eccentricity, so that it is likely to exceed the Panum's area in the periphery while remaining in single binocular vision centrally. Here with intorsion, the superior field expansion is by the right eye and the inferior field expansion is by the left eye. (**B**) Percept diagram for the patient shown in **A** compared with (**C**) the percept diagram of a patient with the same Right HH but with no tortional strabismus. The leg of the woman to the right (in blue) not seen in **C** is seen by the left eye in **B**. Similarly, the head of the woman (in black) is seen by the right eye in **B**.

rotated under associated binocular viewing condition. This may result in perceived torsional diplopia (as reported by patients with acquired torsional strabismus).

Torsional eye deviations with HH

HH in a patient with torsional strabismus enables direct recording of the cyclo-rotated visual fields (rotated vertical meridians) under dichoptic perimetric condition (Satgunam & Peli, 2012), in addition to the rotated blind spot of one eye that may be measured monocularly. Torsional strabismus in conjunction with hemianopia provides field expansion (Figure 12). With right hemianopia and intorsion, a superior field expansion results from the left eye's rotation while the right eye contributes a field expansion inferiorly (Figures 12A and 12B). The lateral extent of the field expansions increases with the vertical eccentricity. The lower field expansion is beneficial in detecting tripping hazards, and the upper expansion is protective from overhead hazards such as open kitchen cabinet doors or low hanging tree brunches. In both cases, the expansion is due to the binocular visual (cyclo) confusion. The field expansions due to both lateral and torsional deviation may combine to provide a wider overall field expansion (Satgunam & Peli, 2012). The overlapping residual hemi field are cyclo-rotated and may be expected to have rotational double vision; diplopia and confusion.

Torsional eye deviations with bitemporal hemianopia

Torsional strabismus may interact with BTH. With intorsional strabismus, the upper eccentricities turn nasally, and the lower eccentricities turn temporally creating esotropia above and exotropia below, respectively. The effect is to create scotoma above the fixation and torsional pure diplopia below the fixation, which is not beneficial at all. With extorsional strabismus, the roles are exchanged between the upper and lower segments. In both cases, the field is compromised but not expanded by the torsional effect.

As in the case of HH, torsional strabismus may be combined with lateral strabismus in patients with BTH. Because these two conditions are uncommon, the combinations of them are likely very rare. Although such cases are likely to exist, we have not seen or read about such cases, so we are leaving the analyses of these situations as a self-exercise for the reader.

Prism-based field expansion for HH

Because the visual confusion caused by the eye deviation (although diplopia coexists) could provide useful field expansion, prisms have been prescribed to provide similar visual confusion for the field expansion in such field loss patients without the strabismus. Although it is frequently stated that prisms are used for field expansion for HH because they shift the view from the blind hemifield to the seeing side, in fact image shifting per se does not expand the field of view, as we explained (Apfelbaum et al., 2013; Jung & Peli, 2018b). The analyses of HH with various types of strabismus above highlighted two important principles; 1) to expand the field-of-view, one needs to induce binocular confusion (Peli, 2001) and 2) diplopia is of no value for field expansion as the diplopic image of an object is already seen by the other (fixating) eye. Thus, effective field expansion devices should be designed to induce visual confusion and avoid diplopia, whenever possible (Apfelbaum & Peli, 2015; Apfelbaum et al., 2013; Jung & Peli, 2014).

As shown in Figure 10C, the field of view is expanded as a result of confusion caused by misalignment of the two eyes. The confusion is a result of presenting a view of object only seen through a monocular prism superimposed over another view seen with the other eye without the prism. The confusion that results from naturally occurring strabismus can be substituted with prism-induced strabismus. If a prism of high enough lateral power is introduced in front of one eye, the patient may not be able to fuse and will end up with a manifest strabismus as in the cases shown in Figure 10. A base-out prism placed in the spectacle lens in front of the right eye of an adult patient with right HH will result in the same effect as the natural exotropia depicted in Figure 10C, assuming the left eye is dominant and is the fixating eye once fusion is broken. The field of view is expanded, but the disturbing side effects—central and peri-central diplopia and confusion—are unacceptable without suppression. Here too the field expansion effect is effective at all positions of gaze, and so are the disturbing side effects of pericentral diplopia and confusion over the whole field of fixation. In distinction from the naturally occurring strabismus, the prism induced strabismus is additionally affected by the various prism distortions (Jung & Peli, 2014).

Because the constant pericentral double vision that accompanies HH field expansion with adult onset of strabismus, either naturally occurring or full prism induced is unacceptable, several designs have emerged that limit the prism extent. A sector prism which limits the prism to the blind hemifield side of the spectacle lens is commonly used (Gottlieb & Miesner, 2004; Perez & Jose, 2003; Perlin & Dziadul, 1991). These sector prisms may be fitted bilaterally or unilaterally. A major limitation is that most of the time, when the patient is in primary position of gaze or is looking in the direction of the seeing hemifield, these prisms have no effect, as they are fully enclosed within the blind hemi field (Apfelbaum et al., 2013). A detailed review of their other limitations, in particular, the occurrence of central and peri-central diplopia and the scope of confusion with the unilateral fitting, as a function of gaze movement, have been provided by Apfelbaum et al. (2013). Typically, prism powers of only about 20Δ (10°) are used in these designs, which is limited by the thickness and weight of the ophthalmic prism lens and by the reduction in visual acuity due to the color dispersion of high-power prisms (Katz, 2004a; Katz, 2004b).

Peripheral prisms for treatment of HH

Peripheral prisms (Figure 13) can overcome many of the limitations of the sector prisms and other prism treatment designs (Peli, 2000; Peli, 2001). First, this design keeps the central field free of prism effects at all positions of lateral gaze (Figures 13A and 13B), eliminating the disturbing and annoying central diplopia and confusion. It limits the effective field expanding confusion (and possible diplopia) to only the upper and lower peripheral fields (Figures 13C–F), where they are much easier to accept and to adapt to. With the peripheral position, where acuity is naturally poor, it is not difficult for the patient to accept the reduced image quality due to color dispersion and spatial distortions that come with high power prisms (Peli, Apfelbaum, Berson, & Goldstein, 2016; Jung & Peli, 2014). This enables us to use high-power Fresnel prisms that have many desirable mechanical and cosmetic properties (Figure 13A) such as low weight and thickness, as well as lower color dispersion, resulting in better contrast sensitivity through Fresnel prism than through the same power ophthalmic prism (Katz, 2004a). However, acuity was better through ophthalmic prism compared to the 3M Press-on Fresnel prisms (Katz, 2004b). Fresnel prisms as high power as 65Δ (providing field expansion of more than 33°) are now routinely used. Recently, 100Δ power with better image quality using cascade of half-penta prisms has been achieved, in a device called the multi-periscopic prisms (Figure 13B) (Falahati, Kurukuti, Vargas-martin, Peli, & Jung, 2023; Peli, Vargas-Martin, Kurukuti, & Jung, 2020), which enables detecting potentially colliding pedestrian at the highest risk bearing angle (45°) (Peli et al., 2016) (Figure 13E). The multi-periscopic prism is largely a reflective device with minimal refractive effect and, therefore, provides a much better image quality than the Fresnel prism.

Because the diplopia is of no value for field expansion, the peripheral prisms need to create mostly visual confusion. With proper design, the useless diplopia can be minimized or eliminated, at least at primary position of gaze (Jung & Peli, 2014). The apical scotoma (shown in Figures 13C and 13E) is equal in angular extent to the deflection power of the prism at the apex (Apfelbaum et al., 2013). The prism apex with its apical scotoma is placed in the peripheral prism design at the lateral periphery on the seeing

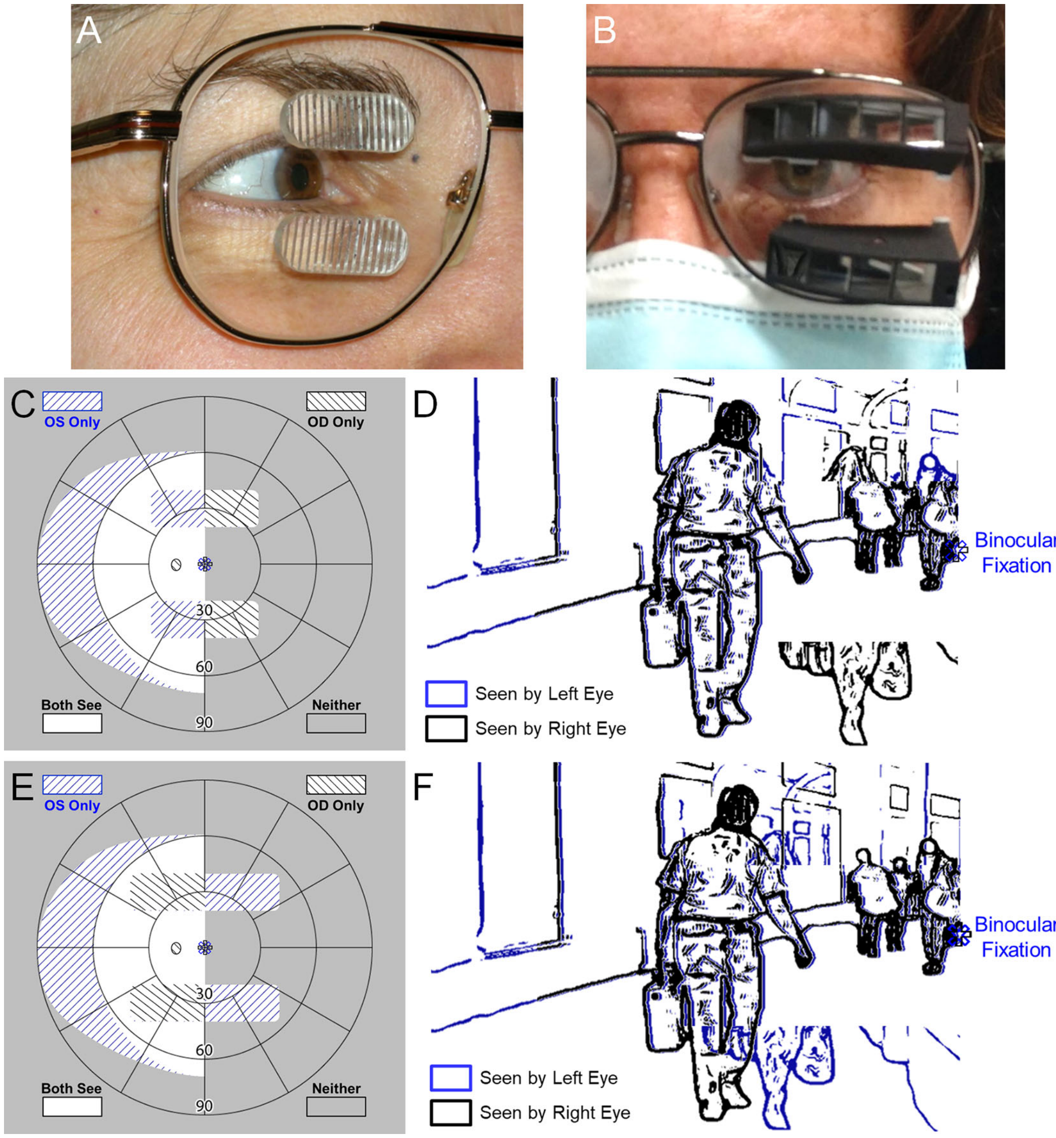

Figure 13. Peripheral prisms for field expansion in right HH. (**A**) Fresnel peripheral prisms of 57Δ, embedded in the right lens with base-right (base-out), and (**B**) Multiperiscopic peripheral prisms of 100Δ embedded in the left spectacle lens (due to limited space on the right lens nasal side (Peli et al., 2020)) with base-right (base-in). The clear area between the upper and lower prism segments enables maintaining single clear binocular central vision. The impact of the prisms is limited to the upper and lower periphery. (**C**) Binocular dichoptic field diagram and (**D**) percept diagram of a patient with right HH wearing the Fresnel peripheral prisms shown in **A** illustrating two 30° × 20° sections of field expansion (seen by the right eye only). The corresponding sections seen by the left eye only are, in fact, the apical scotomas blocking the views from the right eye. In the percept diagram **D**, upper and lower parts of the woman on the blind right side are shifted into the upper and lower periphery of the left seeing field (black as the right eye view), which are superimposed over the left eye view (blue) causing visual confusion. The images are slightly shifted to enable showing the left and right eyes view in the prsim free area between the peripheral prisms segements. (**E**) Binocular field diagram and (**F**) percept diagram of a patient with right HH wearing the multi-periscopic prisms shown in **B** illustrating two 45° × 20° sections of field expansion (seen by the left eye only) through the upper and low prism segments. The right eye compensates for the apical scotoma of the prism. (**F**) In the percept diagram, upper and lower parts of the woman in the blind side are also shifted into the upper and lower periphery of the seeing field (blue representing the left eye views) and are confused with the right eye view (shown in black). Because of the higher power, the woman in the blind side is located farther peripherally than with Fresnel prism in **D** enabling view of farther to the right wall and columns. Because of the proper fitting of the peripheral prisms (i.e., the angular extent of the peripheral prisms within the seeing field is the same as the prism power in degrees), there is no diplopia near the primary position of gaze.

side, whereas in the sector prism design it is located peri-centrally and may cause peri-central scotoma (Apfelbaum et al., 2013). In the peripheral prism design, the apical scotoma actually plays a positive role by largely reducing or eliminating the diplopia leaving only visual confusion.

To achieve visual confusion only, the angular size of the peripheral prism in the seeing field (field-of-view) should be the same as the prism power. For example, a 57Δ peripheral prism is designed to have 30° field of view to replace the view of 30° width in the seeing field (Figure 13C). The binocular viewing of the 30° blind field seen through the prism in one eye and the 30° seeing field seen by the fellow eye at the periphery results in binocular visual confusion, but without diplopia (Figure 13D). In a similar manner, 100Δ peripheral multi-periscopic prism needs to have 45° field of view (Figures 13E and 13F). These illustrated designs are free of diplopia in the primary position of gaze. When patients wearing such glasses shift their eyes to the blind side, they are being exposed to peripheral diplopia over an area as wide as the eye movement (Falahati et al., 2023; Jung & Peli, 2014; Peli et al., 2020).

Discussion

The explanation of the interactions between visual field loss and double vision, presented in this review, benefits principally from the use of the percept diagrams, introduced first by Apfelbaum et al. (2013). Field diagrams have previously been used almost exclusively in describing the effects of field loss. In many cases, it may be sufficient, but when eye deviations such as strabismus exists the binocular percept diagrams are necessary to represent the patients' view and help clarify the analyses and the discussion. In particular, the percept diagrams make it clear and intuitive to understand the important role of binocular confusion in field-of-view expansion. The percept diagram makes explicit the difference between diplopia and confusion, which are not distinct in the binocular (or even dichoptic) field diagram.

The field diagram cannot illustrate visual confusion directly. This is mainly due to the domain that the field diagram is using, the field of view. In conventional perimetry, a single target at a time is projected on the perimetry bowl to measure which portion of the field of view (i.e., area of the perimetry bowl) is visible to the patient with strabismus. If this target at such location is perceived as diplopic (asking the patient to report the number of targets (Jung & Peli, 2014; Jung & Peli, 2018a)), the field diagram can show a specific location as diplopic, although the location of the second diplopic image is not revealed by this process. There are two difficulties in mapping visual confusion perimetrically. First, the visual confusion cannot be measured in this conventional perimetry because there is no visible visual confusion with empty background (i.e., a single target overlaps with blank background). Second, although the visual confusion can be induced by using such patterned background in the perimetry bowl, it is difficult to find the binocular confusion pair (i.e., target location and the other location that overlaps onto the target) with the single target. Dichoptic perimetry or carefully measured physiological blind spots may demonstrate the eye deviation in the perimetry and field diagram, which may indirectly infer the visual confusion pair (i.e., same retinal eccentricities on both eyes) on the field diagram.

With the use of the percept diagrams, we were able to illustrate and analyze the diplopia and the role of the binocular confusion in field expansion and to show that confusion is necessary for field expansion. We were also able to show that confusion is insufficient on its own to expand the field, as in some conditions (e.g., ipsilateral esotropia with HH) confusion exists but does not result in field expansion (Figures 10I and 10J). At the same time, the percept diagram helps illustrating that diplopia has no role in field expansion.

Although in this article we annotated the foveation of each eye in the field diagram, the foveal position of the deviated eye is only estimated by measuring physiological blind spots if there is no dichoptic perimetry and controlled fixations. However, some field loss patients (i.e., BTH, tunnel vision smaller than 15° radius, blind side eye in HH) do not have a residual seeing field around the physiological blind spot and thus the foveation cannot be estimated. As shown in Figures 3C and 6C, without the foveations, the field diagram could be interpreted differently. Knowing the foveations and thus deviation is also mandatory to generate the percept diagram.

Diplopia and confusion are two components of the double vision phenomena, usually coexisting. However, in naturally occurring tropias or with full-field prism-induced strabismus, diplopia is reported more frequently than confusion. When the fixating eye is aimed at an object of interest, that object will always be perceived in diplopia, because its image falls also on a peripheral retinal location in the deviated eye. On the other hand, visual confusion only exists and therefore is noticed by the patient if another salient object exists whose image falls on the fovea of the deviated eye. For that to occur, the other object should be located at an eccentricity equal to the magnitude of the deviation. If the fovea of the deviated eye is pointing to a blank or low-contrast area in the field of view (not to a salient object), visual confusion is not apparent (see Figures 3B and 3C). The latter case is most likely to occur because salient objects are, by definition, less common in most scenes. It is also the case that when a full-field patient with strabismus walks in the three-dimensional space or changes his fixation with eye movements, the fixated (salient) object is always seen in diplopia, but the central confusion may be only intermittently manifested when another salient object image, falls on the deviated eye's fovea by chance. It is also important to realize that suppression does not eliminate the possibility of field expansion in the presence of confusion. If the suppressed image of an object moves due to a movement or another change in the object that created that image, the object becomes visible. As pointed out by Stidwill and Fletcher (2010), "The suppressed image is still being monitored by the visuum during rivalry".

In addition, any movement of the diplopic object because of its own movement or eye movements is synchronized with the movement of the duplicate, which may provide a strong cue to noticing the diplopia. On the other hand, the visual objects of interest seen in confusion could have different independent retinal motion and also move independently on the retina during observer's movements and thus may not benefit from the synchronization.

The possibility that strabismus providing field expansion in HH is adaptive has been raised in the literature, but remained unresolved (Bronstad et al., 2018; Donahue & Haun, 2007; Economides & Horton, 2021; Herzau et al., 1988; Koenraads et al., 2014). The more recent data on the higher prevalence of field expanding configurations in comparison with non-expanding conditions (Bronstad et al., 2018) seems to support the idea that these strabismus configurations are adaptive in a pediatric population. By further reviewing the high prevalence of field expanding strabismus in tunnel vision conditions, such as RP, or advanced glaucoma, we have added further support to the notion that field expansion strabismus may be an adaptive response to field loss. We have also suggested a mechanism for the manifestation of such strabismus in patients with phorias, where the field expanding strabismus may occur accidentally during changes in fixations changes breaking fusion.

Abnormal or anomalous retinal correspondence (ARC) is another sensory adaptation to childhood strabismus (Figure 14). In ARC, the correspondence of the two eyes is remapped in such a way that a nonfoveal region in the deviating eye, the zero point, has the same visual direction as the fovea of the fixating eye. This enables the fixated object to be perceived singly despite the strabismus. If the ipsilateral exotropia is accompanied by harmonious ARC (angle of remapping is equal to the angle of the deviation (Duke-Elder & Wybar, 1973; Kirschen, 1999)) in patients with hemianopia the "panoramic" visual field expansion provides veridical visual direction across the whole residual field, including the expanded field. Several cases of young patients with HH and ipsilateral exotropia were reported to develop ARC (Figure 14) (Herzau, 1996; Levy, Turetz, Krakowshi, Hartmann, & Nemet, 1995).

Most illustrations in this and in other articles dealing with binocular vision use only flat two-dimensional views (assuming the images are displayed on a curved screen at or near the horopter). In these simpler presentations, the disparity between both eyes' images is only a function of the angular misalignment of the eyes and is uniform across the image. The diplopia is the perception that occurs if the disparity is large enough to exceed Panum's fusional area (Fender & Julesz, 1967; Mitchell, 1966). Thus diplopia may be thought of as the manifested/apparent disparity. In the three-dimensional

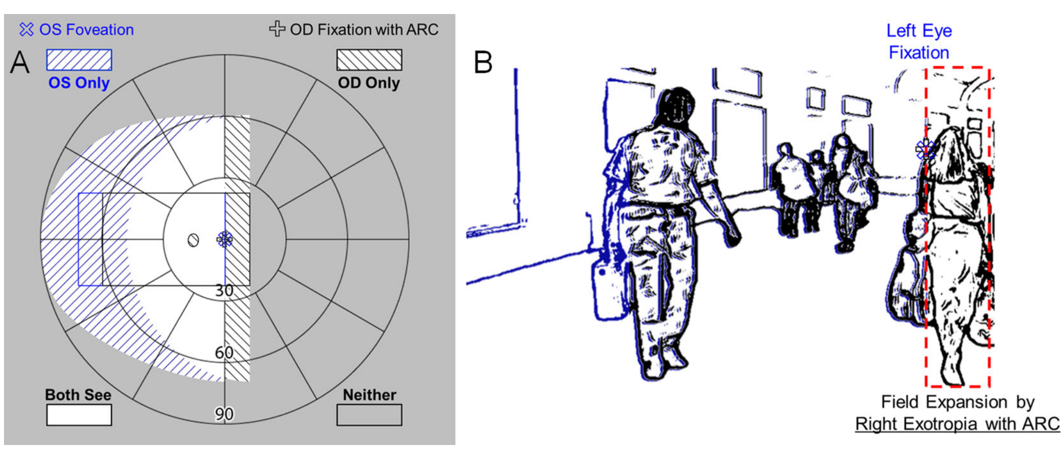

Figure 14. "Panoramic vision" in right HH patients with strabismus and ARC. (**A**) Field diagram and (**B**) percept diagram of ipsilateral exotropia with ARC. Due to the development of ARC, the field expansion achieved from both ipsilateral exotropia or contralteral esotropia (not shown) is without double vision in the peri-peripheral vision. The left eye view (spanning 72°) is shown in blue and right eye view in black (in **B** the two images are slightly shifted to enable showing the two where overlapping). The left eye and right eye fixation points are marked with the open blue x mark and black cross mark, respectively. The blue and black rectangles in **A** mark the angular extent of the left (72°) and right (60°) eyes percepts shown in **B**, respectively.

world, the situation is more complex. In this case, the binocular disparities of different objects' images vary with objects distance (depth) from the fixation target. Such disparities exist even without misalignment of the eyes (e.g., Figures 4A and 4C). When a person fixates on an object in three-dimensional space, other objects that fall within the (horizontal and vertical) binocular horopter (Banks, 2011; Shipley & Rawlings, 1970) are seen singly. The space included within these two horopters occupies a very small volume within the visible space. Objects that fall outside of the horopters are seen in double vision. This so-called "physiological diplopia" (Bishop, 1981) affects the perception of peripheral objects that happen to be at a sufficient distance from the fixated object, exceeding the limits of the horopters. Most of these objects may also be confused with other objects (creating peripheral binocular confusion).

Physiological diplopia is easily demonstrated for a person with patent binocular system (e.g., by fixating a finger closer than arm length while observing any far object, at any peripheral eccentricity, and even pericentrally). Yet peripheral physiological diplopia is rarely reported spontaneously. Peripheral physiological binocular confusion is even less commonly reported. Occasionally, people may notice the peripheral double vision spontaneously and seek care for the phenomena. The low awareness of peripheral double vision demonstrates that the annoyance and disturbance caused by diplopia, and confusion is much more impactful when they involve attended/central/fixated objects. All that is true for full fields and without strabismus.

Maintaining single binocular vision is a difficult task for the visual system. Single vision is desirable because double vision is annoying and can be confusing (in the literal sense of the word) and thus affects visual performance. As stated above, single binocular vision is only possible within a very small fraction of the visual world volume (the horopters). The two components of double vision (diplopia and binocular visual confusion) play different roles in achieving single binocular vision. Diplopia is the signal that can potentially drive vergence to reestablish fusion (Economides et al., 2012). Convergence (or divergence) reduces the magnitude of diplopia (the separation of all the diplopic images) and the direction of vergence needed is indicated by the diplopia being crossed or uncrossed. By eventually eliminating the diplopia, when the two images are fused, the system achieves single binocular vision. Without diplopia, the visual system does not have the control signal needed to reduce the vergence error (Economides et al., 2012).

Visual confusion has no role in driving vergence, as it provides no information regarding the direction or magnitude of the eye misalignment. However, when visual confusion is noticeable (if two different salient objects overlap), it may be more disturbing, annoying, and unnatural than diplopia. Although there is nothing inherently unnatural about seeing two trees, two tigers in the savannah, or two identical kittens in different locations (even when the nonfoveated copy is seen with lower resolution and contrast sensitivity in the periphery), seeing two different people (or two different animals) in the same direction/position is indeed unnatural and physically improbable.

In adult onset strabismus without field loss, binocular confusion may result in binocular rivalry, where one of the two images predominates at a given time (Alais & Blake, 2005). Rivalry can be global, where the image of one eye predominates over the whole field of view or, frequently, it can be local where one eye's image predominates at one place and the image from the other eye predominates at other places in the field of view at any instant. In patients with double vision, the binocular rivalry eliminates the confusion aspect of double vision, as only one view predominates at every instant and location. However, the diplopia does not affect binocular rivalry. In fact, it may be enhancing its perception or break the rivalry because of the elimination/reduction of visual confusion. Suppression of confused images from one eye may be thought of as an extreme case of binocular rivalry where one image/eye predominates almost all the time (Haun & Peli, 2014; Jampolsky, 1955).

It is frequently stated that diplopia is the stimulus for suppression in childhood constant strabismus (Serrano-Pedraza et al., 2011), yet it is the suppression of peripheral retina in the deviating eye that eliminates diplopia (Jampolsky, 1955). Suppression of the fovea of the deviated eye will not relieve diplopia, but it will eliminate confusion (Jampolsky, 1955).

Patients frequently refer to the magnitude of the diplopia as it relates to the angular separation of the images (an expression of the magnitude of the eye deviation). They report larger separation as more diplopia and seem to think that smaller separation is better. This might be a naïve, although understandable, belief that as the angular magnitude of the separation gets smaller the condition is improved. In fact, smaller separation of the diplopic images may result in more disturbance. For example, in reading, small diplopic separation appears like blur and may be more impairing than larger separations.

However, if the separation is very large such as the case in very large strabismus, the patient may have difficulty noticing the diplopic image, as it is farther peripherally away from the attended fixated image and imaged at farther peripheral retina, where resolution and contrast sensitivity are poorer, all making the diplopia less noticeable and thus less bothersome. Some inappropriate prism fittings or eye scanning into the blind side with peripheral prisms (Jung & Peli, 2014) cause diplopia between the views with and without peripheral prisms. However, patients do not report this diplopia and barely notice it even during the perimetry conducted specifically to document that diplopia (Jung & Peli, 2014).

It may be prudent to consider if the patients may express some important observation regarding the relief from symptoms that may result from smaller angle of deviation. For patients who can fuse, it may be possible that with reduced angle of diplopia due to prism or surgery, they will be able to fuse from time to time. Intermittent diplopia with lower rate of occurrence may be reasonably considered as improvement. On the other hand, when the diplopia angle is small, different parts of the same object, seen diplopically, may also be confused with other parts.

As mentioned above, diagnosing of strabismus and determining the magnitude of the eye deviation requires the presence of diplopia of the test target. An important clinical consideration in these cases of strabismus and field loss is the difficulty in measuring the deviation. Most subjective clinical techniques for measuring magnitude of phoria or tropia require diplopia or at least "split diplopia." Faced with confusion without diplopia, these techniques do not work. To be able to measure the deviation, one has to first reduce the deviation using a prism to the point that the field overlaps significantly (this requires a good estimation of the deviation first). This reestablishes diplopia within the residual fields and enables refining the measurement with the standard techniques. We have shown in many conditions of field loss, the lack of diplopic image of the test target interferes with the measurement and may prevent the successful testing procedures.

The interaction of diplopia and confusion with visual field loss and with partial prism, in particular the ability to dissociate the two phenomena may provide experimental tools for further study of the properties and roles of diplopia and confusion in normal and in binocular dysfunction and disease. Better understanding may lead to better treatments and better clinical implementation of rehabilitative devices. The proper design of peripheral prims to reduce or eliminate diplopia (Peli, Bowers, Keeney, & Jung, 2016) is an example of such progress. Dissociation of diplopia and confusion in clinical cases may enable use of such patients to examine questions about binocular vision in general. For example, in condition of confusion without diplopia, one can determine if suppression developed without diplopia and in condition of pure diplopia without confusion, as in BTH and exotropia one can determine if indeed diplopia without confusion may result in suppression. Such superposition is needed to expand the field (the only other known way to expand the field is minification, and minification does not expand the field in HH.

The scotomas addressed in this review; tunnel vision, HH, and BTH are all large scotomas that extend to the end of the natural field. This was not an intentional selection. It happens to be complementary to our recent paper about the invisibility of scotomas (Peli et al., 2023). In that article, the only scotomas addressed were smaller scotomas surrounded by vision, excluding the scotomas included here. To our knowledge, such smaller, usually central scotomas were not reported to result in double vision, even for patients with preexisting childhood strabismus. These different categories of scotomas may have important differences related to their interaction with binocular vision and double vision. These differences needs to be explored further.

Keywords: double vision, diplopia, visual confusion, multiplexing, field loss, strabismus, vision rehabilitation, scotoma

Acknowledgments

Supported by the National Institute of Health (NIH) grants R01EY031777 (JJ), R01EY023385 (EP), and P30-EY003790 (SERI), Margaret and Leo Meyer and Hans M. Hirsch Foundation.

Commercial relationships: Peli has three patents for peripheral prisms, assigned to Schepens, one of these is licensed to Chadwick optical, Inc.
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Appendix 1: Clinical binocular measurements without visual field loss

Clinical tests used to diagnose manifest strabismus in distinction from heterophoria typically depend on diplopia. These tests usually have little to do with confusion. The same is true of the tests used to quantify the magnitude of the deviation. Faced with confusion only without diplopia, these techniques do not work. In both cases (phoria or tropia), the lateral eyes' deviation is further classified as exo (divergent) or eso (convergent) deviations. Vertical deviation is further classified as hyper (upward) deviation versus hypo (downward) deviation. In the case of vertical heterophoria, the right hyper is the same as left hypo deviation. With manifested tropia the deviation is allocated to the non-dominant and non-fixating eye (i.e., right exotropia is different from left exotropia). In addition to the lateral and vertical deviations, the eyes may be misaligned rotationally, resulting in torsional phoria or tropia (Guyton, 2008a; Lemos & Eggenberger, 2013; Sullivan & Kertesz, 1978; Woo, Seo, & Hwang, 2005).

The diagnosis of tropias versus heterophorias is typically achieved with the cover-uncover test (Table A1, Peli & McCormack, 1983; Scheiman & Wick, 1994). In the case of tropia, upon uncovering the dominant eye, it re-establishes fixation of the target with a saccadic movement. However, when uncovering the tropic eye, that eye remains at its deviated position, and no movement is noted. In a patient with heterophoria, the covered eye moved into the phoria position under the cover, using asymmetric vergence, and upon uncovering either eye, the diplopic view of the fixation target triggers the vergence (that is composed of observable unequal saccades of both eyes combined with less visible smooth symmetric or asymmetric vergence movement) to reestablished fusion, Peli & McCormack, 1983). In the absence of diplopia, because of monocular field loss, that test may fail to work upon uncovering one or either eye. This may be the case in patients with the optic nerve syndrome(Swan, 1948) or similar cases where fixated object image falls onto the optic nerve of the deviating eye and thus avoiding the diplopia (Vera-Diaz & Peli, 2008). The Hirschberg and Krimsky tests (Joo, Koo, & Moon, 2013) require the patient to fixate a bright light source but do not require perceptual or eye movements response from the patient. Thus it is not affected by lack of diplopia. Unfortunately, the accuracy of these tests is very poor even for experience strabismologists (Choi & Kushner, 1998).

The magnitude of the deviation is measured using the alternate cover test (Table A2), sometimes called *prism*

Condition	RET	RXT	LET	LXT	EP	XP
Test Action	Observed movement of the uncovered eye					
Uncover RE	No RE movement	No RE movement	RE moves temporally	RE moves nasally	RE moves temporally	RE moves nasally
Uncover LE	LE moves temporally	LE moves nasally	No LE movement	No LE movement	LE moves temporally	LE moves nasally

Table A1. Cover-Uncover test for the diagnosis of lateral strabismus versus heterophoria. Eye movements observed upon uncovering right or left eye of patients with normal complete visual fields with various strabismus conditions. Only one eye can be observed at a time. In this test, it is the eye being uncovered. *Notes*: EP, esophoria; LE, left eye; LET, left esotropia; LXT, left exotropia; RE, right eye; RET, right esotropia; RXT, right exotropia; XP, exophoria.

Condition	RET	RXT	LET	LXT	EP	XP
Test Action	Observed movement of the uncovered eye					
Switching cover from RE to LE	Against the cover movement	With the cover movement	Against the cover movement	With the cover movement	Against the cover	With the cover
Switching cover from LE to RE	Against the cover movement	With the cover movement	Against the cover movement	With the cover movement	Against the cover	With the cover

Table A2. Alternating Cover test for measuring the magnitude of the tropia (or phoria) with normal complete visual fields. The eye movements observed upon switching the cover to the other eye. Here too only the uncovered eye is observed. The prism power needed to neutralize the movements quantifies the eye deviation. *Notes*: EP, esophoria; LE, left eye; LET, left esotropia; LXT, left exotropia; RE, right eye; RET, right esotropia; RXT, right exotropia; XP, exophoria.

alternate cover test. In both tropia and heterophoria, with no field loss, upon alternating of the cover the uncovered eye saccades back to the fixation target. The patient-subjective perception of the direction of the fixation target movement is consistent with the observed direction of the eye movements, being with or against the movement of the cover. The observed eye movements are then neutralized with a prism bar, thus measuring the magnitude of the deviation.

All this works fine with normal visual fields. However, with visual field loss, upon uncovering an eye the fixation target may not be visible if it falls into the scotoma in the just uncovered eye. As the cover is moved, the patient who does not see the expected fixation target may start looking for it by searching randomly to the right or left resulting in inconsistent direction and magnitude of the eye movement. The impact of such effects on binocular testing in various conditions is addressed below. There are numerous other ways for measuring the magnitude of the eye deviation (e.g., the Maddox rod, the von Graefe, and the modified Thorington) (Schroeder, Rainey, Goss, & Grosvenor, 1996). All of these tests are also dependent on patent diplopia to obtain a response from the patient (eye movement or verbal response). The diplopia may not be available if the target falls into a scotoma in one eye. The failures of the test in various field loss conditions are addressed within the sections related to the specific field loss conditions (Tables A1 and A2).

Appendix 2: Diagnosing strabismus using the cover-uncover test in the presence of HH

The presence of HH substantially complicates the use of Cover – Uncover test for the diagnosis of the strabismus. Consider a patient with right HH that also has field-expanding right exotropia (RXT). When the dominant left eye is covered, the right exotropic eye moves nasally to foveate the fixation target and the left eye moves temporally. As the left eye is uncovered the fixation target falls into the blind right hemifield in the left eye while the right eye continues to see the target (unless or until it may be suppressed). Thus the expected nasal movement of the left eye is not seen (at least not at first), a result that is inconsistent with when the test performed on an RXT patient (dominant left eye) with intact visual fields. Covering and then uncovering the right, exotropic, eye results in no movement, as it would with an intact field (Table A1).

Next consider the RXT patient but with left HH. Covering and uncovering the exotropic right eye results in the expected no movement of the right eye (or the left eye), as the left eye continues to foveate the target. When the dominant left eye is covered the right eye moves nasally to foveate the target. The left eye moves temporally (left) under the cover so that when it is uncovered the target is in the seeing right hemifield and retakes the fixation with a nasal movement consistent with the case of a RXT patient with intact field. Thus the test performed ordinarily for the left HH case but not with the right HH (Table A3).

Third let's consider the RET with right HH with the dominant left eye fixating the target; the target is not seen by the right eye because the target is in the bling right hemifield. Covering and uncovering the right eye results in no eye movements, as is the case without the field loss. Covering the left dominant eye eliminate the target view from both eyes. It may take the patient some time to find the target with the right eye using random search. At that time, the left eye under the cover has moved nasally. Upon uncovering of the left eye, the fixation target will be seen on the left hemifield of the left eye triggering the expected eye movement temporally to the left, as it does without the field loss. Therefore, in this case we have normal response when uncovering either eye. Table A3 gives all possible combinations of lateral HHs and lateral tropias and the responses upon uncovering each eye. The responses that are inconsistent with those obtained with strabismic patients with intact visual fields are marked by gray highlight. These differences from the responses observed with patients with intact field are not simple but are possible to analyze and consider when facing such a patient.

Measuring the magnitude of the eye deviation in the presence of HH

Using the alternate cover test to measure the magnitude of the eye deviation in patients with HH will run into the same problems addressed above with the Cover-Uncover. For strabismus cases the combinations highlighted in Table A4 will result in the same lack of movements in these conditions because the fixation target falling into the blind hemi field, the intact field the uncovered eye is always moving, and the prism is used to neutralize the movement. In the case of HH, it is still possible to use the test by observing just the reduction and eventual neutralizing of the movement in the one eye, ignoring the eye that is not moving due to the fixation target falling into the blind hemi field. The difficult is that if the target is not visible the patient may start searching for it with random eye movement, which may be in either direction, and thus

	Right HH				Left HH			
Conditions	RET	RXT	LET	LXT	RET	RXT	LET	LXT
Test Action	Observed movement of the uncovered eye							
Uncover RE	No RE movement	No RE movement	No RE movement	RE moves nasally	No RE movement	No RE movement	RE moves temporally	No RE movement
Uncover LE	LE moves temporally	No LE movement	No LE movement	No LE movement	No LE movement	LE moves nasally	No LE movement	No LE movement

Table A3. Cover-Uncover test for the diagnosis of strabismus versus heterophoria in HH. Eye movements observed upon uncovering right or left eye for various strabismus condition or heterophoria in patients with complete left or right HH. Only one eye can be observed at a time. In this test it is the eye being uncovered. The cells in the table with gray highlighted text indicate the clinical condition and test actions that result in response that is inconsistent with the response of patients with intact visual field. *Notes*: LE, left eye; LET, left esotropia; LXT, left exotropia; RE, right eye; RET, right esotropia; RXT, right exotropia.

	Right HH				Left HH			
Conditions	RET	RXT	LET	LXT	RET	RXT	LET	LXT
Test Action	Observed movement of the uncovered eye							
Cover from RE to LE	No RE movement	With the cover movement	No RE movement	With the cover movement	Against the cover movement	No RE movement	Against the cover movement	No RE movement
Cover from LE to RE	Against the cover movement	No LE movement	With the cover movement	No LE movement	No LE movement	With the cover movement	No LE movement	With the cover movement

Table A4. Alternate Cover Test for measuring the magnitude of the strabismus in HH. Eye movements observed upon uncovering the right or left eye in various strabismus conditions in patients with complete left or right HH. Only one eye can be observed at a time. In this test too, it is the eye being uncovered. The cells in the table with gray highlighted text indicate the clinical conditions and test actions that result in response that is inconsistent with the response of patients with intact visual. *Notes*: LE, left eye; LET, left esotropia; LXT, left exotropia; RE, right eye; RET, right esotropia; RXT, right exotropia.

confusing the observer. The same difficulties occur with measuring the magnitude of the phoria. For the same reason other measurements of eye deviation (e.g., the Maddox rod, the von Graefe, and the modified Thorington) (Schroeder et al., 1996) also fail when diplopia is unavailable in the cases where the target falls into the blind hemi field in one eye. At least in these tests proper questioning of the patient may reveal that they do not see the expected diplopic image in the deviating eye. Although Table A4 looks complicated, to perform the test in these cases all one has to do is to observe just the eye that is moving under the alternate cover test. There is always one, and by applying the prisms to that eye, the test can be perform with no difficulty.