

RESEARCH ARTICLE

Pronounced heritable variation and limited phenotypic plasticity in visual pigments and opsin expression of threespine stickleback photoreceptors

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SUMMARY

Vertebrate colour vision is mediated by the differential expression of visual pigment proteins (opsins) in retinal cone photoreceptors. Many species alter opsin expression during life, either as part of development or as a result of changes in habitat. The latter, a result of phenotypic plasticity, appears common among fishes, but its cellular origin and ecological significance are unknown. Here, we used adult threespine stickleback fish from different photic regimes to investigate heritable variability and phenotypic plasticity in opsin expression. Fish from clear waters had double cones that expressed long (LWS) and middle (RH2) wavelength opsins, one per double cone member. In contrast, fish from red light-shifted lakes had double cones that were >95% LWS/LWS pairs. All fish had single cones that predominantly expressed a short wavelength (SWS2) opsin but ultraviolet cones, expressing a SWS1 opsin, were present throughout the retina. Fish from red light-shifted lakes, when transferred to clear waters, had a ~2% increase in RH2/LWS double cones, though double cone density remained constant. Comparison of visual pigment absorbance and light transmission in the environment indicated that the opsin complements of double cones maximized sensitivity to the background light, whereas single cones had visual pigments that were spectrally offset from the dominant background wavelengths. Our results indicate that phenotypic plasticity in opsin expression is minor in sticklebacks and of questionable functional significance.

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INTRODUCTION

Cone photoreceptors are specialized cells of the retina whose visual pigments capture light to begin the process of photopic vision (Fein and Szuts, 1982). Each visual pigment is composed of a protein (opsin) and a chromophore (a vitamin A derivative). There are four major classes of cone opsins (SWS1, SWS2, RH2 and MWS/LWS) and one rod opsin (RH1) (Yokoyama, 2000). When combined with the chromophore, these opsins form visual pigments with absorbance maxima (λ_{\max}) in the ultraviolet (SWS1), short (SWS2), middle (RH2, MWS, RH1) or long (LWS) wavelength regions of the spectrum (Yokoyama, 2000; Isayama and Makino, 2012). Besides opsin type, visual pigment absorbance can be modulated by the choice of chromophore: coupling of an opsin to the vitamin A1 chromophore, 11-*cis* retinal, leads to a lower λ_{\max} than combination with the vitamin A2 chromophore, 3-dehydro, 11-*cis* retinal (Isayama and Makino, 2012). In most vertebrates, the different visual pigments are distributed in morphologically distinct cone types, and comparison of neural outputs from these cells forms the basis for the perception of colour (Fein and Szuts, 1982). Thus, the molecular constituents of visual pigments are primary substrates for the genetic and environmental modulation of colour vision.

Many non-mammalian vertebrates modulate chromophore usage during life, and this often results from migrations to new photic habitats, as with fishes (Beatty, 1984; Novales Flamarique, 2005),

or following metamorphic transitions, as with amphibians (Isayama and Makino, 2012). Modulation of opsin expression has also been documented during development (Wood and Partridge, 1993; Szél et al., 1994; Xiao and Hendrickson, 2000; Cheng and Novales Flamarique, 2004; Takechi and Kawamura, 2005; Spady et al., 2006; Hoke et al., 2006; Cheng et al., 2007; Applebury et al., 2007; Shand et al., 2008; Cottrill et al., 2009) and, to a lesser extent, following changes in habitat (Fuller et al., 2005; Shand et al., 2008; Cottrill et al., 2009; Hofmann et al., 2010; Fuller and Claricoates, 2011). Studies using fishes and rodents have demonstrated that opsin switching within individual cones is a major mechanism that restructures the chromatic organization of the retina and the colour sensitivity of these animals during development and at early life stages (Szél et al., 1994; Cheng et al., 2006; Cheng et al., 2007; Cheng and Novales Flamarique, 2007; Novales Flamarique, 2013). By contrast, the mechanism(s) underlying, and functional significance of, environmentally induced changes in opsin expression are unknown. Despite the lack of this crucial information, such phenotypic plasticity is commonly assumed to be ecologically relevant (Fuller and Claricoates, 2011).

Studies that report phenotypic plasticity in opsin expression have relied on quantification of opsin transcripts from whole retinas using real-time PCR (Fuller et al., 2005; Shand et al., 2008; Cottrill et al., 2009; Hofmann et al., 2010; Fuller and Claricoates, 2011), a

procedure that does not reveal the cellular patterns underlying opsin changes. Microspectrophotometry, the other technique employed in these studies, can only be used to support correlative trends between cone types and opsin expression as sample size is extremely small, in comparison with photoreceptor numbers in the retina (Fein and Szuts, 1982), and most studied animals have topographical variation in both opsin expression and photoreceptor types across the retina (see Hárosi and Novales Flamarique, 2012). In the above studies (Fuller et al., 2005; Shand et al., 2008; Hofmann et al., 2010; Fuller and Claricoates, 2011), differences in opsin expression are assumed to reflect changes in the abundance of the various cone types or differences in the size and/or visual pigment density of cone outer segments (Fuller and Claricoates, 2011), the ciliary structures whose lamellae house the visual pigments (Fein and Szuts, 1982). These studies further assume that the observed changes in opsin expression reflect fundamental alterations to the colour vision of the animal (Fuller and Claricoates, 2011).

The physiological literature, however, casts doubts on many of these assumptions. First, photoreceptor visual pigment density is likely to be at an optimum for proper lamellar packing and functionality of the phototransduction cascade, with overexpression of opsin resulting in expansion of lamellar volume and disrupted kinetics of the light response (Wen et al., 2009). It is therefore unlikely that visual pigment density would increase as a result of experiencing new photic environments in nature. Second, changes in outer segment morphology have only been reported following long-term exposure to artificial light environments (e.g. monochromatic, very bright light) (Kröger et al., 1999; Williams et al., 1999) that have no equivalent in nature. In contrast, migrations to new environments do not induce changes in cone outer segment morphology (e.g. size, taper) in salmonid fishes, and we are not aware of reports to the contrary for other animals featured in the literature (Hárosi and Novales Flamarique, 2012). It thus seems that the reported phenotypic plasticity in opsin expression of fishes is probably based on changes in the relative numbers of spectral cone types. Such alterations in cell numbers can arise *via* the production and/or pruning of photoreceptors, as occurs in several species (Cornish et al., 2004; Cheng et al., 2006; Hoke et al., 2006; Chen et al., 2008; Hu et al., 2011), or as a switch in the opsin expressed within individual photoreceptors, as has been demonstrated in the rods of the European eel (Wood and Partridge, 1993) and in the cones of salmonid fishes and rodents (Szél et al., 1994; Cheng et al., 2006; Cheng and Novales Flamarique, 2007; Glaschke et al., 2011). The importance of opsin phenotypic plasticity in colour sensitivity, and visual function in general, would then depend on the number and types of cones affected and their retinal distributions. It is the topography of these cells, and their relative outputs, that are primary determinants of visual acuity and the colour contrast detection capabilities of the retina (Fein and Szuts, 1982).

We have chosen the threespine stickleback, *Gasterosteus aculeatus*, to study genetic (heritable variability) and environmental (phenotypic plasticity) changes in opsin expression and their ecological significance. Literature on stickleback visually guided behaviour dates back to the 1830s (Rowland, 1994) and this fish has long been a model of ecology and evolutionary research to explore the role of colour in sexual selection and speciation (Rowland, 1994; Boughman, 2001; Smith et al., 2004; Rowe et al., 2004; Albert et al., 2007; Boulcott and Braithwaite, 2007; Rick and Bakker, 2008). In addition to the well-established role of colour in stickleback behaviour, this species is found in waters that expand the range of photic regimes, from dystrophic lakes dominated by long (red) wavelength light (Reimchen, 1989; McDonald and Hawryshyn, 1995; McDonald et

al., 1995) to mesotrophic lakes and coastal waters characterized by a full visual spectrum (ultraviolet to red) in surface waters and peak transmission in the middle (green) wavelengths (Novales Flamarique et al., 1992; Novales Flamarique and Hawryshyn, 1993; Novales Flamarique and Hawryshyn, 1997; McDonald and Hawryshyn, 1995; McDonald et al., 1995). Thus, comparison of endemic and displaced sticklebacks from various photic regimes can be used to assess heritable variation and phenotypic plasticity in opsin expression, both components assumed important to the visual ecology of this animal and to the evolutionary divergence between populations (Boughman, 2001; Smith et al., 2004).

In this study, we examined the topographical distribution of opsins, visual pigments and photoreceptor types in adult retinas of seven populations of sticklebacks living in photic habitats ranging from red-stained to clear waters. We then compared the retinas of individuals from dystrophic populations after 14 years and within 6 months of transfer to clear waters to evaluate phenotypic plasticity in opsin expression and its photoreceptor origin.

MATERIALS AND METHODS

Animals and sampling locations

Wild adult threespine stickleback (*G. aculeatus* L.) were obtained from seven locations in British Columbia (Canada): Doogan's Lake, Swan Lake, Mayer Lake, Mayer Pond, Drizzle Lake, Drizzle Pond and the Broughton Archipelago (coastal ocean) (Fig. 1). All specimens were in reproductive condition except for those originating from the Broughton Archipelago. Mayer Lake and Drizzle Lake are dystrophic lakes, while Mayer Pond and Drizzle Pond are small mesotrophic ponds. No sticklebacks existed in these ponds until 1993 and 1997, when two of us (C.B. and T.E.R.) transferred sticklebacks from Mayer Lake and Drizzle Lake to Mayer Pond and Drizzle Pond, respectively (Leaver and Reimchen, 2012). Swan Lake is a high productivity, eutrophic, system with large mats of green algae present at various times of the year, but especially during the spring and summer. Doogan's Lake and the oceanic location are mesotrophic systems, characterized by low to medium productivity and clear waters. The dystrophic lakes in this study have no transmission below 500 nm at 1 m depth and no light at 4 m depth (McDonald et al., 1995). The mesotrophic lakes and ocean are characterized by a full light spectrum in surface waters (320–750 nm) and peak transmission in the range 560–565 nm with depth [see comparable systems in previous publications (Novales Flamarique et al., 1992; Novales Flamarique and Hawryshyn, 1993; McDonald and Hawryshyn, 1995; McDonald et al., 1995)]. We measured downwelling and sidewelling light at all locations at 40 cm depth (Fig. 1) using a USB-2000 spectroradiometer equipped with a 600 µm diameter input, 0.22 NA, liquid light guide and a cosine collector (Ocean Optics, Dunedin, FL, USA). The sidewelling light was the average of two scans in the sun and anti-sun directions. Scans were acquired between 11:00 h and 12:30 h in June, with the sun's elevation at ~60 deg. The 40 cm depth is close to the middle of the range (0.1–1 m) at which stickleback nests are found during the breeding season in these water bodies.

Sticklebacks caught in the various locations were either killed on-site, under light adaptation, by quick spinal bisection and decerebration and the retinas fixed for histochemical analyses, or transported live to the aquatic facility of Simon Fraser University (SFU) where they were maintained for up to 6 months. Fish transported to SFU were housed in large aquaria containing water from their locations of origin, or placed in clear water of the same temperature and pH as the source water. Illumination was a 12 h:12 h light:dark cycle provided by tungsten-halogen fluorescent tubes.

Fish were killed upon arrival to SFU for visual pigment measurements and at 3 weeks and 6 months after arrival for histochemical analyses. Supplementary material Table S1 shows the numbers of fish used for the different types of experiments. All experimentation was approved by the Animal Care Committee of SFU, in compliance with guidelines set by the Canadian Council for Animal Care.

Generation of riboprobes and sequencing of opsins

Opsin partial cDNAs were generated by RT-PCR amplification from total RNA isolated from homogenized retina of adult sticklebacks (RNAqueous-Midi; Ambion, Austin, TX, USA). The cDNAs were synthesized (Ready-To-Go RT-PCR beads, Amersham Biosciences, GE Healthcare, Saskatoon, SK, Canada) using the following primers: SWS1 opsin partial cDNA forward 5'-ATG GGG AAA CAC TTC CAC TT-3', reverse 5'-TGG AAC AAC AGA TTC CCA TA-3'; SWS2 opsin partial cDNA forward 5'-TCA GCT GAC AAT CAC ATA AA-3', reverse 5'-AGC CAT CTT TCA AAA GCT AT-3'; RH2 opsin partial cDNA forward 5'-TGG ACA CTT CAC CAC TAT CT-3', reverse 5'-TGA GTA CCA GAG AAC TTG AA-3'; and LWS opsin partial cDNA forward 5'-TTG CAA GTG ACG AGA AAG GT-3', reverse 5'-TCC AGG AGA ACA CTA TTC CA-3'. Reverse transcription was carried out at 42°C for 15 min. Cycling parameters for the subsequent PCR were: 95°C × 5 min, 32 cycles of 95°C × 30 s, 56°C × 30 s, and 72°C × 1 min, and 1 cycle of 72°C × 10 min. Each cDNA was gel purified and cloned into a pCRII-TOPO cloning vector (Invitrogen, Carlsbad, CA, USA) and sequenced by AmpliTaq Dye terminator cycle sequencing (UBC Sequencing Laboratory). The identities of the sequences were confirmed by comparing them to nucleotide sequence databases using the BLASTn program (Altschul et al., 1997). To make each cRNA probe, a PCR fragment containing the insert and an RNA promoter amplified from the pCRII-TOPO vector were used to generate digoxigenin- and fluorescein-labelled RNA sense and antisense riboprobes by *in vitro* transcription (RNA labelling kit, Roche Diagnostics, Laval, QC, Canada).

To compare RH2 and LWS opsin sequences between stickleback populations, full-length opsin cDNAs were generated as described above using the following primers: RH2 opsin partial cDNA forward 5'-TGG ACA CTT CAC CAC TAT CT-3', reverse 5'-TTA AGA CAC AGA GGA CAC TT-3'; LWS opsin partial cDNA forward 5'-TTG CAA GTG ACG AGA AAG GT-3', reverse 5'-TTA TGC AGG AGC CAC AGA-3'. The deduced amino acid sequences were compared using ClustalW2, a multiple sequence alignment program (Larkin et al., 2007).

In situ hybridization

Fish were killed in the light-adapted state. The left eyeball was removed, the iris and lens discarded, and the remaining eyecup, which had been marked on the ventral and nasal retina, immersed in cryo-fixative (4% paraformaldehyde in 0.08 mol l⁻¹ phosphate buffer, pH 7.4). After a minimum 24 h fixation at 4°C, the retina was extracted and flattened on a grid while maintaining its natural orientation. This procedure ensured the analysis of similar pieces of retina between individuals. Each retina was then cut into eight pieces, and each piece embedded in OCT frozen blocks for *in situ* hybridization as per previous studies (Cheng et al., 2006; Cheng and Novales Flamarique, 2007). Sections (8 µm thick) obtained from the blocks were collected serially and deposited on alternating slides for simultaneous double-labelling experiments with riboprobes against the SWS1 and SWS2, and the RH2 and LWS opsin transcripts, respectively. Details of the *in situ* hybridization protocol have been published previously (Cheng

et al., 2006). Digital images of sections were acquired with an E-600 Nikon fluorescence microscope equipped with DIC optics and a DXM-100 digital camera. The images were used to characterize cone types and to compute the percentage of cones that expressed each opsin mRNA. The densities of double and single cones were counted over a 17,926 µm² area using a grid system on the computer monitor, and the ratio of double to single cones was computed for each sector of the retina.

Histology

The eyecup from the right eyeball of the same fish used for *in situ* hybridization was immersed in primary fixative (2.5% glutaraldehyde, 1% paraformaldehyde in 0.08 mol l⁻¹ phosphate buffer, pH 7.4). After 24 h fixation at 4°C, the retina was extracted from the eyecup, rinsed in 0.08 mol l⁻¹ phosphate buffer, and pieces cut using the same procedure as for *in situ* hybridization. These pieces were processed for embedding in EPON resin blocks, which were cut radially in 75 nm steps, as detailed previously (Novales Flamarique, 2011), to reveal the overall morphology and the ultrastructure of cones. Electron micrographs were used to obtain average dimensions of cone outer segments and lamellae, and lamellar spacing.

Microspectrophotometry

Individual fish were dark adapted overnight. Following this adaptation period, the fish was killed, one eye was enucleated, and the retina was removed under infrared illumination. Small pieces of retina were teased apart and prepared for viewing with the dichroic microspectrophotometer (DMSP) as per previous studies (Novales Flamarique and Hárosi, 2000; Cheng et al., 2006; Cheng et al., 2007). The DMSP is a computer-controlled, wavelength-scanning, single-beam photometer that simultaneously records average and polarized transmitted light fluxes through microscopic samples (Novales Flamarique and Hárosi, 2000). The DMSP was equipped with ultrafluar (Zeiss) objectives: 32/0.4 for the condenser and 100/1.20 for the objective. With the aid of reference measurements recorded through cell-free areas, individual photoreceptor outer segments were illuminated sideways with a measuring beam of rectangular cross-section ~2 × 0.6 µm. Absolute absorbance and linear dichroism spectra were computed in 2 nm increments from the obtained transmittance (each spectrum consisted of an average of eight scans). The solid spectra (fits) were derived from experimental data by Fourier filtering (Hárosi, 1987).

RESULTS

Light environments

Spectral irradiance measurements from the various water bodies revealed pronounced differences in light transmission (Fig. 1). The mesotrophic systems had broad spectrum downwelling (300–750 nm) and sidewelling (350–750 nm) light, with the downwelling light being ~4–10 times as intense as the sidewelling light (Fig. 1E,F). Mayer Pond, also a mesotrophic system, had similar broad spectra but the shape of the curve was reduced in the middle to long wavelengths (Fig. 1B). Mayer Lake had a downwelling spectrum shifted toward longer wavelengths, with little downwelling to no sidewelling light below 400 nm, and a ratio of downwelling to sidewelling light of ~33 (Fig. 1A). This light environment is characteristic of dystrophic lakes and is due to the high quantities of dissolved organic matter present in the water. Swan Lake had the most distorted spectra (Fig. 1G), and the ratio of downwelling to sidewelling light was ~4, similar to that of the ocean location (Fig. 1E). Despite the large quantities of algae present in Swan Lake,

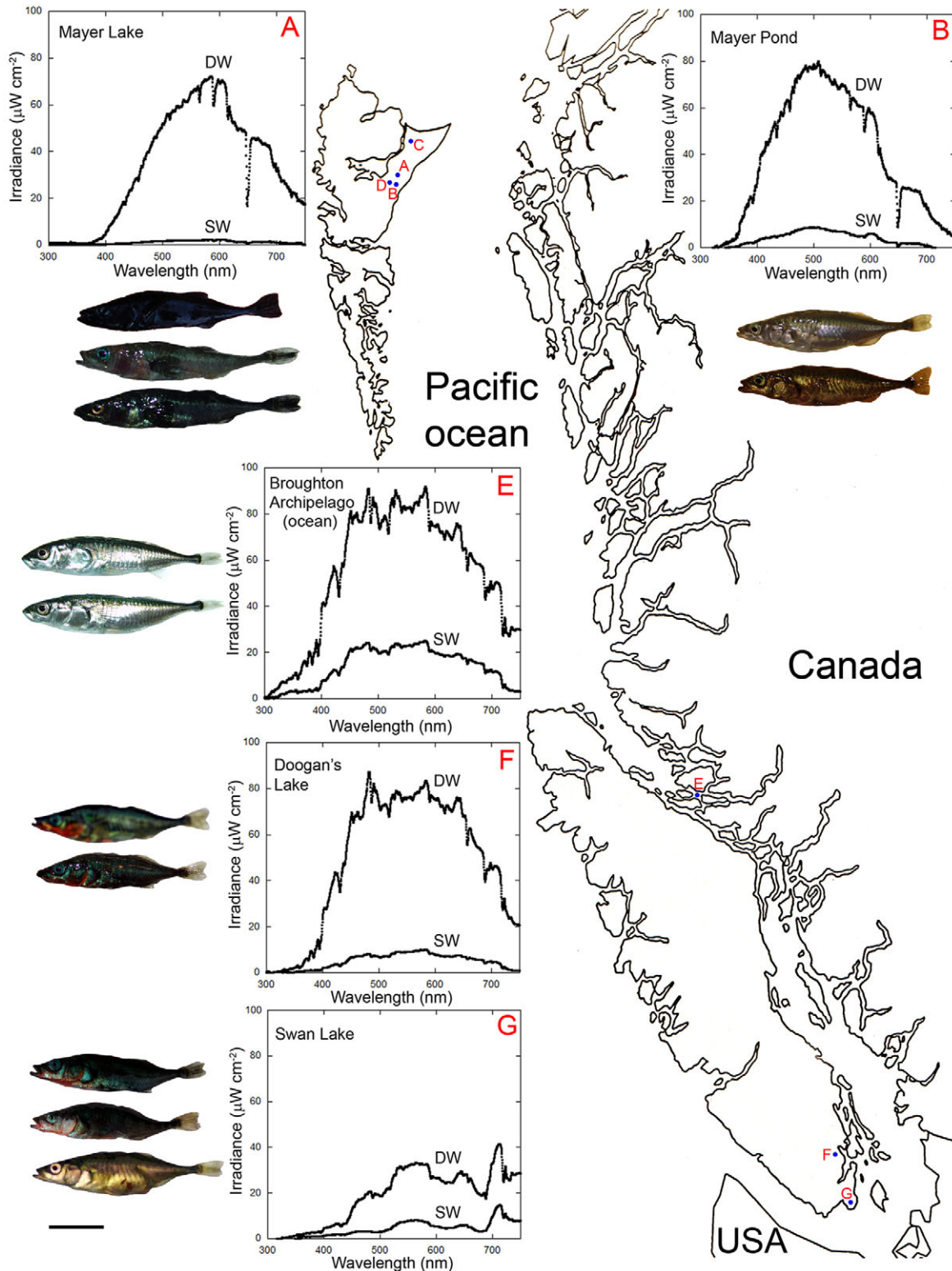


Fig. 1. Map of the stickleback locations studied, including images of representative sticklebacks and light transmission spectra. Locations are designated by red letters and blue spots on the map, corresponding to: (A) Mayer Lake; (B) Mayer Pond; (C) Drizzle Lake; (D) Drizzle Pond; (E) Broughton Archipelago (coastal ocean); (F) Doogan's Lake; and (G) Swan Lake. Spectral irradiance scans of transmitted light in the downwelling (DW) and sidewelling (SW) directions at 40 cm depth are shown for representative water types (i.e. dystrophic, mesotrophic and eutrophic). The data for Drizzle Lake and Drizzle Pond were similar to those from Mayer Lake and Mayer Pond, respectively. The letters on the scans correspond to those on the map. Next to each scan are images of representative adult sticklebacks collected at the corresponding locations. The bottom stickleback associated with Swan Lake is a reproductive female; the rest of the fish in the figure are males. The magnification bar at the bottom left of the figure represents 2.3 cm for the sticklebacks and 42 km for the map.

a broad spectrum of downwelling light (320–750 nm) penetrated surface waters (Fig. 1G).

Visual pigments and opsin sequences

Microspectrophotometry revealed four cone visual pigment types located within double and single cones, and one rod visual pigment present in the rods (Fig. 2). Single cones had either an ultraviolet (UV) or a short wavelength (S) visual pigment, with mean λ_{\max} in the range 365–379 nm and 434–460 nm, respectively (Table 1). Double cones had either a long wavelength (L) visual pigment in both double cone members (mean λ_{\max} range: 566–618 nm), as was predominantly the case in fish from dystrophic lakes or those that had been transferred into clear waters, or an L visual pigment in one member and a middle wavelength (M) visual pigment in the other (mean λ_{\max} range: 514–547 nm), as was always the case in fish from the remaining water bodies (Table 1). Rods contained a rhodopsin visual pigment with mean λ_{\max} in the range 507–531 nm. The mean λ_{\max} values measured for the Broughton Archipelago (ocean) population are consistent with λ_{\max} values of vitamin A1-conjugated visual pigments in other fish species (see Hárosi, 1994). None of the outer segments examined showed multiple α -band absorbance peaks, which would indicate multiple visual pigments within a photoreceptor (see Cheng et al., 2006; Cheng et al., 2009).

We used semi-empirical models (Hárosi, 1994) to predict the λ_{\max} shifts of visual pigments when the opsin remains the same but the chromophore is switched from vitamin A1 to vitamin A2. These calculations revealed the following visual pigment A1–A2 pairs, computed based on the λ_{\max} of vitamin A1-based visual pigments measured: 365–382 nm (UV), 434–441 nm (S), 514–546 nm (M), 566–638 nm (L) and 507–535 nm (rod). With the exception of the S pigment, the absorbance range of all other visual pigments could be accounted for by variable use of vitamin A1 and A2 chromophores within individual photoreceptors. The lower and upper extremes in the visual pigment absorbance ranges originated from cones of non-reproductive and reproductive fish, respectively. These denote retinas based primarily on vitamin A1 or A2 chromophore, as occurs in other non-mammalian vertebrates at different life stages or seasonally (Beatty, 1984; Novales Flamarique, 2005; Hárosi, 1994; Isayama and Makino, 2012).

Although the proportions of the two chromophores varied between populations, and between photoreceptors within populations, our results indicate vitamin A2-dominated retinas in dystrophic systems and vitamin A1-dominated retinas in the clear waters of the Broughton Archipelago (ocean) (Table 1). Such variation in chromophore use is in line with that found in a related species, the nine-spined stickleback (*Pungitius pungitius*), where the absorbance of all visual pigments (except S) could be accounted for by chromophore shifts (Saarinen et al., 2012). It therefore appears that, in both stickleback species, chromophore use varies between photoreceptor types and multiple SWS2 opsins may be expressed within the single cone population.

Sequencing of the LWS and RH2 opsins, corresponding to the L and M visual pigments (Fig. 2), which showed the greatest ranges in λ_{\max} (Table 1), revealed only three amino acid differences in the LWS opsins and nine amino acid differences in the RH2 opsins between populations from dystrophic and mesotrophic systems (Figs 3, 4). The differences among the LWS opsins involved three amino acid substitutions (Fig. 3), two located in the N-terminus and one in the fifth transmembrane helix. None of these changes were within proximity of the chromophore and, as such, should be functionally inconsequential (Smith, 2010). In addition, none of these alterations occurred at any of the five key sites that produce major shifts in visual

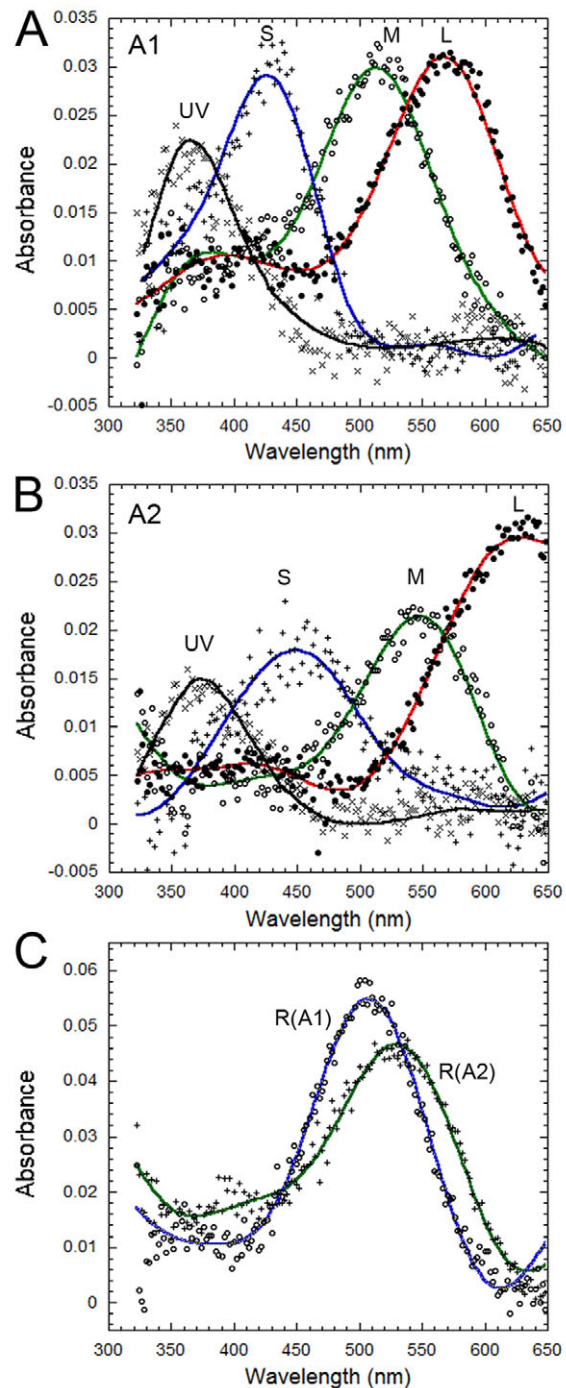


Fig. 2. Representative absorbance spectra of photoreceptors in adult stickleback retina [spectra are means from 3–7 photoreceptors per visual pigment, from 3–5 fish from the Broughton Archipelago (A) and Mayer Lake and Drizzle Lake (B)]. (A,B) Single cones contained a visual pigment maximally sensitive to ultraviolet light (UV) or to short wavelength light (S). Double cones had a visual pigment maximally sensitive to long wavelength light (L) in both double cone members, or one member contained an L visual pigment whereas the other housed a visual pigment maximally sensitive to middle wavelength light (M). Spectra in A correspond to vitamin A1-based visual pigments while those in B correspond to vitamin A2-based visual pigments (see Hárosi, 1994). (C) Rod visual pigments (R), maximally sensitive to middle wavelength light. Visual pigments based on the vitamin A2 chromophore had spectra that were broader and shifted toward longer wavelengths with respect to those from the corresponding vitamin A1-based visual pigments.

Table 1. Stickleback visual pigments

Photoreceptor parameter	Mayer Lake	Drizzle Lake	Swan Lake	Mayer Pond	Drizzle Pond	Doogan's Lake	Broughton Archipelago
UV							
λ _{max}	379±6 (N=4)	377 (N=2)	373 (N=1)	372±5 (N=3)	372 (N=1)	369 (N=1)	365±5 (N=3)
HBW	4495±612	4803		4387±736			4287±706
S							
λ _{max}	460±5 (N=11)	459±5 (N=6)	449±8 (N=4)	447±7 (N=8)	455±6 (N=8)	445±9 (N=5)	434±3 (N=14)
HBW	4913±541	4795±718	4664±518	4695±523	4680±603	4752±702	4839±490
M							
λ _{max}	547±7 (N=6)		543±10 (N=14)	543±8 (N=5)		526±10 (N=11)	514±8 (N=26)
HBW	4681±398		4354±455	4496±495		4165±372	4418±340
L							
λ _{max}	616±10 (N=32)	618±8 (N=21)	613±12 (N=16)	603±11 (N=27)	609±12 (N=14)	593±7 (N=17)	566±8 (N=22)
HBW	3734±457	3655±573	3746±298	3611±542	3497±410	3506±525	3618±363
Rod							
λ _{max}	531±7 (N=15)	530±6 (N=18)	521±7 (N=6)	524±4 (N=9)	527±4 (N=13)	518±8 (N=13)	507±5 (N=10)
HBW	4743±369	4409±369	4543±353	4410±403	4385±291	4385±369	4250±276

Data are means ± s.d.

The opsins expressed by the various photoreceptors belong to the following gene families: SWS1 (UV), SWS2 (S), RH2 (M), LWS (L) and RH1 (rod). The Broughton Archipelago (ocean) specimens were not in reproductive condition. One reproductive adult collected in another oceanic location near Richmond (BC, Canada) had cone visual pigments with average λ_{max} at 366 nm (UV), 445 nm (S), 536 nm (M) and 603 nm (L).

λ_{max} is the wavelength of maximum absorbance and HBW is the bandwidth at half-maximum. The number of photoreceptors examined, N, is given in parentheses and applies to the corresponding HBW. The missing data are due to a lack of measurements or reliable spectra.

pigment absorbance (Yokoyama et al., 2008). Comparison of RH2 opsin sequences also showed conservation of amino acids at the five key sites between stickleback populations (Fig. 4). Except for position 114, all the differences between sequences involved amino acids

belonging to the same, weakly charged, group (Smith, 2010). At position 114, Swan Lake fish had a glutamate (E), a negatively charged amino acid, whereas Mayer Lake and Broughton Archipelago fish had a glycine, a non-polar residue (Fig. 4). Position 114, however, is

Mayer Lake	M A E E W G K Q A F A A R R Y N ---E D T T R G S M F V Y T S N N T K D P F E G E N Y H I A P R W V Y N L S T L W M	57
Mayer Pond	M A E E W G K Q A F A A R R Y N ---E D T T R G S M F V Y T S N N T K D P F E G E N Y H I A P R W V Y N L S T L W M	57
Drizzle Lake	M A E E W G K Q A F A A R R Y N ---E D T T R G S M F V Y T S N N T K D P F E G E N Y H I A P R W V Y N L S T L W M	57
Drizzle Pond	M A E E W G K Q A F A A R R Y N ---E D T T R G S M F V Y T S N N T K D P F E G E N Y H I A P R W V Y N L S T L W M	57
Swan Lake	M A E E W G K Q A F A A R R Y N ---E D T T R G S M F V Y T S N N T K D P F E G E N Y H I A P R W V Y N L S T L W M	57
Broughton Ocean	M A E E W G K Q A F A A R R Y N --- D E T T T R G S M F V Y T S N N T K D P F E G E N Y H I A P R W V Y N L S T L W M	57
Human LWS	M A Q Q W S L Q R L A G R H P Q D S Y E D S T Q S S I F T Y T S N S T R G P F E G E N Y H I A P R W V Y H L T S V M	60
Mayer Lake	F I V V A L S V F T N G L V L V A T A K F K L Q H P L N W I L V N L A I A D L G E T V F A S T I S V C N Q F F G Y F I	117
Mayer Pond	F I V V A L S V F T N G L V L V A T A K F K L Q H P L N W I L V N L A I A D L G E T V F A S T I S V C N Q F F G Y F I	117
Drizzle Lake	F I V V A L S V F T N G L V L V A T A K F K L Q H P L N W I L V N L A I A D L G E T V F A S T I S V C N Q F F G Y F I	117
Drizzle Pond	F I V V A L S V F T N G L V L V A T A K F K L Q H P L N W I L V N L A I A D L G E T V F A S T I S V C N Q F F G Y F I	117
Swan Lake	F I V V A L S V F T N G L V L V A T A K F K L Q H P L N W I L V N L A I A D L G E T V F A S T I S V C N Q F F G Y F I	117
Broughton Ocean	F I V V A L S V F T N G L V L V A T A K F K L Q H P L N W I L V N L A I A D L G E T V F A S T I S V C N Q F F G Y F I	117
Human LWS	I F V V T A S V F T N G L V L A A T M K F K L R H P L N W I L V N L A V A D L A E T V I A S T I S V I N Q F V S G Y F V	120
Mayer Lake	I G H P M C V E G Y V S V C G I T A L W S L T I I S W E R W I V V C K P F G N V R F D A K W A T A G I V F S N I W S	177
Mayer Pond	I G H P M C V E G Y V S V C G I T A L W S L T I I S W E R W I V V C K P F G N V R F D A K W A T A G I V F S N I W S	177
Drizzle Lake	I G H P M C V E G Y V S V C G I T A L W S L T I I S W E R W I V V C K P F G N V R F D A K W A T A G I V F S N I W S	177
Drizzle Pond	I G H P M C V E G Y V S V C G I T A L W S L T I I S W E R W I V V C K P F G N V R F D A K W A T A G I V F S N I W S	177
Swan Lake	I G H P M C V E G Y V S V C G I T A L W S L T I I S W E R W I V V C K P F G N V R F D A K W A T A G I V F S N I W S	177
Broughton Ocean	I G H P M C V E G Y V S V C G I T A L W S L T I I S W E R W I V V C K P F G N V R F D A K W A T A G I V F S N I W S	177
Human LWS	I G H P M C V E G Y T V S L C G I T G L W S L A I I S W E R W L V V C K P F G N V R F D A K I V G I A F S W I W	180
Mayer Lake	A V W C A P P I F G W S R Y W P H G L K T S C G P D V F S G S E D P G V Q S Y M I V I M I T C C L I P L A I I L C Y L	237
Mayer Pond	A V W C A P P I F G W S R Y W P H G L K T S C G P D V F S G S E D P G V Q S Y M I V I M I T C C L I P L T I I L C Y L	237
Drizzle Lake	A V W C A P P I F G W S R Y W P H G L K T S C G P D V F S G S E D P G V Q S Y M I V I M I T C C L I P L A I I L C Y L	237
Drizzle Pond	A V W C A P P I F G W S R Y W P H G L K T S C G P D V F S G S E D P G V Q S Y M I V I M I T C C L I P L A I I L C Y L	237
Swan Lake	A V W C A P P I F G W S R Y W P H G L K T S C G P D V F S G S E D P G V Q S Y M I V I M I T C C L I P L G I I L C Y L	237
Broughton Ocean	A V W C A P P I F G W S R Y W P H G L K T S C G P D V F S G S E D P G V Q S Y M I V I M I T C C L I P L G I I L C Y L	237
Human LWS	A V W T A P P I F G W S R Y W P H G L K T S C G P D V F S G S S Y P G V Q S Y M I V I M V T C C I I P L A I I M L C Y L	240
Mayer Lake	A V W L A I R A V A M Q Q K E S E S T Q K A E R D V S R M V V M I V A Y I V C W G P Y T T F A C F A A N P G Y A F H	297
Mayer Pond	A V W L A I R A V A M Q Q K E S E S T Q K A E R D V S R M V V M I V A Y I V C W G P Y T T F A C F A A N P G Y A F H	297
Drizzle Lake	A V W L A I R A V A M Q Q K E S E S T Q K A E R D V S R M V V M I V A Y I V C W G P Y T T F A C F A A N P G Y A F H	297
Drizzle Pond	A V W L A I R A V A M Q Q K E S E S T Q K A E R D V S R M V V M I V A Y I V C W G P Y T T F A C F A A N P G Y A F H	297
Swan Lake	A V W L A I R A V A M Q Q K E S E S T Q K A E R D V S R M V V M I V A Y I V C W G P Y T T F A C F A A N P G Y A F H	297
Broughton Ocean	A V W L A I R A V A M Q Q K E S E S T Q K A E R D V S R M V V M I V A Y I V C W G P Y T T F A C F A A N P G Y A F H	297
Human LWS	Q V W L A I R A V A K Q Q K E S E S T Q K A E K E V T R M V V M I F A Y C V C W G P Y T T F A C F A A N P G Y A F H	300
Mayer Lake	P L A A A M P A Y F A K S A T I Y N P V I Y V F M N R Q R F R S C I M Q L F G K E V D D G S E V S - T S K T E V S -	353
Mayer Pond	P L A A A M P A Y F A K S A T I Y N P V I Y V F M N R Q R F R S C I M Q L F G K E V D D G S E V S - T S K T E V S -	353
Drizzle Lake	P L A A A M P A Y F A K S A T I Y N P V I Y V F M N R Q R F R S C I M Q L F G K E V D D G S E V S - T S K T E V S -	353
Drizzle Pond	P L A A A M P A Y F A K S A T I Y N P V I Y V F M N R Q R F R S C I M Q L F G K E V D D G S E V S - T S K T E V S -	353
Swan Lake	P L A A A M P A Y F A K S A T I Y N P V I Y V F M N R Q R F R S C I M Q L F G K E V D D G S E V S - T S K T E V S -	353
Broughton Ocean	P L A A A M P A Y F A K S A T I Y N P V I Y V F M N R Q R F R S C I M Q L F G K E V D D G S E V S - T S K T E V S -	353
Human LWS	P L M A A L P E Y F A K S A T I Y N P V I Y V F M N R Q R F R N C I L Q L F G K E V D D G S E L S S A S K T E V S S V S	360
Mayer Lake	V A P A	357
Mayer Pond	V A P A	357
Drizzle Lake	V A P A	357
Drizzle Pond	V A P A	357
Swan Lake	V A P A	357
Broughton Ocean	V A P A	357
Human LWS	V S P A	364

Fig. 3. Amino acid sequence comparison between long wavelength-sensitive (LWS) opsins of various stickleback populations and humans. Yellow regions are the predicted transmembrane helical domains, blue letters indicate differences between stickleback sequences, and green letters point to the locations of the five key sites (Yokoyama et al., 2008). The amino acids at the five key sites of middle wavelength-sensitive (MWS) and LWS opsin sequences are solely responsible for the spectral tuning of these opsins (Yokoyama et al., 2008).

Mayer Lake	MANEGGLE-PNGTEGKNFYIPMSN-----RTGVVRSFFEYQYYLLADPIMFKLILALYM	52
Swan Lake	MANEGGLE-PNGTEGKNFYIPMSN-----RTGVVRSFFEYQYYLLADPIMFKLILALYM	52
Broughton Ocean	MANEGGLE-PNGTEGKNFYIPMSN-----RTGVVRSFFEYQYYLLADPIMFKLILALYM	52
Human MWS	MAQQNSLRQLRAGRHFDQSDYEDSFSQSSIFPTYNSTNSSTRGPFEGPNHYHAPRWVYHLZSVVM	60
Mayer Lake	FFLICGTFPINGLTLVTAQNKLRQLPLNYLLVNLAVAGLIMCAFQFTITITSAVNGYFI	112
Swan Lake	FFLICGTFPINGLTLVTAQNKLRQLPLNYLLVNLAVAGLIMCAFQFTITITSAVNGYFI	112
Broughton Ocean	FFLICGTFPINGLTLVTAQNKLRQLPLNYLLVNLAVAGLIMCAFQFTITITSAVNGYFI	112
Human MWS	IFVVIASVFTNGLVLAATMKFKLHRLNLVNLAVADLAETVIASTISVNVQVYGFV	120
Mayer Lake	LGATACVEGFMATLGGVALWLSLVLAVERYIVVCKRPMGSKFSGTHAGAGVLFWTIMA	172
Swan Lake	LGATACVEGFMATLGGVALWLSLVLAVERYIVVCKRPMGSKFSGTHAGAGVLFWTIMA	172
Broughton Ocean	LGATACVEGFMATLGGVALWLSLVLAVERYIVVCKRPMGSKFSGTHAGAGVLFWTIMA	172
Human MWS	LGHPMCVLEGYTIVSLCGITGLWSLAIISWERRMVCKPFGNVRFDALKLAIVGIAFSWIV	180
Mayer Lake	MACAAPPPLFGWSRYLPEGMQCSGDPDYITLAPGFNNESYVIMFVVHFFTPVFIIFFTYG	232
Swan Lake	MACAAPPPLFGWSRYLPEGMQCSGDPDYITLAPGFNNESYVIMFVVHFFTPVFIIFFTYG	232
Broughton Ocean	MACAAPPPLFGWSRYLPEGMQCSGDPDYITLAPGFNNESYVIMFVVHFFTPVFIIFFTYG	232
Human MWS	AVWTAPPVIFGWSRYWLSLKSISGDPDVFSGSSYFGVQSYMLVLMVTCITPLSIIIVLCYL	240
Mayer Lake	SLVLTVKA AAAAQQSEESTQRAEREVTRMCLMVFGLVAVVPIASFAWIFLNKGAPFS	292
Swan Lake	SLVLTVKA AAAAQQSEESTQRAEREVTRMCLMVFGLVAVVPIASFAWIFLNKGAPFS	292
Broughton Ocean	SLVLTVKA AAAAQQSEESTQRAEREVTRMCLMVFGLVAVVPIASFAWIFLNKGAPFS	292
Human MWS	QVWLAIRAVAKQKQSEESTQRAEREVTRMCLMVFGLVAVVPIASFAWIFLNKGAPFS	300
Mayer Lake	ALTRAIAPAFPAKSSALYNPVIYVLLNQFRNCLMTTIGMGMVEDETSV-ASKTEVSSV	351
Swan Lake	ALTRAIAPAFPAKSSALYNPVIYVLLNQFRNCLMTTIGMGMVEDETSV-ASKTEVSSV	351
Broughton Ocean	ALTRAIAPAFPAKSSALYNPVIYVLLNQFRNCLMTTIGMGMVEDETSV-ASKTEVSSV	351
Human MWS	FLMAALPFPFAKSAIYNPVIYVPMNRQFRNCLLQFGK--KVDGSELSASKEVSSV	358
Mayer Lake	S-----	352
Swan Lake	S-----	352
Broughton Ocean	S-----	352
Human MWS	SSVSPA	364

Fig. 4. Amino acid sequence comparison between RH2 opsins of various stickleback populations and the human MWS opsin. Symbols as in Fig. 3.

located in extracellular loop 1 of the stickleback RH2 opsin, which is not in the vicinity of the retinal chromophore and should therefore not influence the absorbance of the visual pigment (Smith, 2010; Yokoyama et al., 2008). Overall, these results corroborated the conclusion reached from visual pigment data that all stickleback populations studied had the same opsins.

Cone mosaics and distributions of opsins

In accordance with the correspondence between visual pigments and morphological cone types, single cones contained a SWS1 or SWS2 opsin (Fig. 5) and double cones contained either LWS opsin or RH2 and LWS opsins, one per double cone member (Figs 6, 7). At the ellipsoid level, single and double cones formed square mosaics in the ventral retina (Fig. 5G) and mostly row mosaics in the rest of the retina (Fig. 5D). As is the case for the majority of fish species that have been studied (see Hárosi and Novales Flamarique, 2012), the square mosaic unit of the threespine stickleback consisted of four double cones forming a square, or cruciform, arrangement and a variable number of single cones, from 1 to 5 (Fig. 5A–C, G–I). Single cones were predominantly central in the mosaic unit, at the hypothetical intersection of neighbouring double cone partitions (Novales Flamarique, 2001; Cheng et al., 2006), but a few corner cones could also be found in the central and centro-dorsal areas of the retina (Fig. 5A, B). In contrast to reports on the adults of other fish species (Cheng et al., 2006; Cheng and Novales Flamarique, 2007), corner cones expressed SWS2 opsin, whereas the neighbouring centre cones expressed predominantly SWS1 opsin (Fig. 5A–F). In the ventral retina, where corner cones were absent, the remaining (centre) cones expressed primarily SWS2 opsin, though a minority expressed SWS1 opsin (Fig. 5G–I). UV cones were substantially smaller than S cones (Table 2) and showed proportionately smaller areas of mRNA expression in the cone myoids (Fig. 5J–L). All stickleback populations examined had similar distributions of UV and S cones. The highest densities of UV cones occurred in the centro-dorsal and centro-temporal areas, and S cones were always more numerous than UV cones throughout the retina (Fig. 8).

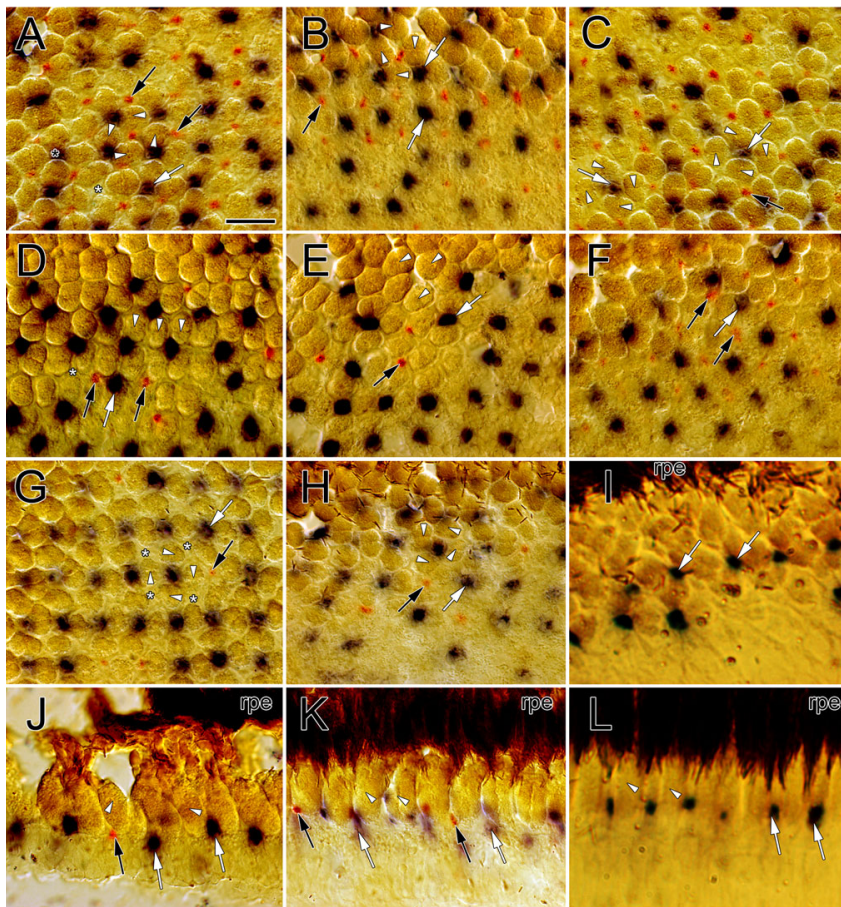


Fig. 5. Micrographs of sections from the retinas of sticklebacks following double label *in situ* hybridization with riboprobes encoding the SWS1 and SWS2 opsin mRNAs. (A–C) Transverse section through the centro-dorsal retina of sticklebacks from Mayer Lake (A), Mayer Pond (B), and Mayer Lake after 3 weeks of transplantation to full-spectrum clear waters in the laboratory (C). All the single cones, and none of the double cones, labelled with either of the two riboprobes. Most corner cones were S cones, labelling with the SWS2 riboprobe (blue colour, white arrow), while most centre cones were UV cones, labelling with the SWS1 riboprobe (red colour, black arrow). The cones formed primarily a square mosaic with double cones making the sides of the unit square (white arrowheads point to the double cone partitions). Corner cones could be present (black asterisk) or absent (white asterisk). (D–F) Transverse section through the centro-temporal retina of sticklebacks from Mayer Lake (D), Mayer Pond (E), and Mayer Lake after 3 weeks of transplantation to full-spectrum clear waters in the laboratory (F). The mosaic in this part of the retina was primarily a row. (G–I) Transverse section through the ventral retina of sticklebacks from Mayer Lake (G), Mayer Pond (H) and Swan Lake (I). Here, the cone mosaic was square and the corner cones had disappeared. The remaining single (centre) cones were predominantly S cones, but some were UV cones. (J–L) Radial section through the centro-dorsal retina of sticklebacks from Mayer Lake (J), Mayer Pond (K) and Swan Lake (L). The UV cones were noticeably smaller than the S cones. rpe, retinal pigment epithelium. Scale bar in A represents 10 µm and holds for all panels except I, where it represents 12.5 µm.

Table 2. Microspectrophotometry-derived parameters for stickleback cones from fish inhabiting the range of photic environments examined

Cone	A_{\max}	R	d (μm)	S_{\perp} (μm^{-1})	l_{os} (μm)
UV ($N=7$)	0.018 \pm 0.0033	1.7 \pm 0.13	1.3 \pm 0.068	0.018 \pm 0.0031	7.1 \pm 1.9
S ($N=15$)	0.025 \pm 0.0042	1.8 \pm 0.14	2.1 \pm 0.073	0.015 \pm 0.0024	8.4 \pm 1.6
M ($N=21$)	0.025 \pm 0.0050	1.7 \pm 0.12	2.9 \pm 0.084	0.011 \pm 0.0025	11 \pm 2.3
L ($N=23$)	0.030 \pm 0.0015	1.6 \pm 0.09	2.9 \pm 0.079	0.013 \pm 0.0017	11 \pm 2.5

Data are means \pm s.d.

A_{\max} refers to the absorbance at λ_{\max} , R is the dichroic ratio, d is the mean outer segment diameter, l_{os} is the length of the outer segment, and S_{\perp} is the transverse specific density.

Double cones from dystrophic lake populations were predominantly (>95%) L/L pairs, the rest were M/L pairs (Fig. 6A,D, Fig. 7A–J, Fig. 8A). Double cones from transplanted populations, whether to mesotrophic ponds 15–20 years ago (Fig. 6B,E, Fig. 7B) or to full-spectrum holding tanks and examined at 3 weeks and 6 months post-arrival (Fig. 7C), were also overwhelmingly (>93%) L/L double cones. The ~2% increase in M cones over the entire retina following transplantation was nonetheless statistically significant (ANOVA, $F=24.93$, $P<0.001$), and *post hoc* comparison tests (Student–Newman–Keuls, Tukey, with $\alpha=0.05$) revealed that M cone numbers were the same between transplanted populations, regardless of holding time, and different from the source (dystrophic lake) population. The highest increases in M cones occurred away from the central retina, primarily in the ventral and temporal regions of the retina (Fig. 6D,E, Fig. 7D,E, Fig. 8B,C), though numbers between sectors were not statistically different. The M cone population did not exhibit any discernible topographical pattern (Fig. 6A,B,D,E, Fig. 7A–J) but appeared randomly distributed throughout the retina, reminiscent of the smaller populations of UV cones, blue cones and ‘green’ rods in the retinas of amphibians (Chen et al., 2008). In contrast, double cones of fish from the remaining water bodies were M/L pairs, alternating in position within the mosaic unit (Fig. 6C,F, Fig. 7K,L, Fig. 8D). As in salmonid fishes (Beaudet et al., 1997; Cheng and Novales Flamarique, 2007), the highest cone densities occurred in the ventral and nasal periphery, which were the areas characterized by the lowest UV cone presence (Fig. 8).

Cone morphology and ultrastructure

Cone dimensions of fish from the various populations were statistically the same (Table 2). Ultrastructure investigations revealed that lamellar thickness and inter-lamellar spacing were also invariant between populations, with means of 14.5 nm and 9.1 nm, respectively. In particular, these means \pm s.d. for the dystrophic lake populations were 14.4 \pm 0.95 nm and 9.3 \pm 1.8 nm ($N=63$ cones, 6 fish), and 14.7 \pm 0.89 nm and 9.2 \pm 1.6 nm ($N=75$ cones, 8 fish) for the

transplanted populations. These numbers, which are in the range reported for other fishes (Borwein and Hollenberg, 1973; Collin et al., 1996), indicate no changes in outer segment morphology as a result of transplantation.

DISCUSSION

Heritable variation in opsin expression tuned to the spectral background

Genetic variation in opsin expression between populations was restricted to the longer wavelength opsins, RH2 and LWS. Dystrophic lake populations had double cones that were overwhelmingly L/L pairs whereas fish endemic to clear water systems had M/L double cones, each member alternating in position within well-organized mosaics (Figs 6–8). There was a clear correspondence between the mean λ_{\max} of double cones, weighted by their cone fractions, and the light environments that fish inhabited. Based on our downwelling irradiance measurements and those in the literature (Novales Flamarique et al., 1992; Novales Flamarique and Hawryshyn, 1993; McDonald and Hawryshyn, 1995; McDonald et al., 1995), we computed the depth at which the integrated light power transmission median (λP_{50}), a measure of the prevailing ambient quanta (McFarland and Munz, 1975), best approximated the weighted λ_{\max} of double cones. Surprisingly, this depth (60 cm) was the same for both dystrophic and mesotrophic systems, and was within 5 cm of the mid-range for nest deposition, an activity that marks the time when adult sticklebacks are found close to the water surface. At 60 cm depth, the mean λP_{50} was 610 and 565 nm for dystrophic and mesotrophic systems, respectively. These numbers are almost a match for the weighted λ_{\max} of double cones from the corresponding fish populations, with a mean of 613 nm for fish originating from dystrophic systems and 562 nm for those from mesotrophic systems. Such close correspondence, based on the vitamin A2-conjugated opsins found in reproductive fish, indicates evolutionary selection for double cone visual pigments with maximum sensitivity to the ambient light spectrum.

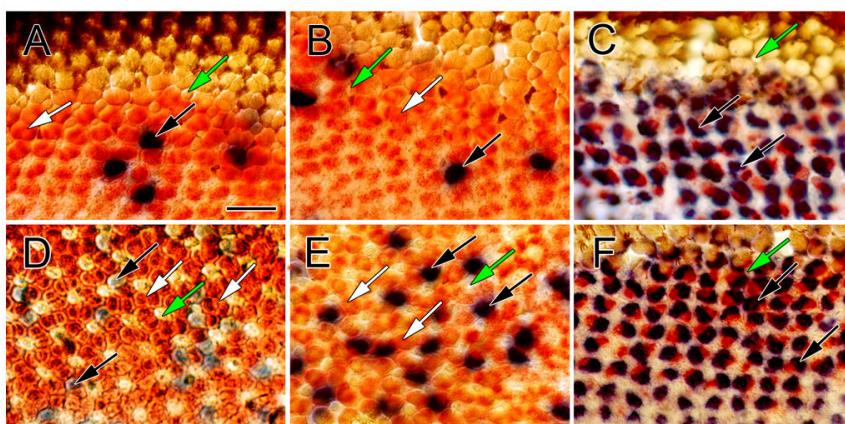


Fig. 6. Micrographs of sections from the retinas of sticklebacks following double label *in situ* hybridization with riboprobes encoding the RH2 and LWS opsin mRNAs. Dorsal (A–C) and ventral (D–F) sections from Mayer Lake (A,D), Mayer Pond (B,E) and Swan Lake (C,F). The Swan Lake population had double cones that were M/L pairs (the M member, blue colour, is designated by a black arrow); the double cones of the Mayer Lake and Mayer Pond populations were overwhelmingly L/L pairs (red colour, white arrows). Green arrows point to single cones, which were not labelled by either riboprobe. Scale bar in A represents 10 μm and holds for all panels.

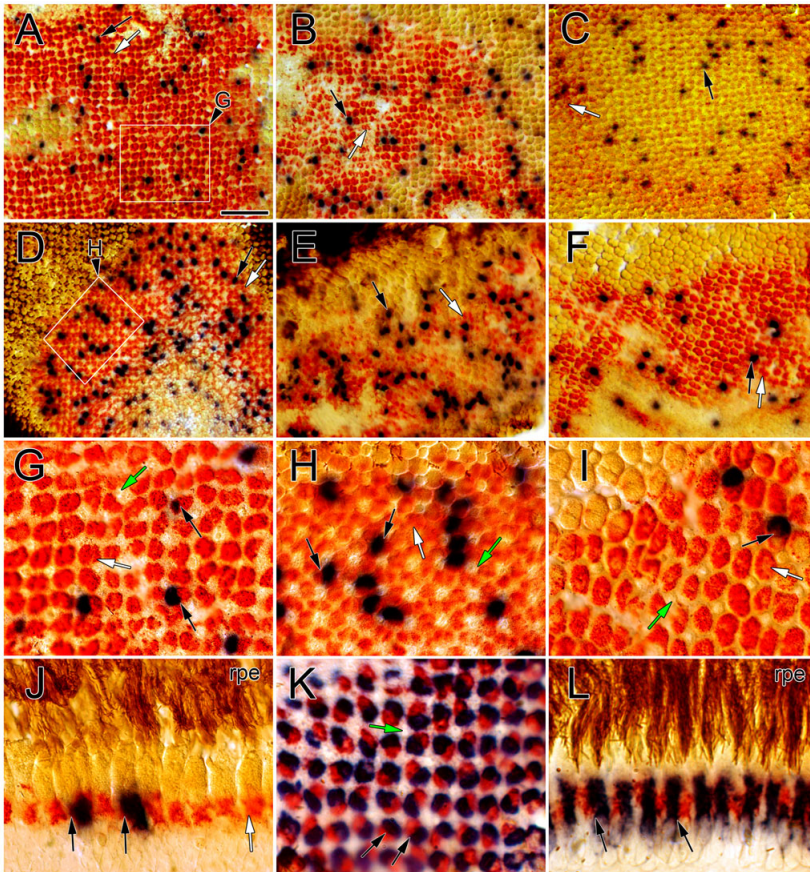


Fig. 7. Micrographs of sections from the retinas of sticklebacks following double label *in situ* hybridization with riboprobes encoding the RH2 and LWS opsin mRNAs. (A–C) Transverse section through the dorsal retina of sticklebacks from Mayer Lake (A), Mayer Pond (B), and Mayer Lake after 3 weeks of transplantation to full-spectrum clear waters in the laboratory (C). All the double cones, and none of the single cones, labelled with either of the two riboprobes. Most double cones were L/L pairs (white arrow), both members labelling with the LWS riboprobe (red colour). A minority of double cones were M/L pairs (black arrow), one member labelling with the RH2 riboprobe (blue colour) and the other with the LWS riboprobe (red colour). (D–F) Transverse section through the ventral (D), nasal (E) and centro-temporal (F) retina of a stickleback from Mayer Pond. RH2 opsin mRNA expression increased toward the naso-ventral retina. (G–I) Higher magnification views of cone mosaics from dorsal (G), ventral (H) and centro-temporal (I) retina. G and H are magnifications of the regions shown in A and D, respectively. Green arrows indicate single cones. (J) Radial section through the centro-dorsal retina of Mayer Lake. (K,L) Transverse (K) and radial (L) sections from the central retina of Swan Lake stickleback. All the double cones were M/L pairs and the M member alternated with the L member around the square mosaic unit. Other symbols and abbreviations as in Fig. 5. Scale bar in A represents 30 μm for A–F and 10 μm for G–L.

There were two cases where the λP_{50} at 60 cm depth and the weighted λ_{max} of double cones were distant from each other. These involved fish transplanted to clear water ponds ($\lambda P_{50} \approx 540$ nm and $\lambda_{\text{max}} \approx 603$ nm) and those from Swan Lake ($\lambda P_{50} \approx 613$ nm and $\lambda_{\text{max}} \approx 578$ nm). The lack of correspondence in these cases reveals the slow pace of evolution and major differences in population ecology between water bodies. Stickleback populations from the dystrophic and mesotrophic systems examined are genetically very stable, having evolved over thousands of years in relative isolation (Deagle et al., 1996). In contrast, the Swan Lake population undergoes frequent genetic drift as this small water body becomes periodically anoxic, resulting in the death of resident fish, and marine stickleback populations can readily invade as a result of the ocean's proximity. Thus, the Swan Lake population, though living in an environment dominated by long wavelengths, has an opsin complement resembling that found in mesotrophic waters and probably reflects the latest oceanic invasion. Similarly, the relatively recent introduction (15–20 years ago) of fish from dystrophic lakes into mesotrophic ponds has failed to change the inherited pattern of opsin expression from the source populations. As several generations of fish have been produced in the new environments, it appears that maximizing the sensitivity of double cones to the light background of surface waters, though beneficial in the long term, is not crucial for immediate survival.

Intraspecific, heritable, variation in opsin expression has also been reported in killifishes and in African cichlids using real-time PCR and microspectrophotometry. In Lake Victoria, cichlid populations living at greater depths have increased expression of LWS opsin alleles that absorb at longer wavelengths compared with those from surface-dwelling populations (Carleton et al., 2005; Hofmann et al.,

2010; Smith et al., 2011). There is also an apparent increase in L/L double cones, as opposed to L/M double cones, in cichlids inhabiting murkier waters (Carleton et al., 2005). In Lake Victoria, the differential expression of LWS alleles with depth is thought to drive speciation according to the premises of the 'sensory bias' hypothesis (Terai et al., 2006; Seehausen et al., 2008), though such a scheme does not hold for Lake Malawi populations (Smith et al., 2011). In killifishes, populations from 'tea-stained' swamps appear to have fewer UV and violet cones than populations from clear water springs (Fuller et al., 2003), and this result correlates with mRNA expression of these opsins (Fuller et al., 2004). The topographical organization of spectral cone types in the retinas of cichlids and killifishes is unknown, however, making functional interpretation difficult.

By comparison, our study shows the chromatic organization of the retina of sticklebacks from a wide range of photic regimes, revealing a difference in double cone opsin expression that is much greater than that estimated for cichlid and killifish cones based on microspectrophotometry data (Fuller et al., 2003; Carleton et al., 2005). This difference in double cone opsin expression is reflected in the spectral sensitivity of ganglion cells as measured by compound action potential recordings from the optic nerve (McDonald and Hawryshyn, 1995). Such extracellular potentials indicate a single sensitivity peak in the long wavelengths (600–620 nm) in sticklebacks from dystrophic lakes and two peaks, in the middle (540–560 nm) and long (600 nm) wavelengths, in fish from a mesotrophic lake (Quamichan Lake, BC, Canada) with similar spectral characteristics to the one studied here (Doogan's Lake). There is therefore a dominant contribution of the L cone mechanism to the spectral sensitivity of sticklebacks from dystrophic lakes, a result that is in line with expectations from our findings.

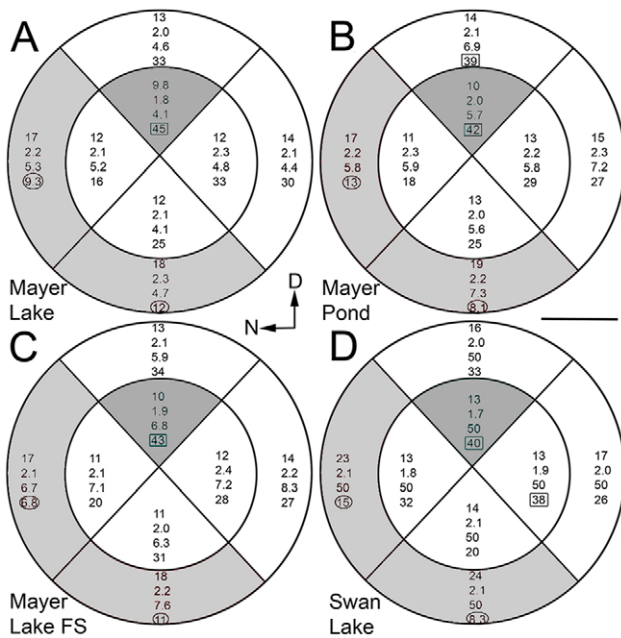


Fig. 8. Retinal maps of cone distributions in the retinas of sticklebacks from different photic regimes. Each retinal sector has four numbers arranged in a column. These are averages of 5–8 replicate observations, depending on retinal sector. From top to bottom, the first is the average number of double cones (in thousands per mm^2), the second is the average ratio of double cones to single cones, the third is the average percentage of RH2 mRNA-expressing cones within the double cone population, and the fourth is the average percentage of single cones that are labelled with the SWS1 riboprobe. For each retina, light and dark grey sectors indicate double cone densities that are 1 s.d. above or below the retinal average, respectively. SWS1 percentages that are 1 s.d. above or below the retinal average are bounded by a rectangle or ellipse, respectively. Over the entire retina, only the percentage of cones expressing RH2 was significantly different (at $\alpha=0.05$) between the Swan Lake population and the other three fish groups shown. Mayer Lake FS depicts the average combined retinal statistics from Mayer Lake fish after 3 weeks ($N=4$) and 6 months ($N=3$) following transplantation to full-spectrum clear waters in the laboratory; the retinas were grouped together because the averages were statistically the same. Drizzle Lake and Drizzle Pond fish had analogous photoreceptor distributions to those from Mayer Lake and Mayer Pond, while fish from Doogan's Lake and the Broughton Archipelago had similar distributions to those from Swan Lake. The scale bar represents 1.8 mm. D, dorsal retina; N, nasal retina.

It is intriguing yet enigmatic that the previous electrophysiological study failed to find any spectral sensitivity functions corresponding to either the UV or S cone mechanisms (McDonald and Hawryshyn, 1995). In fact, even the presence of an M cone mechanism in Swan Lake sticklebacks could not be clearly discerned. The electrophysiological technique used relied on extracellular recordings from a subset of optic nerve fibres and this limitation, along with restricted illumination of the ventral retina (McDonald and Hawryshyn, 1995), could easily have resulted in the absence of detected signal from smaller cone populations. Other taxa, like amphibians, also have reduced populations of UV and S cones dispersed throughout the retina (accounting for ~1–6% of all cones) (Chen et al., 2008), and their physiological presence was only revealed following action potential recordings from the entire retina (Koskelainen et al., 1994; Deutschlander and Phillips, 1995). In primates, S cones (expressing a SWS1 opsin) are present in reduced numbers (<10%) compared with other cone types (Roorda et al., 2001), yet play a role in non-foveal vision. In the case of adult

sticklebacks, it is important to note that these fishes often feed in surface waters, where a full spectrum of light is present, providing the necessary wavelengths to stimulate UV cones.

Phenotypic plasticity in opsin expression: cellular origin and functional significance

Fish transplanted to clear waters from dystrophic lakes had the same ~2% increase in M cones regardless of residence time in the mesotrophic ponds or in aquaria exposed to a full light spectrum. Such an increase could have resulted from apoptosis of L cones and their replacement by newly differentiated M cones, or by a switch in opsin expression from LWS to RH2 within individual cones. Although we did not perform experiments to distinguish between these two possibilities, it is worth noting that full differentiation of cones in goldfish takes approximately 3 weeks (Wu et al., 2001). Apoptosis followed by differentiation, two processes that are usually sequential (Candal et al., 2005), would take longer than our first sampling time (3 weeks) to complete. Thus, our data suggest opsin switching as the cellular mechanism behind the double cone phenotypic plasticity observed. In the retinas of salmonid fishes and rodents, cell labelling studies with proliferation and differentiation markers have shown that cone production in the main (non-peripheral) retina is absent after development (Julian et al., 1998; Candal et al., 2005; Cheng et al., 2009; Glaschke et al., 2011). Our histological analyses further indicated that cone density and morphology did not change following transplantations. This result, together with the similarity in absorbance curves obtained for the various visual pigments between populations, strongly suggests that opsin density remained the same following transplantations.

The timing of M cone density increase, occurring within 3 weeks of transfer to clear waters, is in line with reported differences in opsin mRNA expression between adult killifish following 1–3 days of rearing in new light environments (Fuller and Claricoates, 2011). It is also consistent with the timing of the opsin switch in the single cones of salmonid fishes after 3–5 days of exogenous treatment with thyroid hormone (Cheng et al., 2009; Gan and Novales Flamarique, 2010).

In contrast to the opsin switches that occur during development of salmonid fishes and rodents (Cheng et al., 2006; Cheng and Novales Flamarique, 2007; Applebury et al., 2007), the increase in M cone density reported here for sticklebacks does not appear to have any significance for the visual ecology of the animal. This is because the total photon catch of M cones in the retina would be altered by less than 1% (see Novales Flamarique, 2013). Similar changes in cone numbers following metamorphosis of amphibians are considered inconsequential (Chen et al., 2008). Our results are in line with those from cave-dwelling mollies, where differences in LWS opsin mRNA expression between populations living in different light environments show little to no phenotypic plasticity (Tobler et al., 2010). It remains to be determined whether the changes in opsin mRNA expression due to phenotypic plasticity reported for other fishes (Fuller et al., 2005; Shand et al., 2008; Hofmann et al., 2010; Fuller and Claricoates, 2011) are ecologically meaningful.

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Table S1. Number of fish used for different parts of the study

Technique	Mayer Lake	Drizzle Lake	Mayer Pond	Drizzle Pond	Doogan's Lake	Broughton Archipelago	Swan Lake
MSP	5	5	5	3	4	5	4
<i>In situ</i> hybridization	8	5	7	4	3	4	7
Histology	3	3	4	4	3	3	4
Opsin sequencing	5	4	5	4	0	4	5
MSP, microspectrophotometry.							