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Eye-Transcriptome and Genome-Wide Sequencing for Scolecophidia: Implications for Inferring the Visual System of the Ancestral Snake

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Abstract

Molecular genetic data have recently been incorporated in attempts to reconstruct the ecology of the ancestral snake, though this has been limited by a paucity of data for one of the two main extant snake taxa, the highly fossorial Scolecophidia. Here we present and analyze vision genes from the first eye-transcriptomic and genome-wide data for Scolecophidia, for *Anilios bicolor*, and *A. bituberculatus*, respectively. We also present immunohistochemistry data for retinal anatomy and visual opsins-gene expression in *Anilios*. Analyzed in the context of 19 lepidosaurian genomes and 12 eye transcriptomes, the new genome-wide and transcriptomic data provide evidence for a much more reduced visual system in *Anilios* than in non-scolecophidian (=alethinophidian) snakes and in lizards. In *Anilios*, there is no evidence of the presence of 7 of the 12 genes associated with alethinophidian photopic (cone) phototransduction. This indicates extensive gene loss and many of these candidate gene losses occur also in highly fossorial mammals with reduced vision. Although recent phylogenetic studies have found evidence for scolecophidian paraphyly, the loss in *Anilios* of visual genes that are present in alethinophidians implies that the ancestral snake had a better-developed visual system than is known for any extant scolecophidian.

Key words: gene loss, opsins, phylogeny, regressive evolution, Squamata, vision.

Introduction

The origin of major lineages (higher taxa) is a topic of broad interest in evolutionary biology (e.g., Darwin 1859; Smith and Szathmary 1997; Holland et al. 2008; Kemp 2015; Lane 2015; Eme et al. 2017), and the origin of snakes (Serpentes) is exemplary in this respect (e.g., Bellairs and Underwood...
The origin of snakes is subject to ongoing, high-profile debate. We present the first eye-transcriptomic and substantial genome-wide sequencing data for any scolecophidian snake (Scolecophidia are dedicated burrowers and form one-half of the oldest divergence in the snake tree). Comparative analyses of the presence of functional vision genes among lizards and snakes strongly indicate that the visual system (especially that adapted for bright-light vision) of scolecophidians is too reduced to be a good model for the visual system of the ancestral snake, thus challenging the hypothesis that snakes evolved from extreme burrowers.

Significance

The presence or absence results for vision genes based on BLAST and phylogenetic analyses are summarized in table 1. Of the 48 vision-associated genes studied here, all but seven occur in snakes. These seven are the genes coding for the phosphodiesterase subunit PDE6A, the rhodopsin kinase GRK1, the transducin gamma subunit GNGT1, the solute carrier SLC24A1, the retinol dehydrogenase RDH11, and the protein MDK.

Results

Vision-Gene Complements

The origin of snakes is subject to ongoing, high-profile debate. We present the first eye-transcriptomic and substantial genome-wide sequencing data for any scolecophidian snake (Scolecophidia are dedicated burrowers and form one-half of the oldest divergence in the snake tree). Comparative analyses of the presence of functional vision genes among lizards and snakes strongly indicate that the visual system (especially that adapted for bright-light vision) of scolecophidians is too reduced to be a good model for the visual system of the ancestral snake, thus challenging the hypothesis that snakes evolved from extreme burrowers.

However, thus far these data are available only for a relatively small sample of alethinophidians, such that ascertaining whether inferred genomic changes occurred in the snake stem or the alethinophidian stem (within the snake crown group) has not been possible. Furthermore, interpretation of the few molecular genetic data that are available has been complicated by disagreement among phylogeneticists as to whether Scolecophidia is a monophyletic (i.e., comprising one half of the basal divergence among crown snakes: e.g., Lee et al. 2007) or paraphyletic (e.g., Wiens et al. 2012; Miralles et al. 2018; Burbink et al. 2020) outgroup of all other crown snakes (Alethinophidia). Thus, the extent to which phenotypes of extant scolecophidians might represent highly derived adaptations to fossoriality and/or potentially plesiomorphic conditions present in the ancestral snake remains contentious.

Here, we contribute to the debate by presenting analyses of vision-associated gene sequence data from the first eye-transcriptome and genome-wide sequence data and retinal immunohistochemistry data for Scolecophidia. The visual system has played a prominent role in debates about snake origins (Bellairs and Underwood 1951; Caprette et al. 2004; Simões et al. 2015; Miralles et al. 2018), and we expect genomic data on vision genes to provide insight into the eco-phenotype of the ancestral snake. For example, ancestral fossoriality can be predicted to have resulted in the last common ancestor of extant snakes having a proportionately greater loss of functionality in genes associated with bright-light (photopic) than dim-light (scotopic) vision, such as occurs, for example, in highly fossorial mammals (Emerling and Springer 2014).

Results

Vision-Gene Complements

The presence or absence results for vision genes based on BLAST and phylogenetic analyses are summarized in table 1. Of the 48 vision-associated genes studied here, all but seven occur in snakes. These seven are the genes coding for the phosphodiesterase subunit PDE6A, the rhodopsin kinase GRK1, the transducin gamma subunit GNGT1, the solute carrier SLC24A1, the retinol dehydrogenase RDH11, and the protein MDK.
Table 1

Pattern of presence and absence of 48 visual-system genes across the available genomes and eye transcriptomes for Sphenodon, 15 lizard and 16 snake species: see supplementary table S2, Supplementary Material online for full details. Genes are grouped into cone, rod, and rod and cone phototransduction genes, and visual cycle genes. ● = gene present, X = gene not present; genomes and eye transcriptomes in darker and paler symbols, respectively. Prot. = Protobothrops; higher taxa abbreviated as follows: An = Anguiformes; Co = Colubridae; El = Elapidae; Ge = Gekkota; He = "Henophidia"; Ig = Iguania; La = Lacertoida; Rh = Rhynchocephalia; Sc = Scolecophidia; Vi = Viperidae

| Cone                  | Lepidosauria | Squamata | Serpentes (snakes) | Lizards’ | Caenophidia |
|-----------------------|-------------|----------|-------------------|----------|------------|
|                      | Sphenodon punctatus | Gecko japonicus | Elapidae | Scolopendra | Protobothrops |
| arr3                  | ●           | ●        | ●                 | ●        | ●          |
| grk7                  | ●           | ●        | ●                 | ●        | ●          |
| rh2                   | ●           | ●        | ●                 | ●        | ●          |
| sws1                  | ●           | ●        | X                 | ●        | X          |
| sws2                  | ●           | ●        | X                 | ●        | X          |
| lws                   | ●           | ●        | X                 | ●        | X          |
| gnat2                 | ●           | ●        | X                 | ●        | X          |
| gntg2                 | ●           | ●        | X                 | ●        | X          |
| gnb3                  | ●           | ●        | X                 | ●        | X          |
| pde6h                 | ●           | ●        | X                 | ●        | X          |
| pde6c                 | ●           | ●        | X                 | ●        | X          |
| cngb3                 | ●           | ●        | X                 | ●        | X          |
| cnga3                 | ●           | ●        | X                 | ●        | X          |
| slc24a2               | ●           | ●        | X                 | ●        | X          |
| sag                   | ●           | ●        | X                 | ●        | X          |
| rh1                   | ●           | ●        | X                 | ●        | X          |
| gntg1                 | ●           | ●        | X                 | ●        | X          |
| gntg1                 | ●           | ●        | X                 | ●        | X          |
| pde6a                 | ●           | ●        | X                 | ●        | X          |
| pde6b                 | ●           | ●        | X                 | ●        | X          |
| pde6g                 | ●           | ●        | X                 | ●        | X          |
| cngb1                 | ●           | ●        | X                 | ●        | X          |
| cnga1                 | ●           | ●        | X                 | ●        | X          |
| gnb1                  | ●           | ●        | X                 | ●        | X          |
| slc24a1               | ●           | ●        | X                 | ●        | X          |
| rcvrn                 | ●           | ●        | X                 | ●        | X          |
| grk1                  | ●           | ●        | X                 | ●        | X          |
| pdc                   | ●           | ●        | X                 | ●        | X          |
| gpsm2                 | ●           | ●        | X                 | ●        | X          |
| gnb5                  | ●           | ●        | X                 | ●        | X          |
| guca1e                 | ●           | ●        | X                 | ●        | X          |
| guca1b                 | ●           | ●        | X                 | ●        | X          |
| gucy2d                 | ●           | ●        | X                 | ●        | X          |
| gucy2f                 | ●           | ●        | X                 | ●        | X          |
| rgs9                  | ●           | ●        | X                 | ●        | X          |
| rgs9q                 | ●           | ●        | X                 | ●        | X          |
| irat                  | ●           | ●        | X                 | ●        | X          |
| rbp1                  | ●           | ●        | X                 | ●        | X          |
| rbp2                  | ●           | ●        | X                 | ●        | X          |
| rbp3                  | ●           | ●        | X                 | ●        | X          |
| rdh8                  | ●           | ●        | X                 | ●        | X          |
| rdh12                 | ●           | ●        | X                 | ●        | X          |
| sphn                  | ●           | ●        | X                 | ●        | X          |
| rpe6s                 | ●           | ●        | X                 | ●        | X          |
| rgr                   | ●           | ●        | X                 | ●        | X          |
| rdb5                  | ●           | ●        | X                 | ●        | X          |
| rdb10                 | ●           | ●        | X                 | ●        | X          |
| rdb11                 | ●           | ●        | X                 | ●        | X          |
visual opsins RH2 and SWS2. Four of these genes are absent also in lizards, pde6a, gntg1, slc24a1, and rh11. Among the 41 vision-associated genes occurring in at least some of the sampled snake genomes and eye transcriptomes, we found evidence for 28 in the Anilios bicolor eye-transcriptome and 29 in the A. bituberculatus genome-wide data (table 1; 27 of these genes common to both). One visual-cycle gene (gucy2f) and one cone and rod phototransduction gene (gucy2f) found in the A. bituberculatus genome-wide sequencing were not found in the A. bicolor eye transcriptome, and so are perhaps not being expressed in the Anilios eye. Similarly, gucy2f is found in the genome but not eye transcriptome of Thamnophis sirtalis (table 1). Despite the relatively low coverage of the genome-wide data for A. bituberculatus, only one visual-cycle gene (lrat) was not detected that was however found in the A. bicolor eye transcriptome.

We inspected sequences of some of the 29 (selected at random) genes in the A. bituberculatus genome-wide data (supplementary table S3, Supplementary Material online) for evidence consistent with sequencing and/or assembly error. We took vision-gene sequences from the A. bicolor transcriptome and used blastn to search for the corresponding genes in the A. bituberculatus genome-wide data. In all examined cases (two examples are shown in supplementary appendix S4, Supplementary Material online), observed fragmentation in genome-wide sequences can be explained (beyond low coverage) fully by intron-exon boundaries, and coverage for the ends of fragments is typical of overall coverage. Additionally, we extracted the best-possible homologous sequences of the leading candidates for possible Anilios vision pseudogenes—the two genes in the A. bituberculatus genome-wide data that are absent in the A. bicolor transcriptome (rpb1 and gucy2f) via exon-by-exon tblastx queries of the genome-wide data using sequences from the closest available relatives (Python and Boa). The extracted and assembled A. bituberculatus rpb1 and gucy2f sequences lack unexpected stop codons or frameshift indels, and phylogenetic analysis confirms their identity and demonstrates that they do not form unexpectedly long terminal phylogenetic branches (supplementary fig. S1, Supplementary Material online) that would be indications of pseudogenes or sequencing error. Among the genes for which we found evidence in Anilios spp. is the visual opsin gene lws, previously thought to be absent in scolecophidians (Simões et al. 2015). Phylogenetic trees (supplementary figs. S2–S4, Supplementary Material online) for snake visual opsins confirm the identity of the A. bicolor and A. bituberculatus rh1 and lws.

There are 12 vision genes for which we found no evidence in Anilios spp. but which are present in at least one other, non-scoleophidian snake. None of these 12 is associated exclusively with the rod phototransduction pathway (of eight such genes in total), seven are associated with cone phototransduction (of 12 total, 58.3%), two with both rod and cone phototransduction (of 10 total, 20%), and three (of 12 total, 25%) with the visual cycle (table 1; supplementary tables S4 and S5, Supplementary Material online). Of the 20 exclusively rod or cone phototransduction genes found in snakes, the probability of the seven gene absences in Anilios spp. all being cone phototransduction genes by chance is 0.01 (13/20 × 12/19 × 11/18 × 10/17 × 9/16 × 8/15 × 7/14 × 6/13), such that it is extremely unlikely that the apparent diminution of cone phototransduction genes in the genomes of this genus is explained by random failure to detect cone genes via eye transcriptomes or relatively low-coverage genome-wide sequencing.

Inspection of the retinal protein networks for phototransduction (fig. 1) highlights the proportionately greater absence of evidence for genes more typically associated with photopic (typically cone-based) vision in Anilios spp. For both phototransduction and visual-cycle networks, there is a substantial degree of overlap between genes likely lost in Anilios and those seemingly lost in the genomes of the highly fossorial mammals possessing reduced visual systems studied by Emerling and Springer (2014).

Retinal Immunohistochemistry

The two sampled Anilios species provided similar results. General eye anatomical information, including size, is presented in supplementary appendix S3, Supplementary Material online. There are no obvious differences among outer nuclear layer (ONL) nuclei or notable heterogeneity in size and appearance of inner segments (supplementary fig. S5c, Supplementary Material online), that is, there are no indications for a dichotomy with morphologically different rods and cones comprising a duplex retina. Immunolabeling revealed a dense population of RH1-containing photoreceptors (fig. 2a and b) and a less dense but still substantial population of LWS-containing photoreceptors (fig. 2c and d; supplementary fig. S5a, Supplementary Material online). The RH1 (rod) opsin antiserum labeled outer segments most intensely, but also labeled many somata more faintly, a feature seen in many vertebrates including other snakes (Gower et al. 2019). The SWS1 opsin antiserum showed no labeling of photoreceptors (or other retinal cells) in sections and the wholemount (supplementary fig. S5a, Supplementary Material online). Immunohistochemistry corroborates the genetic analysis in terms of the absence of functional sws1, and the presence of functional rh1 and lws, in both species.

Many photoreceptors were labeled for both RH1 and LWS, indicating co-expression of rod and cone opsin (fig. 2e1–e3; supplementary fig. S5d1–d3, Supplementary Material online). Some photoreceptors were exclusively labeled by either the RH1 antibody or LWS antiserum (colored arrowheads in fig. 2e3). It was not feasible to assess population densities of RH1 and LWS photoreceptors, nor to morphologically identify the photoreceptors as cones or rods, or to assess whether double cones or double rods are present. The LWS-labeled outer segments are long and thin, superficially more rod- than cone-like (supplementary fig. S5a, Supplementary Material online).
FIG. 1.—Network (modified from Emerling and Springer 2014: fig. 1) for 34 phototransduction proteins indicating absences in squamates and fossorial mammals as determined from genomic data. Note that loss of PDE6B and GRK1 in fossorial mammals is provisional, based on negative BLAST results rather than synteny analyses (Emerling and Springer 2014). Of the 36 phototransduction genes in table 1, protein products for the cone phototransduction (visual opsins) genes sv2 and rh2 are not shown because they are absent in all snakes and mammals.
Furthermore, the PNA labeling was restricted to a band of punctate structures at the boundary between the ONL and photoreceptor inner segments, that is at the position of the external limiting membrane (supplementary fig. S5b, Supplementary Material online), it did not show the typical cone outer-segment labeling seen in other snakes.

**Discussion**

Our data and analytical results can be robustly interpreted as providing clear evidence for very substantial reduction of the photopic elements of the visual system of *Anilios* spp. relative to that of the ancestral snake. Given that cone photoreceptors have not been reported for scolecophidians (e.g., Underwood 1997), this strongly suggests that the functional loss of cones in *Anilios* spp. is a derived feature of this group.
1967, 1970, 1977 and studies cited therein), that previous PCR surveys of retinal cDNA (Simões et al. 2015) failed to amplify any visual-opsin genes except rh1 (typically expressed in rods and used in scotopic vision), and that MSP studies have found only a single, RH1-like pigment (Simões et al. 2015), we predicted that among vision genes that had been lost or become nonfunctional in scolecophidian genomes these would disproportionately have been linked functionally with photopic (cone-associated) rather than scotopic (typically rod-associated) vision, and this matches our results.

Our genome-wide sequencing data for Anilios bituberculatus are low coverage, but the fact that irat (the shortest of the studied genes) is the only targeted vision gene that we could not find in the A. bituberculatus genome-wide sequencing data but that was present in the A. bicolor transcriptome encourages the interpretation that these genome-wide data are nonetheless informative for the purposes of this study. This is supported by lack of evidence for sequencing and/or assembly error. There is no evidence that the two vision genes absent in the A. bicolor transcriptome but present in the A. bituberculatus genome-wide data are pseudogenes in the latter—this pattern might also be explained by gene silencing in the eye and/or because of differences between the two species. Although we cannot be certain that the cone phototransduction associated genes that we failed to find in the A. bicolor eye-transcriptome and the A. bituberculatus genome-wide data are all completely absent or nonfunctional in the genomes of these species (because we did not find the pseudogene remains of these genes), we are very confident that at least most are genuinely nonfunctional or absent, and we emphasize that none of the candidate losses (relative to the inferred ancestral snake) occurs among exclusively rod-associated phototransduction genes. Although we cannot rule out that any vision genes absent in the Anilios genome-wide and eye transcriptome data are pseudogenes, we predict that few if any of them are. This is because we have no evidence for any pseudogenization, and because the loss of these genes from the genome is plausible, given that extant scolecophidians all have a small-eyed, highly fossorial ecomorphology and they likely diverged from closest extant relatives (Alethinophidia) that retain these genes in the Cretaceous, more than 65 Ma (e.g., Burbank et al. 2020). It is noteworthy that the vast majority of the genes potentially lost in Anilios spp. are also absent in highly fossorial mammals with reduced visual systems (fig. 1; Emerling and Springer 2014), suggestive of adaptive convergence. Thus, we can be confident that: 1) multiple visual genes likely present in the ancestral snake have been lost in Anilios, and 2) that loss is almost exclusively associated with genes mediating photopic vision. The Anilios visual system is clearly adapted for low-light conditions. These conclusions are robust despite the limitations that, beyond some previously reported rh1 sequences (Simões et al. 2015), data on vision-related genes in scolecophidians are restricted currently to the eye transcriptome of A. bicolor (based on ~80M raw reads) and the low-coverage genome-wide data for A. bituberculatus reported here.

The presence of lws in the Anilios bituberculatus genome-wide data and A. bicolor eye transcriptome (and of its product LWS in immunohistochemical preparations of their retinas) raises the question as to whether lws is present also in the genomes of the scolecophidians Liotyphlops beui, Typhlops squamosus, Amerotyphlops brongersmianus, and Habrophallos collaris, with a previous failure to detect this gene in retinal cDNA (Simões et al. 2015) perhaps explained by its non- or very low-level expression in the eye. It might be noted that lws is generally the most persistent of the ancestral vertebrate photopic visual-opsin genes in cases where some of these genes are lost (e.g., Davies et al. 2012). Despite the expression of lws in photoreceptors, our immunohistological data agree with previous microscopic studies (Underwood 1967, 1970, 1977) in finding no evidence for morphologically cone-like photoreceptors in scolecophidians. A functional lws in taxa living primarily in dark environments might have a nonvisual function (Nei et al. 1997), perhaps in the control of circadian rhythms, and the expression of this gene in the pineal gland as well as the eye of at least the lizard Anolis carolinensis (Kawamura and Yokoyama, 1997) is consistent with this. If lws in Anilios does retain a visual function, it is perhaps integrated in the rod pathway given that many of the cone-pathway genes have been lost. Expression of rod visual-opsin genes in cone-like photoreceptors and vice versa has been reported in some vertebrates (e.g., Kojima et al., 2017; Simões et al. 2016b; Schott et al., 2016; Bhattarcharya et al. 2017) In this context, the identity and role of the photoreceptors expressing lws need further analysis.

Concerning the majority of Anilios photoreceptors that coexpress rh1 and lws, we are not aware of the coexpression of rh1 and typical cone opsin genes in single photoreceptors of any other vertebrates (e.g., Simões et al. 2016b; Schott et al. 2016). Coexpression of two or even three cone opsins in particular cones has been found in various vertebrate species from fish to mammals (e.g., Lukáš et al. 2005; Dalton et al. 2014; Hunt and Peichl, 2014; Isayama et al. 2014), but the coexpression of a rod and a cone opsin appears unique.

Despite the unexpected detection of functional lws in Anilios spp., the molecular data for this genus are consistent with anatomical data (e.g., Underwood 1977) that demonstrate that the scolecophid visual system is simplified (reduced) in comparison to that of other (alethinophidian) snakes. Alethinophidians themselves have a simplified version of the genetic composition of the visual system that was likely present in the ancestral squamate. Figure 3 shows our interpretation of visual-gene loss among the squamates sampled in this study. Thus far, scolecophidians (at least Anilios spp.) are the only lepidosaurian reptiles presenting evidence for loss of the cone phototransduction genes arr3, gnat2, gntg2, pde6c, and gngb3, the cone and rod phototransduction
genes guca1b and rgs9bp, and any visual-cycle genes other than rdh11 (fig. 3; supplementary tables S4 and S5, Supplementary Material online). Figure 3 summarizes three main episodes of vision gene loss within Squamata: the loss of mostly rod phototransduction genes in presumably highly photopic stem geckos, the loss of three cone phototransduction genes in presumably scotopic stem snakes, and the very substantial loss of photopic transduction and visual-cycle genes in Scolecophidia (at least Anilios).

Recently, Miralles et al. (2018) provided strong evidence for scolecophidian paraphyly, and they argued on this basis that a “scolecid” phenotype, including reduced eyes without cone photoreceptors, was likely characteristic of the ancestral snake. In contrast, Simões et al. (2015) argued that absence of two visual-opsin genes (sws1, lws) in addition to the morphological simplifications in scolecophidian eyes made them a poor model for the nature of the ancestral snake eye, whether or not Scolecophidia is paraphyletic. Although we now know that lws is not absent in (all) scolecophidians, the evidence available thus far (presented here) adds substantial weight to the argument presented by Simões et al. (2015), in that it is highly unlikely that the ancestral snake lost functional copies of a large number of vision (especially cone phototransduction) genes that were subsequently re-evolved within Alethinophidia. Exceptions to Dollo’s law of evolutionary irreversibility for loss of functional genes are considered extremely unlikely (e.g., Collin and Miglietta 2008), especially over longer timescales and for instances involving multiple genes. Available data indicate that the morphology and molecular machinery of the visual system of extant scolecophidians are substantially apomorphically reduced from that likely present in the ancestral snake. Clearly, examining the molecular genetic and anatomical components of a wider sample of scolecophidians would help to further advance this debate.

Materials and Methods

Genome-Wide Data

The new genome-wide data analyzed here are for a single individual of the Australian typhlopid scolecophidian Anilios bituberculatus (Peters 1863), obtained from the pet trade in 2009. There is no voucher specimen, but DNA sequences of mitochondrial and nuclear systematic markers very closely match those available on GenBank for A. bituberculatus (supplementary appendix S1, Supplementary Material online). All animal procedures complied with University of Leiden ethical guidelines. Genomic DNA was isolated from blood using a Qiagen Blood and Tissue DNeasy kit. A descriptive summary of the sequencing is reported in supplementary table S1,
Supplementary Material online. A paired-end sequencing library with a target insert size of 500 bp was prepared from 5 μg DNA using a Paired-End Sequencing Sample Prep kit (Illumina Inc., San Diego). After amplification the library was analyzed on a Bioanalyzer 2100 DNA 1000 series II chip (Agilent, Santa Clara). The library was sequenced on an Illumina GAIIx instrument (3 lanes, 151 nucleotides paired-end), yielding a total of 26.2 Gbp of sequencing data. The reads were preprocessed to remove low-quality basecalls and adapter contamination, and assembled using the CLC Assembly Cell version 3.2 (CLC Bio, Aarhus) with a k-mer size of 25. This yielded a 1.69 Gbp draft genome assembly with a contig N50 of 1,917 nucleotides. Aligning the original sequencing data to the assembly shows that coverage is 7x. For comparative analyses, we downloaded DNA sequence data from NCBI (ncbi.nlm.nih.gov) for nine publicly available snake genomes, all of them alethinophidians (noncoleophidians), nine lizards, and the tuatara Sphenodon punctatus (supplementary table S2, Supplementary Material online).

Eye-Transcriptomic Data
RNALater-preserved eyes of one specimen of Anilios bicolor (supplementary appendix S2, Supplementary Material online) were macerated in TRIzol and RNA purified using the PureLink™ RNA Mini Kit (Life Technologies/Ambion) using the manufacturer’s protocol. The mRNA-Seq library was double-indexed and prepared with the mRNA-Seq Library Prep Kit v2 (Lexogen) following the manufacturer’s protocol. It was sequenced with 56 other libraries in equimolar concentrations in one lane of an Illumina NovaSeq. A descriptive summary of the sequencing is reported in supplementary table S1, Supplementary Material online. Low-quality reads were identified using Trimmomatic (Bolger et al. 2014) and removed. The remaining 59,727,054 read pairs were assembled using Trinity (Haas et al. 2013). Transcripts assembled by Trinity were then examined in Transdecoder (github.com/TransDecoder/TransDecoder/wiki) to predict ORFs and long coding regions. Transcripts were BLASTed (e-value of 1e-5) (Camacho et al. 2009) against the genome of Python bivittatus (GCA_000186305.2) and the Uniprot database (The UniProt Consortium 2018), and then annotated with Trinotate (Bryant et al. 2017). For comparative analyses, we downloaded data from publicly available eye transcriptomes of six snakes and of six lizards (supplementary table S2, Supplementary Material online).

Molecular Data Analyses
We selected 48 genes of interest for visual-system biology, focusing on the retinal phototransduction and visual-cycle (cascade) genes that were also analyzed by Emerling and Springer’s (2014) study of regression of the visual system in fossorial mammals. Each of the genomes was interrogated by the Basic Local Alignment Search Tool, BLAST (Camacho et al. 2009) under tblastn, once for each of the 48 vision genes, using small (two or three-taxon) seed sequence sets. Sequences with low BLAST e values (<e-20) were then subjected to a second BLAST analysis using tblastn against vertebrate entries in NCBI’s non-redundant protein database to verify that they were not homologous with other genes not under consideration. Following this, the BLAST e-value threshold was lowered (<e-7) and newly identified sequences were subjected to the same retesting process to greatly reduce the chance that highly divergent sequences were missed due to low similarity to the limited seed data set. These results were then supplemented by NCBI searches of the candidate genes to ascertain whether sequences not recovered during the BLAST searches had nonetheless been generated for individuals of the same species.

For sequences recovered by BLAST that belong to gene families of multiple genes having high similarity (GNGT*, GNAT*, CNGA*, CNGB*, GRK*, GUCA* GUCY*, RDH*, RBP*) phylogenetic analyses were used to further assess the identification of the 48 vision genes. Vision genes that had sequences recovered by BLAST (and verified by phylogenetic analysis) that lacked unexpected stop codons and/or framlshift indels in the consensust regions of the protein (as determined from the Prosite and EMBL-EBI databases: prosite.expasy.com and ebi.ac.uk, respectively) were interpreted as present and potentially functional.

Visual-opsin gene sequences identified in the Anilios bicolor transcriptome and A. bituberculatus genome-wide data were added to a database comprising publicly available snake and lizard visual-opsin gene sequences, and were aligned using default settings in MAFFT (Katoh et al. 2002). Alignments were inspected by eye for nucleotides and amino acids, and adjusted manually to ensure nucleotides were in-frame and that indels did not include partial codons. Trees were inferred with RAxMLv8 (Stamatakis 2014) using majority rule bootstrapping (Pattengale et al. 2010), randomized MP starting trees, and a fast hill-climbing algorithm, under the GTR+G+I model (determined as best-fitting for all visual opsin alignments using jModelTest 2; Darriba et al. 2012). Visual-opsin gene trees were rooted using Axs based on previous studies of opsin gene phylogenetics (e.g., Pisani et al. 2006; Feuda et al. 2012), with individual opsin trees rooted with Sphenodon.

Ancestral-state estimation was undertaken using parsimony, with putative gene losses considered irreversible. Functional vision genes were considered to be present in the ancestral snake and the ancestral alethinophidian (i.e., the ancestor of all noncoleophidian snakes) where they are present in the genomes of at least one alethinophidian and one lizard, with absences in Anilios interpreted as possible loss in at least this scolecophidian lineage.

Retinal Immunohistochemistry
Whole heads of two Anilios bituberculatus and one A. bicolor (supplementary appendix S3, Supplementary Material online) were fixed in 4% (w/v) paraformaldehyde in 0.01 M
phosphate-buffered saline (PBS, pH 7.4) for less than 1 day, then stored in PBS with 0.05% sodium azide at 4 °C. Later, eyes were removed and stored in the same buffer. The very small eyes were measured with calipers, but orientation could not be recorded. Opsin immunohistochemistry was performed on frozen transverse sections of eyes. Whole eyes were cryoprotected by successive immersion in 10%, 20%, and 30% (w/v) sucrose in 0.1 M phosphate buffer (PB, pH 7.4) and transferred to Tissue Freezing Medium (Leica Biosystems, Wetzlar, Germany). Eyes were embedded and frozen in blocks, oriented to obtain sections parallel to the anterior–posterior axis, sectioned to 16 μm with a cryostat, and collected on SuperFrost slides (Menzel GmbH, Braunschweig, Germany). Due to the small eye size, only the most central sections yielded good transverse aspects of the retina, in more peripheral sections the retina was sectioned more obliquely.

Immunolabeling followed protocols previously used to label opsins in snake retinas (Hauzman et al. 2014; Gower et al. 2019). Rod opsin RH1 was detected with the mouse monoclonal antibody rho4D2 (dilution 1:1,000; kindly provided by R. S. Molday: Hicks and Molday 1986). Cone opsins were detected with the rabbit antiserum JH492 against the longwave-sensitive LW5 cone opsin (dilution 1:2,000; kindly provided by J. Nathans: Wang et al. 1992), and with the goat antiserum sc-14363 against the shortwave-sensitive SWS1 cone opsin (dilution 1:500; Santa Cruz Biotechnology Inc., Heidelberg, Germany). Binding sites of primary antibodies were visualized by indirect immunofluorescence. Omission of primary antibodies from incubation solutions resulted in no staining. Double-labeling was done by incubating sections in a mixture of primary and secondary antibodies. For some sections, staining with Alexa 647-conjugated peanut agglutinin (PNA; dilution 1:250; Invitrogen) was added to the opsin immunolabeling. PNA is a cone marker in various vertebrates, including snakes (Hauzman et al. 2017; Gower et al. 2019). Sections were counterstained with 4,6-diamidino-2-phenylin-dole (DAPI) to visualize retinal nuclear layers. One unsectioned A. bituberculatus retina was immunolabeled for cone opsins free-floating, then flat-mounted on a slide with the photoreceptor side up. Here incubation was in a mixture of the cone opsin antiserum JH492 and sc-14363 for three days at room temperature, incubation in the secondary antiserum mixture was for 1 h.

Stained tissue was analyzed with a laser scanning microscope (LSM) Olympus Fluoview 1000 using the FV 1.7 software (Olympus). LSM images and z-stack projections were examined with ImageJ (http://imagej.nih.gov/ij/). Images for illustration were adjusted for brightness and contrast using Adobe Photoshop.

Supplementary Material
Supplementary data are available at Genome Biology and Evolution online.

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Authors’ Contributions
JFF and BFS carried out the vision gene bioinformatics (helped by CVH) and phylogenetics. FJV, HMLK, NRC, CVH, and MKR contributed genome-wide sequencing; BFS and KLS eye-trascriptome sequencing. LP and SM generated and analyzed immunohistochemistry data. DJG conceived of and designed the study with help from JFF, DP, MKR, and BFS. All authors contributed to writing.

Data Availability
The data underlying this article are available in the article, in its online supplementary material, and GenBank accessions MK895004–031.

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