

The evolution of forebrain contralaterality as a response to eye development: the path of least resistance

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Abstract

The origins of vertebrate forebrain contralaterality remain to be adequately explained. A new and novel idea outlined previously by this author as the *Inversion Hypothesis* (2009) proposed that the vertebrate forebrain developed its 'wrong-sidedness' as a response to the inversion of visual images in an ancestral vertebrate possessing a single frontal eye. Here we develop further the likely mechanisms such processes would entail. Using the single frontal eye of ancestral protochordates as a theoretical starting point for the evolution of bilateral vision in early vertebrates, a simple evolutionary pathway involving incremental improvements in retinal design shows how forebrain contralaterality could evolve due to the requirements set by geometric optical physics alone. This untested proposition, while challenging in many respects, provides a concise and credible framework based on established biological data, from which testable corollaries can now be drawn.

Keywords: Contralaterality, Inversion Hypothesis, visual evolution, cyclopia.

1. Introduction

The eye is a sensor of light photons that has evolved in a variety of forms ranging from the simple ocellus of invertebrates to the complex camera eye of vertebrates but its function differs according to its form. In some it acts only as a crude sensor of the presence of light. In others it alerts its possessor to the direction and movement of a nearby predator. In still others it gives to its owner a detailed, focussed image equipping it with formidable predatory advantage over its prey.

All such varieties of form, associated as they might be with a multitude of different body forms, developed supportive and integrative neural systems incrementally as selective and adaptive pressures allowed. In simple forms such as echinoderms a simple reflexive system might suffice. In early vertebrates, however, a complex forebrain, including midbrain, were required due to the increasing sophistication both of the evolving camera eye and the numerous sensorimotor systems with which it required integration. This appears to have taken place in the context of an 'arms race' toward increasing predatory power (Northcutt and Gans, 1983).

The enigmatic contralateral nature of these integrative systems of the vertebrate forebrain is thought by some to have developed to facilitate escape from predators (Sarnat and Netsky, 1974). An

earlier idea, the influential theory of Cajal (Ramon y Cajal, 1898. Llinas, 2003), posited that contralaterality was required in order to correct the inversion of images made by two lateral imaging eyes. These and other theories were based on the assumption that the vertebrate forebrain evolved its contralateral format *after* the acquisition of two eyes, and all fail to make convincing arguments more favourable than their alternatives. With respect to escape mechanisms, to invest so heavily in a contralateral forebrain simply for escape when an ipsilateral brain could have sufficed, would suggest evolution is not always efficient. As for correcting inverted images, invertebrate cephalopods, which possess chambered eyes like vertebrates, correct the inversion of images without resorting to a contralateral brain. These theories fail also to consider that the proximate ancestor to vertebrates appears to have had a single frontal eye; that the eventual chambered eye must have developed incrementally in a predictable pathway from this single rudiment of retinal cells; and since having encouraged the formation of a primitive retina, the laws of optics set rules of engagement that were absolute, framing parameters with which supporting neuroanatomy must comply.

Nilsson and Pelger's theoretical design for the evolution of the vertebrate eye (Nilsson and Pelger, 1994), if applied to an ancient craniate ancestor with

a *single* frontal eye similar to the extant protochordate *amphioxus*, reveals a process of evolving bio-optics that allows little alternative but for the development of a supporting contralateral forebrain. Such a proposed process might best be described in two stages as in the *Inversion Hypothesis*, previously published by this author (Loosemore, 2009). In the first, *Inversion*, the incremental evolution of the initial single eye from a primitive retina to a camera eye with a lens, dictated the establishment of contralaterality, firstly in the retina (Fig 1), and subsequently in the supporting adnexal forebrain infrastructure (Fig 2). In the second, *Chiasmation*, the fully developed single imaging eye bifurcated to form two lateral eyes in a counter-intuitive way dictated by the already conserved contralateral requirements of the diencephalon (Fig 2, Fig 3). In figures 1 and 2, only the changing shape of the retina has been borrowed from Nilsson and Pelger (1994).

2. The Eyes of Chordates

A variety of forms in both number and structure of vertebrate eyes have existed at different times. While there is no argument that two frontolateral imaging eyes have been primary for vertebrates for most of their history they have shown considerable flexibility with respect to their size, structure, position, field overlap, and possibly number. Based on fossil evidence alone, however, it might be reckless to assume that the earliest vertebrates also possessed two frontolateral eyes. The remarkably well preserved specimens of the Devonian agnathan *Euphanerops longaevus*, which may well be a stem lamprey (Janvier, 2008), certainly don't appear to. For a thorough description and analysis of these fossils see Janvier and Arsénault (2007).

Even once established as the primary vertebrate form, two frontolateral eyes altered their arrangement through a range of adaptive presentations. In modern fish, for example, the eyes are lateral and the visual fields do not overlap. In primates the eyes are frontally placed with overlapping fields providing stereoscopic vision. The agnathan hagfish has eyes buried beneath the skin (Kusunoki and Amemiya, 1983) and cavefish are blind because of genetic selection for living in caves (Borowsky, 2008). Flounder have both eyes on one side of the head and evolutionary attempts at four eyes have been made in fish allowing both aquatic and aerial vision (Schwab et al, 2001). Throughout their history vertebrate eyes have shown remarkable adaptive flexibility.

Secondary visual systems in vertebrates have been equally diverse. The dorsal parietal, or pineal, eye

was present in placoderms, all major groups of bony fish of the Devonian Period, ancestral amphibians, and reptiles (Cronly-Dillon and Gregory, 1991). It persists in different forms today in many fish and reptiles, and even humans carry its vestige in the form of the pineal gland. Other more primitive light sensors have also existed in vertebrates such as the ocellus-like light sensitive cells in the lateral-line system of some fish.

As for the nature of chordate eyes that preceded those of vertebrates there remains much conjecture. Modern forms of such species are our only source of information. Such species belong to the two other chordate subphyla, the urochordates (tunicates) and cephalochordates (lancelets).

Modern urochordates, primarily appendicularians, ascidians, doliolids, salps and pyrosomes, display a variety of primitive light sensors thought mostly to be reduced, and none have the imaging ability of vertebrates (Lacalli and Holland, 1998). The larvae of most families of ascidians possess only a single ocellus with a pigment cup, though some ascidian ocelli have ciliary lamellae which may be reduced versions of the amphioxus lamellar body or the remnant of an ancestral frontal eye (Lacalli, 2001). The ascidian *Botryllus* has a photolith which combines a pigment-containing cell with a cluster of sensory cell processes. The single eye of salps appears to be a dorsal structure without homology in other known tunicates and is possibly homologous to the dorsal lamellar body of amphioxus (Lacalli, 1998).

The extant cephalochordate amphioxus, on the other hand, has a frontal 'eye' that has some retina-like features and is apparently not reduced from something more complex (Lacalli et al, 1994). Though single, it is considered by Lacalli to have been the homologue in primitive cephalochordates of the bilateral vertebrate eyes that were later to follow. Unfortunately the intervening period of evolution is poorly understood due to a paucity of both fossils and extant species representative of the time. Fragmentary pieces of conodont fossils, for example, fail to adequately inform us of early vertebrate visual structure (Donoghue et al, 1998) and extant craniates such as the lamprey are so sophisticated neurologically compared with cephalochordates that they lie outside the parameters of this endeavour to explore earlier transitional visual evolution in craniates.

3. The Optic Chiasm

The optic chiasm of vertebrates, the midline decussation of the optic nerves formed by the need for the eyes to connect to their contralateral forebrain,

has been the focus of much study over the years and is thought to hold the key to our knowledge of the chemotactic factors that induce midline brain morphogenesis (Jeffery, 2001).

The optic chiasm lies at the base of the hypothalamus in all vertebrates except the hagfish where it is contained within the diencephalon (Kusunoki and Amemiya, 1983). The vertebrate chiasm's most surprising feature is its highly diverse architecture. The size of the decussating portion of fibres at the chiasm, while in all vertebrates is larger than the uncrossed portion, varies between complete and partial and is proportionately smallest in animals that have frontal eyes such as primates (Jeffery and Erskine, 2005). In humans, while a sizeable proportion of optic fibres decussate at the chiasm, an almost equal proportion fail to do so. In teleost fish the decussation is largely complete (Mogi et al, 2009) and many birds have very small uncrossed pathways (O'Leary et al, 1983). In the agnathan lamprey a small proportion are ipsilateral (Kosareva, 1980. de Miguel et al, 1990). Traditionally, across all vertebrates, the relative size of the decussating bundle of fibres compared to that of the non-decussating fibres is thought to be inversely proportional to the overlap of the visual hemifields (Jeffery and Erskine, 2005).

Of the fibres that decussate there is also variation in the architecture of their decussation. Sometimes they cross left over right; in others right over left; in still others the fibres mesh in a variety of ways (Mogi et al, 2009). Why the fibres should decussate at all has not yet been satisfactorily explained.

4. Protochordates as ancestral vertebrate models

The long-running debate as to which of the protochordates, urochordates (tunicates) or cephalochordates (lancelets) were most proximate ancestrally to vertebrates continues to this day. Recent phylogenetic analyses based on genomic sequencing in tunicates have called for a reappraisal of the traditional view that cephalochordates are more closely related to vertebrates by suggesting tunicates are phylogenetically closer to vertebrates while being molecularly and morphologically highly derived (Delsuc et al, 2006). While this debate has some way to run it remains that the cephalochordate *amphioxus* has a more complete and fully developed complement of sensory structures and cell types making it a better model for the ancestral condition of the CNS (Lacalli, 2001). It is the only surviving prevertebrate segmented chordate (Berrill, 1987), and it lacks degeneration and signs of genomic duplication of

vertebrate genomes (Holland, 1996). *Amphioxus* continues to be, therefore, the key organism for modelling the protochordate ancestor to vertebrates (Holland, 2006).

Lacalli's detailed prosectional work on the rostrum of *amphioxus* allows the construction of a provisional model of a proximate ancestor to vertebrates based on the following rostral homologies in *amphioxus* (Lacalli, 1996);

- The single frontal eye is homologous to the lateral eyes of vertebrates.
- The cerebral vesicle is homologous to the forebrain (prosencephalon) of vertebrates.
- Row 2 cells of the frontal eye complex are homologous to the retina of vertebrates.
- Row 4 cells of the frontal eye complex are homologous to the optic chiasm of vertebrates.

Based on the absence in such a model of rostral contralaterality or an actual chiasm, it follows that forebrain contralaterality, the formation of the optic chiasm, and the bifurcation of the single eye to form lateral eyes must have been later developments in basal vertebrates. Assuming the bilateral eyes of vertebrates evolved incrementally from the single homologous frontal eye of an ancestral protochordate, what would have been the quickest and most direct evolutionary path that incorporated bifurcation, contralaterality, and formation of the chiasm?

Based on the evolutionary principle of incremental improvements in design, the first major evolutionary change from a single non-imaging frontal eye in a vulnerable herbivore would have been to a single frontal *imaging* eye because the alternative, two non-imaging eyes, would have offered no evolutionary advantage (Fig 4; A,B,C). The next landmark stage would have been the *bifurcation* of the single imaging eye to form two imaging eyes, the placement and connections of which would be dictated by the needs of the pre-established forebrain infrastructure (See Section 5). Not only would two frontolaterally placed eyes be a simple development neurologically, laterally placed eyes provide wider visual fields, useful to animals that need to be aware of those hunting them (Jeffery and Erskine, 2005). As for the alternatives at this stage; two frontal eyes without decussation would have been blind to images (See Section 5 and Fig 4; D,E); two frontal eyes with visual field overlap would have required a complex partial decussation (Fig 4; G), an implausibly large evolutionary leap. Two frontolateral eyes with complete decussation (Fig 4; F) would, therefore, have been the most parsimonious next step in terms of incremental viability. From here a complex partial

decussating chiasm would then have been very achievable (Fig 4; H).

Nilsson and Pelger (1994) have shown, for other reasons and in a generic sense, that a complex imaging eye, such as the vertebrate eye, might have evolved within a few hundreds of thousands of years. They simulated simple incremental additions to the existing retinal structure beginning with a small cluster of retinal cells and culminating in a sophisticated camera eye with lens (Fig 2: a;i). If we adopt this model also, applying it to the single-eyed common ancestor of cephalochordates and vertebrates, we would find that the contralaterality of the vertebrate brain was a very early development in non-imaging craniates and predated the bifurcation of the single eye. As shown below, the incremental development of contralaterality firstly by the retina and consequently by the diencephalon was dictated by the increasing concavity over time of the single non-imaging retina.

5. Proposed mechanisms of contralateral forebrain evolution in craniates

This section seeks to bring greater clarity to the two primary processes of early vertebrate visual evolution, *inversion* and *chiasmation*, first proposed by this author in a previous paper (Loosemore, 2009). In that paper, inversion referred to the contralateralisation of the early vertebrate forebrain as a consequence of the inverting of visual images in an ancestral vertebrate that possessed a single frontal imaging eye. Chiasmation referred to the later process that bifurcated the single eye to produce two lateral eyes with an optic chiasm. This present paper further develops these ideas, particularly inversion, by introducing Nilsson and Pelgers' theory (1994) of incremental improvements in retinal design to the *Inversion Hypothesis* (Loosemore, 2009). In this way, inversion can be seen as beginning a little earlier than the acquisition of imaging, beginning as the retina first began to develop its concavity and only concluding with acquisition of the lens and imaging.

The word *craniate* is used here loosely to identify those animals that have features of both protochordates and vertebrates but which cannot strictly be classified as one or the other. Their legacy is to have evolved to the highly successful chordate subphylum *Vertebrata* but our knowledge of them as yet is largely only inferred, directly by their scant fossils and indirectly by way of a few surviving descendants. Such elusive ancestral craniates, or stem vertebrates, were the animals in which cyclopean chordate vision is likely to have evolved to become

bilateral and where the forebrain developed its contralaterality (Loosemore, 2009). They possessed bony brain cases which provided protection for the evolving brain, a stable platform from which the eyes could focus, and a structure from which appendages such as a jaw would later become operable. The stable head eventually decoupled from its rigid association with a body that was continually flexing thereby providing further stability for fixation of the eyes (Lacalli, 2001).

Prior to such stability, however, the side to side oscillation of the primitive protochordate head while swimming, as observed today in modern amphioxus, must have been necessary for the single eye to be of navigational benefit. The reason for this is that a primitive cluster of retinal cells at the anterior snout, not yet fashioned into a cup eye, might only inform the animal of the direction of a light source if the head rocked back and forth (Dawkins, 1996). The difference in intensity of light from one side of the arc to the other might have allowed some primitive assessment of the light source's direction. Without such oscillations a primitive single retina was powerless to judge the direction of a light source and even with such oscillations, amphioxus today has difficulty navigating intentionally, displaying only limited ability to detect ominous shadows (Lacalli, 2001).

If applied to cyclopean ancestral craniates, the development of the eye in the manner suggested by Nilsson and Pelger (1994) from a few photocells backed by a screen which gradually deepened centrally to form a cup, would have dictated an incremental decreasing need for sideways oscillation of the head due to increasing deselection of lateral streams of photons by the increasing curvature of the retina (Fig 1). This decreasing need for an oscillating head due to increasing discrimination of light source direction, would ultimately have led to the decoupling of the head from the movements of the body.

Although rapidly acquired, as shown by Nilsson and Pelger (1994), the evolution of the eye from a small cluster of retinal cells to a cup eye with a focussing and inverting lens (Fig 2: a;i) allowed its possessor to change gradually from an herbivorous non-imager toward being a high performance predator. This appears to have taken place in the context of a biological 'arms race' (Northcutt and Gans, 1983) in which improved technical design dominance required an equivalent surge in integrative computational power. This neural growth surge was particularly so for the forebrain and midbrain, the integration centres eventually supporting a pair of sophisticated stereoscopic imaging eyes where,

unlike the hindbrain, systems developed in a contralateral format.

With increasing curvature from a single flat retina to a concave screen-backed retina the incoming lateral extremes of the visual field were increasingly restricted to the contralateral retina due to increasing deselection of photons (Fig 1). With further concavity this contralateral retinal favouritism extended also to the more central retina until finally, with the development of an inverting lens by condensation of the anterior vitreous mass (Nilsson and Pelger, 1994), complete and exclusive retinal contralaterality was achieved. This process of *inversion* was a gradual process in the evolution of the single eye from a simple retina without hemifield discrimination to a retina that not only discriminated hemifields contralaterally but ultimately, due to the lens, discriminated them contralaterally, exclusively, and inverted the images across the midline (Fig 1). The final step of acquisition of a lens was a landmark for visual topological mapping in a primitive brain that was already established contralaterally but without prior discernment of images.

The first simple retina containing just a few photoreceptors and lacking the power to discriminate light source direction, and therefore lacking contralaterality, would likely have fed into a primitive brain without need of decussating connections. As in modern amphioxus, it would have been enough for each retinal cell to connect caudally and identically to the brain by way of single bifurcated ganglions informing both 'hemispheres' of the same retinal impulses (Fig 5).

As the retina expanded and the pit deepened, favouring discrimination of contralateral light sources, new non-bifurcated retinofugal connections might then have simply connected the new retinal extremes to their proximal ipsilateral diencephalon (Fig 2: a;ii). With increasing concavity and greater retinal favouritism for the contralateral fields, increasing numbers of ipsilateral connections would then have replaced the need for central bifurcated connections until, with complete contralaterality achieved by acquisition of the lens, only ipsilateral connections remained. It would not therefore be the imaging power of the lens or its inverting of images per se that initiated development of contralaterality. Simpler optics would have generated the primitive contralateral forebrain, initially by a growing retinal discrimination of photons received from the contralateral field and only later by complete bifurcation of the hemifields by acquisition of the lens. Contralaterality, and later contralateral imaging, would therefore predate the development of bilateral eyes and become the enduring format for the vertebrate forebrain, ultimately proving conservative

despite variations to sensor arrangements such as regressive blindness or unilateral eyes.

The next step in improving visual prowess in craniates, referred to as *chiasmation*, involved another small increase in effect, specifically as a further extension in the lateral range of visual imaging. Though requiring a significant mutational change in embryonic development it required no significant change to the topological mapping in the adult diencephalon. From morphogenetic evidence in vertebrate embryos, the diencephalon appears early in evolution to have moved forward to dissect the single optic primordium, and in the process generated a swap in sides of progenitor retinal cells across the midline (Varga et al, 1999) thus creating an optic chiasm (Loosemore, 2009). The resulting decussation in the adult, a crossing of the retinofugal fibres from each half of the original single retina, proved enduring, an apparent advantage over those animals without it (Fig 2: b;ii., Fig 3).

This bifurcation and midline crossing of progenitor retinal cells (PRCs) was demonstrated by Varga et al, whose study used a very specific fatemapping technique where a single PRC in the optic primordium of zebrafish embryos was injected with dye and its point of termination in the eye of the older embryo traced. After repeated dissections of different embryos for a range of different cells traced, around 80% of PRCs were shown to cross the midline irrespective of their prior proximity to the midline. Although emphatic, this discovery wasn't the focus of the study and the finding, because not emphasized, needs sifting from the data. More recent visually elegant studies of the same process of optic primordium bifurcation using 3D movie reconstructive techniques show all PRCs moving initially toward the midline as if to cross but apparently failing mostly to do so (Remboldt et al, 2006. England et al, 2006). It is likely that these later studies, while impressively sensitive, fail to track the crossing of the midline demonstrated by Varga et al because of the relatively non-specific technique of staining PRCs en masse.

The reason for the crossing of PRCs in the embryo and the resultant optic chiasm in the adult must relate to the already conserved contralateral diencephalon which matured to receive contralateral inverted visual inputs and which, in the process, had become irreversibly integrated topologically with complex motor effector systems. This somewhat hardwired arrangement, because of its complexity, would forever be favoured over the more flexible retinal arrangements. Retinal non-switch offspring (Fig 4; D,E) might still perceive the presence of a light source but would be born blind to visual images because their retinas no longer informed the

diencephalon of the inverted hemifields for which it was topologically built. Full-switch offspring however (Fig 4; F), would, if the resultant eyes were angled appropriately, experience no change to the way retinal images were received in the diencephalon except that images could be further sharpened and the range expanded by dedication of a complete eye solely to one hemifield (Fig 3). This sudden and potentially catastrophic bifurcation of the single eye of craniates, rather than inflicting demise, actually maintained and expanded the already longstanding relationship between the diencephalon and its contralateral visual hemifields.

In time, as the new bilateral arrangement of the retinas and their dependant optic chiasm varied across species between extensive overlap of visual fields and total exclusion of visual field overlap, the total crossing of the optic nerves at the chiasm incorporated varying degrees of ipsilateral non-crossed optic fibres.

Predictions of the hypothesis

The processes of inversion and chiasation raise a number of hitherto untested claims and in so doing invite falsification on a number of fronts. And since no craniates from this period remain extant today to help verify anatomically the existence of the neural pathways described, authenticity will rest with more subtle and varied demonstrations. These might be grouped in three ways, one palaeontological and the other two embryological.

1. A re-examination of known early vertebrate fossils possessing a single circular frontal stain without bilateral circular stains (such as *Euphanerops*) should consider the possibility that the single median stain is actually the remnant of a single frontal eye. If this finds favour in such Silurian and Devonian species we would then await the discovery of their similarly endowed ancestors from the Cambrian and Ordovician, periods which at present yield very few clues.
2. If the trans-vertebrate fetal abnormality of true cyclopia (lobar holoprosencephaly, or HPE1), thought to be the default condition when cyclopia-nulling genes simply fail to activate (Varga et al, 1999), represents the primitive visual condition, examination of cyclopes' retino-diencephalic connections should, if untainted by the various genetic

and chromosomal mutations that cause partial cyclopia, accord with those of inversion. That is, the globe, lens, retina and optic nerve should all be single and the optic chiasm should be absent.

3. The counter-intuitive prediction that follows from chiasation, that most progenitor retinal cells should cross the midline on bifurcation of the single optic primordium in all vertebrate embryos, should be re-examined and more emphatically demonstrated.

Conclusion

Based on the current best model for vertebrate visual and forebrain homologues in the common ancestor of protochordates and vertebrates, the most parsimonious pathway of visual evolution can be constructed using Nilsson and Pelger's theoretical evolutionary design of the eye and is supported by data-specific studies of optic morphogenesis. The resultant pathway reveals that the contralateral nature of neural infrastructure required to support an evolving primitive single frontal eye was a consequence of the interplay between a gradually evolving single retina and the laws of simple optical physics. In essence, contralaterality developed proportionately to the increasing concavity of the single frontal retina.

Such a dynamically evolving design, based on a single eye only, suggests brain contralaterality was an early development in single-eyed non-imaging craniates which later dictated the formation of the optic chiasm when cyclopean imaging craniates switched to bilateral non-stereoscopic vision.

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Conflicts of interest

This paper is based on the research of a single author, without financial or research relationships to any other bodies.

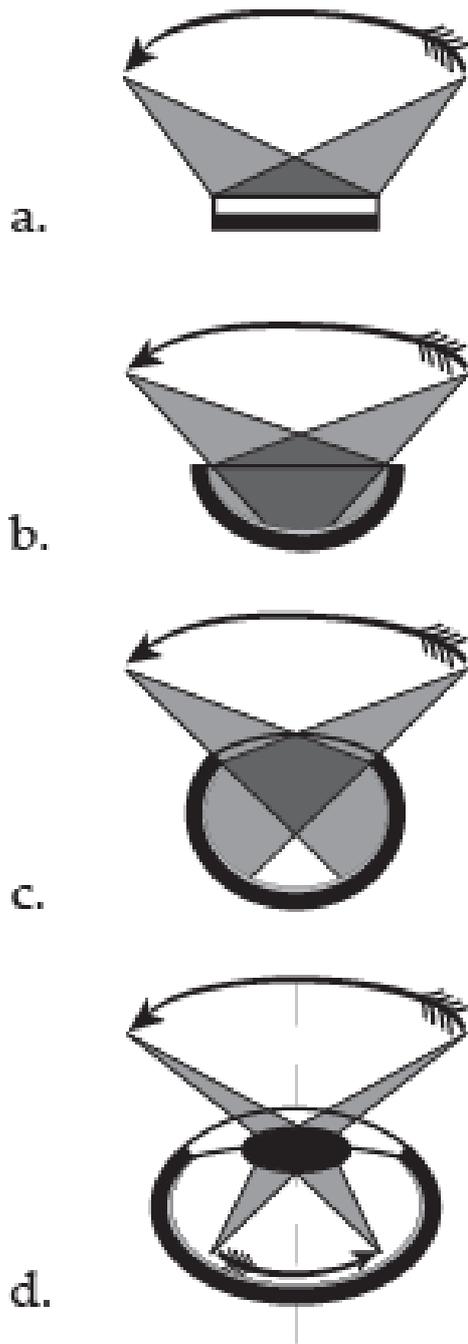


Fig 1. The evolution of increasing contralateral retinal discrimination of a light source in the early craniate retina. Dorsal cross-sectional view. Only the depiction of the retina is adapted from Nilsson and Pelger (1994). A rostral visual object is represented by an arrow. Shading represents all photon streams that reach the retina from the lateral extremes of the visual object.

- a) A simple flat retina cannot discriminate the direction of a light source because such a retina receives photon streams from all point sources equally.
- b) A deepening of the retinal pit favours increasing contralateral discrimination of light sources by ipsilateral deselection of photons.
- c) Contralateral discrimination of a light source extends, over generations, toward the midline as the retinal curvature increases.
- d) With acquisition of a lens all light is fully directed contralaterally and images are formed, and inverted.

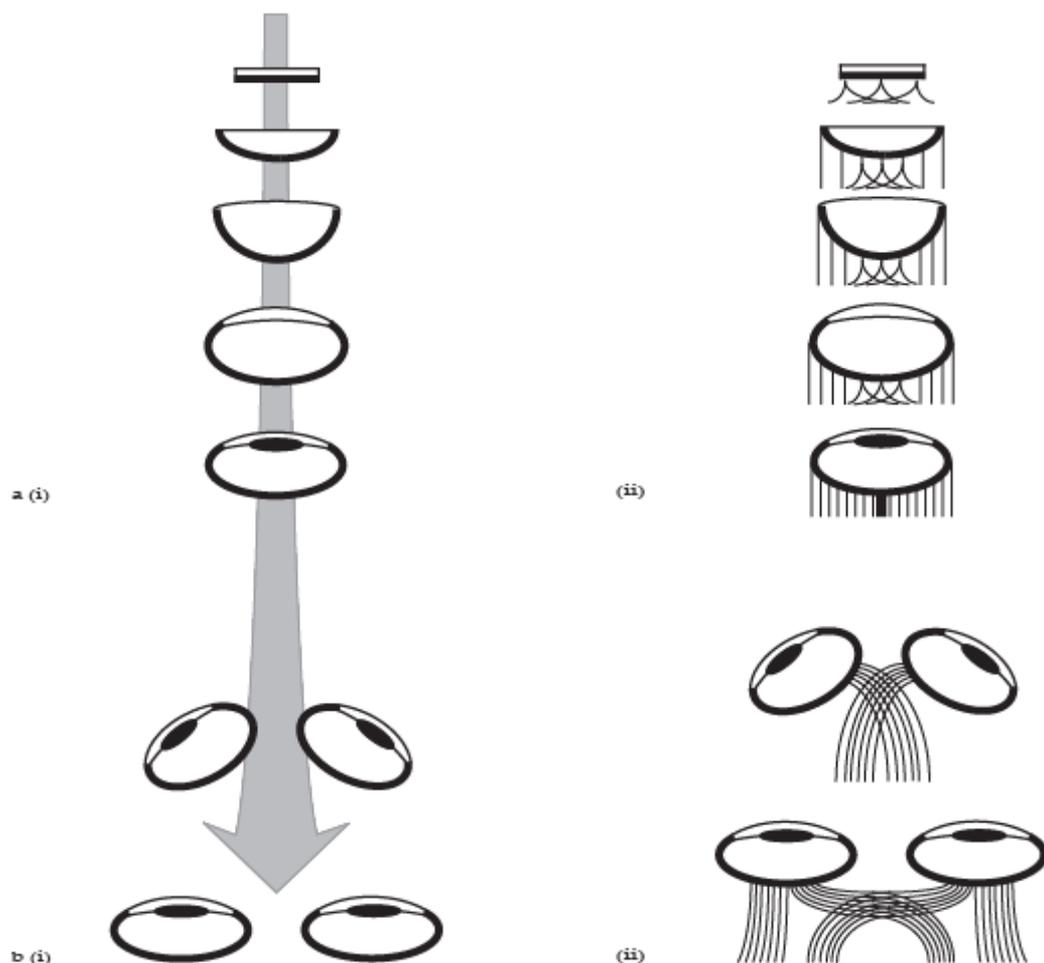


Fig 2. The Path of Least Resistance. Schematic dorsal cross-sectional view of the evolving retina in early craniates. Primitive to modern is represented by the shaded arrow. Rostral is to the top. Caudal attachments to the retina represent retinofugal ganglia.

- a) *Inversion*: the process of increasing contralateral retinal representation as the single retina in early craniates evolved to a chambered eye.
- i) Incremental evolutionary changes from a rudimentary retina to a chambered eye; adapted from Nilsson and Pelger and applied here to a single-eyed craniate.
 - ii) The same pathway with addition of proposed retinofugal ganglia beginning with bifurcated ganglia, as in modern amphioxus, changing to ipsilateral non-bifurcated ganglia as the retina increasingly discriminated contralateral light sources.
- b) *Chiasmation*: the process of bifurcation of the single imaging eye of primitive craniates resulting in the optic chiasm and bilateral eyes.
- i) The single imaging eye of early craniates bifurcates (by embryonic bifurcation of the single optic primordium) to produce bilateral, and later bifrontal imaging eyes.
 - ii) At bifurcation of the optic primordium, progenitor retinal cells cross the midline resulting initially in a complete chiasm in the adult, and later an incomplete chiasm when stereoscopy evolved.

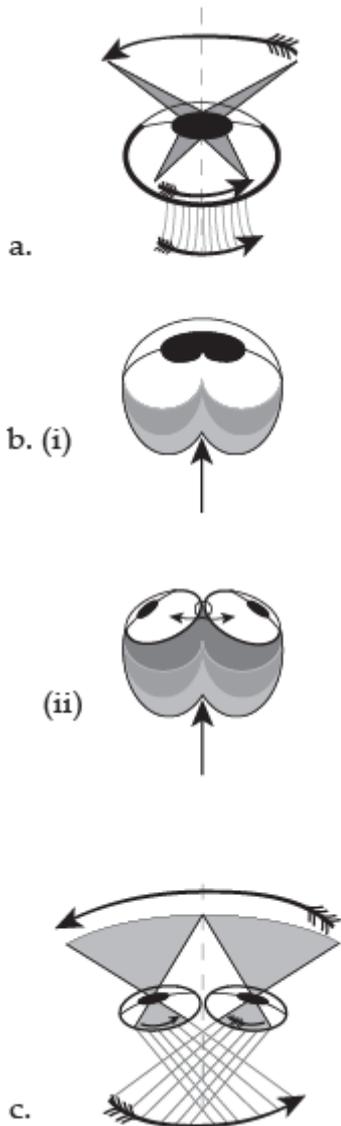


Fig 3. From Inversion to Chiasmation. Dorsal cross-sectional view of the evolving primitive eyes from a single imaging eye. A rostral visual object (arrow) is projected inversely in the diencephalon and is not altered significantly by the very disruptive chiasmatic process. Rostral is to the top.

- a) With the acquisition of a lens in the adult single-eyed craniate, the retina that previously received largely contralateral inputs now received images that were inverted and completely contralateral. Ipsilateral retinofugal ganglia would inform the diencephalon of the inverted images in an equivalent topological format (caudal arrow).
- b) At chiasmation, anterior movement of the diencephalon to bifurcate the optic primordium in the embryo (i) resulted in bilateral eyes in the adult (ii), each formed from half the original retina but with positions switched across the midline (vertical arrows represent anterior movement of the embryonic diencephalon).
- c) In the resultant two-eyed adult craniate the crossing of the optic fibres at the midline involves no significant change to the orientation of images received in the diencephalon (caudal arrow).

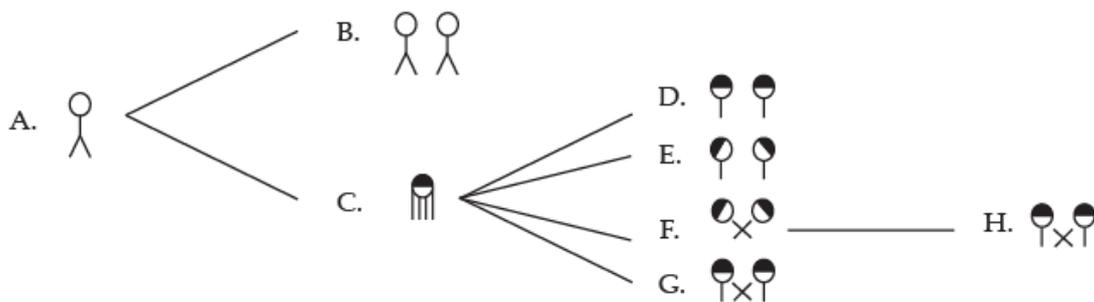


Fig 4. Potential alternative evolutionary pathways from a single frontal non-imaging eye in an early craniate. The most parsimonious pathway is A-C-F-H. Eyes are represented by circles; unshaded if non-imaging; shaded if imaging. Attachments to circles represent retinal ganglia; crossed or uncrossed; bifurcated or non-bifurcated.

- A- single non-imaging eye with bifurcated ganglia
- B- bifrontal non-imaging eyes
- C- single imaging eye with ipsilateral non-bifurcated ganglia
- D- non-switch frontal imaging eyes (ganglia type uncertain)
- E- non-switch bilateral imaging eyes (ganglia type uncertain)
- F- Full-switch bilateral imaging eyes with complete chiasm
- G- Full-switch stereoscopic imaging eyes with partial decussation
- H- Full-switch stereoscopic imaging eyes with partial decussation

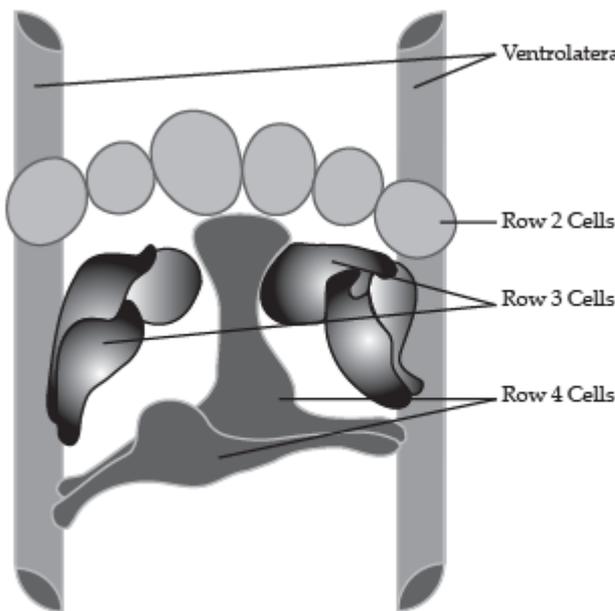


Fig 5. Dorsal schematic view of cells in Rows 2,3,4 of the frontal eye complex of amphioxus and the paired ventrolateral nerve tracts. Adapted from Lacalli, 1996. Row 4 cells are the bifurcated ganglia that connect the retinal cells (Row 2) to both ventrolateral tracts. Rostral is to the top. For a more detailed diagram see Fig 7 in Lacalli, 2002.

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