Magnetic field effect on melanophores of the European whitefish *Coregonus lavaretus* (Linnaeus, 1758) and vendace *Coregonus albula* (Linnaeus, 1758) (Salmonidae) during early embryogenesis

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**Abstract**

The effects of a magnetic field (1, 3 and 5 mT), applied during short- (1, 3, 5, 30 and 60 minutes) and long-term (from the beginning of embryogenesis) exposure, on melanophores of the European whitefish, *Coregonus lavaretus* and vendace, *Coregonus albula*, were investigated. Short-term magnetic field exposure effects on the behaviour of melanophores at the stage when the eye and body pigment on whitefish and vendace were distinctly visible in the embryos. The short-term embryo exposure to the magnetic fields induced the pigment of the body cells to move to the central parts of the cells. In the control, we did not observe displacement of the pigment within the melanophores. The long-term exposure to the magnetic field was found to delay the pigment appearance in the eyeballs and on the body of embryos of both investigated species. The number of melanophores in the body of embryos exposed to the magnetic fields was lower than that in the control. The pigment showed an increasing tendency to concentrate in individual embryonic and larval cells with increasing magnetic field strength. Melanophore index in embryos and larvae of whitefish and vendace was found to differ significantly between the control and all the magnetic field treatments.

Our results can be extrapolated to other organisms and will allow us to broaden the knowledge on pigment cell magnetoreception in vertebrates.

**Keywords:** Melanophores, magnetic field, European whitefish, vendace, melanophore index

**Introduction**

Fish body colour and changes in skin pigmentation are due to the presence of chromatophores, known also as pigment cells (Burton 2002). Based on structural differences and pigments in the cells, chromatophores have been divided into four groups: allophores (cells with greenish pigments), guanophores (whitish), melanophores (brown to black), and lipophores, further subdivided into xanthophores (yellowish) and erythrophores (red) (Kelsh 2004). So far, most attention has been paid to melanophores. These usually star-shaped cells engage in numerous cytoplasmic processes. A melanophore contains membrane-bound organelles called melanosomes, i.e. oval bodies with the pigment melanin (Rogers et al. 1997; Van Den Bossche et al. 2006). The major function of melanosomes is to protect the DNA in the spinous-layer cells from harmful ultraviolet (UV) radiation (Lanzing 1984).

Environmental factors and changes occurring within the body activate the melanophores, their increasing activity being manifested as intracellular responses. Numerous fish species change their body colour so that they can blend in with the background (Logan et al. 2006). Changes in skin pigmentation are frequently a result of endocrine, disease-related or genetic processes (Alexander et al. 1998). Light is the most common external stimulus influencing fish
pigmentation, which may change in a circadian cycle or as a response to changes in light intensity and colour (Fuji 2000; Zagal Skaya et al. 2005). Melanophores also respond to certain drugs or chemicals (Dwivedi 1978) as well as to toxins and bacteria (Chaplen et al. 2002).

In recent decades, considerable attention has been paid to the effects of generated (static and alternating) magnetic fields on living organisms. The interest in those effects was generated by the need to explain organisms’ spatial orientation and by the growing “magnetic pollution” of the Earth’s biosphere produced by civilisation development and the resultant increase in the number of different devices emitting magnetic and electromagnetic fields.

Experiments on magnetic field effects have been carried out on various living organisms, from bacteria to invertebrates to lower and higher vertebrates, including fishes (Kalmijn 1982; Kirschvink 1997; Valles 1998; Kirschvink et al. 2001; Wiltschko & Wiltschko 2005; Holland et al. 2008). As shown by numerous studies, magnetic fields considerably affect various developmental stages of fishes. Juvenile fishes were reported to change directional responses (Quinn & Groot 1983). Magnetic field was observed to prolong sperm motility (Winnicki & Formicki 1993; Formicki 2008; Formicki et al. 2015), to slow down water absorption by fish eggs (Formicki et al. 1993; Sadowski et al. 2007), to accelerate cardiac contractions in embryos and larvae (Winnicki et al. 2004), and to increase the respiration rate (Formicki & Perkowski 1998). Magnetic fields were also observed to affect the orientation of embryos (Tański et al. 2005) as well as that of larvae and adults (Walker et al. 2002; Formicki et al. 2004a,b).

Effects of magnetic fields on fish chromatophores have also become a focus of attention. Effects of high-intensity magnetic fields on melanophores were investigated in a number of black tetra Gymnocorymbus ternetzi Boulenger, goldfish Carassius auratus L., rainbow trout Onchorhynchus mykiss Walbaum, eel Anguilla anguilla L. and trout Salmo trutta m. trutta L. (Wannitikul et al. 1993; Testorf et al. 2002; Sawaguchi et al. 2003). In black tetra, melanin in melanophores was found to disperse in the magnetic fields, while in experiments with rainbow trout, eel and trout, no such effect was observed. Also an increase of ammonia content in goldfish was found. Preliminary observations of magnetic field effects on early developmental stages were reported from pike Esox lucius L.; here the pigment was observed in numerous melanophores comparatively to the control (Brysiewicz et al. 2007).

The present work brings the first description of effects of short- (1, 3, 5, 30 and 60 minutes) and long-term (from the beginning of embryogenesis) exposure to generated static 1-, 3- and 5-mT fields (relative to the Earth’s geomagnetic field) on melanophores in embryos and larvae of the European whitefish, Coregonus lavaretus (Linnaeus, 1758) and vendace, Coregonus albula (Linnaeus, 1758), focusing on the first appearance of pigments in the eyes and body of embryos as well as on melanophore abundance and behaviour of individual melanophores in embryos and larvae.

Material and methods

Source of fish and gamete collection

The experiment was carried out on embryos and larvae of the European whitefish (average total length (Lt) females: 50 ± 0.5 cm, range 47–53 cm, males: 39 ± 0.5 cm, range 33–45 cm) and vendace (Lt females: 18 ± 0.5 cm, range 16–20 cm, males: 16 ± 0.5 cm, range 14–18 cm) originating from fish caught in Lake Morzycko, north-western Poland (52°51′50″N, 14°24′33″E), close to the Polish–German border. Fish of both species were caught using commercial gill nets and trawls. Sperm and eggs were collected by gently pressing the abdomen of fish on the site of capture, and then transported in Eppendorf resolls (2 hours) separately from each individual in containers in isothermal conditions in constant temperature (3 ± 0.2°C). Fertilisation of both species (dry method) was effected in the isothermal laboratory at a constant temperature (3 ± 0.2°C), at the Department of Hydrobiology, Ichthyology and Biotechnology of Reproduction: eggs of 10 females were fertilised with sperm of 10 males. In the experiment 500 eggs were collected from each female, mixed in the container and fertilised with the sperm of all 10 males. The fertilisation rate was 96%.

Magnetic field

Static magnetic fields of 1, 3 and 5 millitesla (mT) in strength were generated with magnets. The control was placed between plastic dummy magnets (sham exposure). The experiment was conducted in the natural geomagnetic field. The direction of each experimental field was concomitant with Earth’s magnetic field lines. The value of the field was measured pointwise inside a crystalliser (hallotrone Teslamer HTN-12 m, Institute of Telecommunication and Acoustics, Wroclaw Technical University).

Incubation

The fertilised eggs of the European whitefish and vendace were incubated in 600-mL aerated round crystallisers (ø 16 cm) exposed to the static magnetic fields generated. In each of the crystallisers (variants
of the experiment) 1000 eggs were incubated. The eggs of both species (10 eggs of whitefish and 10 eggs of vendace) were examined daily to assess the development of melanophores. The two sets – the one subject to the magnetic field values and the control set – were within the natural magnetic background. The water in the crystalliser was partially (150 mL) changed at 2-day intervals. Hatched larvae of both species were incubated in the same conditions (temperature 3.0 ± 0.2°C). The duration of embryonic development were given in degree days (D° – the product of the number of days of embryogenesis and the average daily temperature).

**Long-term exposure to magnetic field**

The eggs developing from the beginning of embryogenesis in the generated magnetic fields and in the control were examined and recorded daily under a microscope (Nikon ECLIPSE TE-2000 S equipped with a camera Sony DSLR-A330) to detect the appearance of melanophores in the eyes of the embryos (10 eggs of whitefish and 10 eggs of vendace daily). The appearance of five melanophores was assumed to be the commencement of eye pigmentation. The moment of appearance of melanophores on the embryonic body was noted as well (five melanophores), the mean number of melanophores being recorded. In determining the melanophore development (eye pigmentation and melanophores on the body), we observed 50 embryos of both species in each variant of the experiment. The degree of melanosome concentration in the embryonic and larval melanophores was assessed and expressed as melanophore index, determined from the images recorded, evaluating the degree of pigment concentration or dispersion in melanophores (scale 1 – aggregated melanosomes, to 5 – dispersed melanosomes) (Srivastava & Jaju 1981; Patil & Jain 1993; Daiwile et al. 2015). Twenty-five eggs were examined from each variant of the experiment. Prior to the beginning of exposure, the eggs were acclimated to the experimental conditions for 40 minutes, and the behaviour of the melanophores in the magnetic field was recorded (Nikon ECLIPSE TE-2000 S with a Sony DSLR-A330 still camera). To this end, three chromatophores on the head, where the cells were clearly visible and did not overlap, thus ensuring measurement precision, were randomly selected. The degree of melanin concentration within the melanophore was measured by tracing the outline of the spreading pigment. The recorded images were analysed with the NIS Elements software.

**Statistical methods**

The data obtained were analysed using the STATISTICA v. 10 PL software. The eye pigmentation was analysed with the Kolmogorov–Smirnov test, as the observations were carried out over a prolonged period of time to cover the melanophore formation in the eyeballs. Data on the melanophore index and melanophore abundance on the embryo and larval body reflected the moment of the melanophores’ appearance and were subject to analysis of variance (ANOVA).

**Short-term exposure to magnetic field**

Responses of melanophores to short-term exposure to magnetic fields (1, 3, 5, 30 and 60 minutes) were analysed as well. The eggs were then incubated in the Earth’s magnetic background until the melanophores were fully formed and contained the pigment shifting inside them. Then, the eggs were placed individually in specially prepared 4 cm³ Plexiglas chambers (to ensure good oxygen supply throughout the period of exposure) and the chambers were exposed to 1-, 3- and 5-mT magnetic fields, or sham-exposed (Figure 1).

We examined 25 eggs of each species individually in each variant of the experiment. Prior to the beginning of exposure, the eggs were acclimated to the experimental conditions for 40 minutes, and the behaviour of the melanophores in the magnetic field was recorded (Nikon ECLIPSE TE-2000 S with a Sony DSLR-A330 still camera). To this end, three chromatophores on the head, where the cells were clearly visible and did not overlap, thus ensuring measurement precision, were randomly selected. The degree of melanin concentration within the melanophore was measured by tracing the outline of the spreading pigment. The recorded images were analysed with the NIS Elements software.

![Figure 1. Plexiglas chambers used for recording of melanophores on developing embryos of whitefish *Coregonus lavaretus* (Linnaeus, 1758) and vendace *Coregonus albula* (Linnaeus, 1758) in the magnetic field and control.](image-url)
Results

Observations of the early developmental stages of the two fish species studied showed that melanophores responded to the static magnetic fields applied.

Long-term exposure to magnetic field

Embryonic eye pigmentation. The first melanophores in the whitefish embryos’ eyeballs were observed to appear in the control after 86.5 D°. Subsequently (92 D°), melanophores appeared in the embryos exposed to 1- and 3-mT fields. The embryos exposed to the 5-mT field were the latest to acquire their eye pigmentation (105 D°). The differences in timing of embryonic eyeball pigment appearance between all the treatments were significant (Table Ia; Figure 2). Embryonic development of whitefish in control was 399 D°, in magnetic field 1 mT and 3 mT – 405 D°, in 5 mT – 414 D°.

In the vendace embryos, the earliest (97.5 D°) melanophores to appear in the eyeballs were those in the control. Eleven degree days later, pigment was visible in the eyes of the embryos exposed to the 1-mT field; the embryos kept in the 3-mT field acquired their eyeball pigment after 119.5 D°. The embryos exposed to the 5-mT field took the longest (125 D°) to acquire the eye pigment. As in the case of the whitefish embryos, the treatments differed significantly in the timing of the embryonic eye pigment appearance (Table Ib, Figure 3). Embryonic development of vendace in the control was 331 D°, 1 mT – 373 D°, 3 mT – 382 D° and 5 mT – 397 D°.

Melanophores on the embryo body

Counting melanophores in both species was carried out after 10 D° when they appeared on the body of the embryos in each variant of the experiment. The first melanophores to appear on the whitefish body

Table I. Distributions of eye pigmentation in (a) whitefish Coregonus lavaretus and (b) vendace Coregonus albula embryos exposed to 1-, 3- and 5-mT static magnetic fields and in constant (geomagnetic field) (Kolmogorov–Smirnov test; significant differences ≥ 1.36). * significant difference.

|        | Control | 1 mT  | 3 mT  | 5 mT  |
|--------|---------|-------|-------|-------|
| (a)    |         | 2.07  | 2.74  | 3.52  |
| Control|         | 1.65  | 2.96  | 1.87  |
| 1 mT   |         | 2.07  | 1.65  | 2.96  |
| 3 mT   |         | 2.74  | 1.65  | 1.87  |
| 5 mT   |         | 3.52  | 2.96  | 1.87  |

| (b)    |         | 1.47  | 3.66  | 4.50  |
|        |         | 3.66  | 2.50  | 3.10  |
| Control|         | 4.50  | 3.10  | 1.47  |
| 1 mT   |         | 1.47  | 2.50  | 3.10  |
| 3 mT   |         | 3.66  | 2.50  | 1.47  |
| 5 mT   |         | 4.50  | 3.10  | 1.47  |

Figure 2. Eye pigmentation of whitefish Coregonus lavaretus (Linnaeus, 1758) embryos in magnetic field (115 D°): (a) geomagnetic field (control); (b) 1 mT; (c) 3 mT; (d) 5 mT.
were those on the yolk sac and in the caudal part. In the control they appeared after 129.5 D°, and later in the embryos subject to the artificial magnetic fields. The timing of melanophore appearance increased with the magnetic field strength (146 D° in 1 mT, 162.5 D° in 3 mT, and 173.5 D° in 5 mT). The melanophore abundance differed significantly between the control and the treatment involving exposure to the 5-mT magnetic field. The corresponding differences between the remaining experimental treatments were not significant, but the melanophore abundance tended to decrease with increasing magnetic field strength (Figure 4a).

In the vendace embryos, melanophores appeared initially in the caudal section of the body. The first melanophores to appear (158 D°) were those in the embryos exposed to the 1-mT magnetic field. After 164 D° melanophores were visible in the control embryos, those exposed to the 3-mT field showed their first melanophores after 172.5 D°. The last to appear (192 D°) were the melanophores in the embryos exposed to the 5-mT field. The

Figure 3. Eye pigmentation of vendace Coregonus albula (Linnaeus, 1758) embryos in magnetic field (132 D°): (a) geomagnetic field (control); (b) 1 mT; (c) 3 mT; (d) 5 mT.

Figure 4. Effects of magnetic field on melanophore abundance 10 D° after appearing in embryos kept in the Earth’s geomagnetic field (control) and exposed to 1-, 3- and 5-mT static magnetic fields; (a) whitefish Coregonus lavaretus (Linnaeus, 1758) analysis of variance (ANOVA) F-test = 4.1358; confidence interval (CI) = 2.98–4.39; variance (p) = 0.01207; b: vendace Coregonus albula (Linnaeus, 1758) ANOVA F-test = 1.7501; CI = 2.98–4.39; p = 0.17226.
melanophore abundance in the embryos incubated in the geomagnetic field (control) was somewhat higher than that in the embryos exposed to the experimental fields (Figure 4b).

**Melanophore index**

Melanophore indexes of the whitefish embryos and larvae were found to differ significantly between the control and all magnetic field treatments (Figure 5). In the whitefish embryos, the differences between the 1-mT vs 3- and 5-mT magnetic field treatments were also significant (Figure 5a). In the larvae, in addition to significant differences between the control and the magnetic field treatments, the differences between the 1- and 3-mT vs the 5-mT magnetic field treatments were also significant (Figure 5b).

In the vendace embryos, melanin concentration was observed to increase with increasing magnetic field strength (significant differences relative to the control). Differences in the melanophore indices between the eggs incubated in the 3- and 5-mT magnetic fields were not significant (Figure 5c).

The vendace larvae showed distinct pigment concentration occurring in all the treatments. The lowest melanophore index was typical of the larvae exposed to the 1-mT magnetic field and differed significantly from the indices recorded in the remaining treatments. Differences between the indices in the 3- and 5-mT treatments were also significant (Figure 5d).

**Short-term exposure to magnetic field**

Melanosome translocation in melanophores. The results of short-term exposure of the whitefish embryo melanophores to magnetic fields are illustrated in Figure 6. The control embryos showed virtually no melanin shifting in the cells (Figure 6a). In contrast, translocation of the pigment was visible in all of the magnetic field treatments. Melanin in the embryos exposed to 1 mT shifted in various directions throughout the experiment (Figure 6b). Those embryos exposed to the 3- and 5-mT fields exhibited clear differences in pigment translocation, with melanin shifting to the central part of the cell (Figure 6c, d).

![Figure 5. Melanophore index: whitefish Coregonus lavaretus (Linnaeus, 1758) embryos (a) incubated in the geomagnetic field (control) and exposed to 1-, 3- and 5-mT static magnetic fields; analysis of variance (ANOVA) F-test = 27.497, confidence interval (CI) = 3.58–3.73; variance (p) = 0.0000; larvae (b) in the geomagnetic field (control) and exposed to 1-, 3- and 5-mT static magnetic fields; ANOVA F-test = 54.918, CI = 3.51–3.69; p = 0.0000; vendace Coregonus albula (Linnaeus, 1758) embryos (c) incubated in the geomagnetic field (control) and exposed to 1-, 3- and 5-mT static magnetic fields; ANOVA F-test = 47.115; CI = 2.94–3.13; p = 0.0000; larvae (d) in the geomagnetic field (control) and exposed to 1-, 3- and 5-mT static magnetic fields; ANOVA F-test = 16.075; CI = 1.69–1.85; p = 0.0000.](image-url)
Figure 7 shows melanin translocation in melanophores on the whitefish embryo head. A distinct tendency of the pigment to move towards the central part of the melanophore with the time of exposure is visible.

Short-term exposure of vendace embryos to magnetic fields showed a clear tendency of melanin to shift to the central part of the melanophores, the tendency intensifying with time of exposure (Figure 8). Significant differences between melanophores exposed to 1- and 5-mT fields appeared between exposure minutes 5 and 30, and remained until termination of exposure (Figure 8b, d).

Figure 9 illustrates the melanin shifting in melanophores on the vendace embryo head. The changes in Figure 9e and f are particularly pronounced.

Discussion
This study on early developmental stages of two fish species, the European whitefish and the vendace, showed static magnetic fields to affect melanophores in the developing organisms.

The earliest appearance of the first melanophores (long-term exposure) in the eyeballs and on the body occurred in both species in the control. The appearance of pigmentation on the embryo bodies and in the eyes was delayed in the generated magnetic fields, the delay increasing with increasing field strength. The latest pigment acquisition by the eyes of both species occurred in the 5-mT magnetic field treatment; the delay in the appearance of the first melanophores on the embryo body was the longest in that field as well.

Embryos of both species showed fewer melanophores on the body when exposed to a magnetic field. The highest number of melanophores on the body of embryos and larvae was typical of the control, the lowest number being recorded in the 5-mT magnetic field treatment.

The degree of melanosome aggregation – short-term and long-term exposure (melanophore index) – showed a tendency for melanin to concentrate in the central part of the melanophore in all of the magnetic field treatments, the strongest pigment dispersion being observed in the control. The only deviation from this pattern occurred in the vendace larvae, which showed the strongest melanin dispersion in the 1-mT magnetic field treatment.

Melanophore behaviour was observed to change also during short-term exposure to magnetic fields. The whitefish and vendace embryos kept in the geomagnetic field (control) showed no change in melanophore responses. In contrast, the melanosome was
observed to shift in the embryos and larvae exposed to generated magnetic fields. In all of the treatments, melanosome tended to concentrate in the central part of the melanophore. The whitefish embryos exposed to the 3- and 5-mT fields differed significantly. In the vendace embryos, significant differences occurred after 5 minutes of exposure to the 1-mT magnetic field.

So far, studies targeting fish melanophores have involved magnetic fields of several hundred millitesla as well as several tesla (Wannitikul et al. 1993; Testorf et al. 2002; Sawaguchi et al. 2003; Zagal’Skaya et al. 2005; Gnyubkin & Maksimovich 2008). Among other problems, in vivo and in vitro effects of static magnetic fields were followed in, inter alia, eel (Anguilla anguilla), rainbow trout (Oncorhynchus mykiss) and trout (Salmo trutta m. trutta). Exposure to 160–600-mT magnetic fields produced distinct changes in melanocytes, compared to the control (Wannitikul et al. 1993). Magnetic field effects on colour change in the “goldfish” and on the amount of urine in the body were studied as well (Sawaguchi et al. 2003). The amount of urine was found to decrease in the 62 mT–50 Hz magnetic field; fish body colouration was observed to change after more than 20 hours. Effects of 8- and 14-T magnetic fields on the anal fin melanophores were studied in the black tetra (Gymnocorymbus ternetzi). As early as after 5 minutes of exposure to the 14-T field, melanin was observed to become aggregated,
the largest changes occurring after 60 minutes (Testorf et al. 2002). As shown by our study, even low values of magnetic fields are capable of inducing a melanophore response. Also, research on Oreochromis mossambicus showed that the melanophore index decreased over time, after exposure of fish to lead nitrate, phenol and hexachlorocyclohexane (HCH) (Daiwile et al. 2015).

The melanophore organelles include microtubules, which are involved in melanosome translocation (Van Den Bossche et al. 2006). Microtubules are cylindrically elongated, narrow and elastic structures constituting an integral part of melanophores; they may contract or elongate (Fujii 2000). During concentration or dispersion, pigment grains slide along microtubules. Microtubules ensure that pigment grains are arranged in parallel columns. In addition, they determine – and are indispensable in – pigment ordering and translocation (Bruno et al. 2008). In xanthophores, microtubules may aid pigment transport towards the cell centre, but are not necessary in the reverse process, i.e. dispersion. Pigment translocation ceases when fish microtubules are disturbed by colchicin, high hydrostatic pressure, high temperature, or vinblastine (Chen & Wang 1993).

Numerous fish species have been shown to contain magnetite ($Fe_3O_4$) particles, which are frequently synthesised throughout the individual’s life span (Kirschvink et al. 1985; Walker et al. 1997; Diebel et al. 2000). So far, no connection between magnetic particles and the nervous system has been found, although the latter is involved in colour reactions and is closely associated with melanophores. The magnetic material present in the fish body occurs in the form of chains of single-domain particles (Hanson & Westerberg 1987; Ogura et al. 1992; Walker et al. 1997). The single-domain magnetite particle chains may be connected by microtubules with ion channel openings; when changing their location in the magnetic field, those microtubules may open or close ion channels in membranes, thus inducing changes in membrane permeability (Kirschvink et al. 2001; Walker et al. 2002). Ion channels are opened by microtubules, which may be pulled by magnetite crystals. The opened ion channels cause changes in potential and permeability of cell membranes. This in turn may affect the transport of melanosomes within the melanophores – they are transported between the cell centre and its periphery (Vancoillie et al. 2000). It is then highly probable

Figure 8. Pigment translocation in melanophores (220 D°) of vendace Coregonus albula (Linnaeus, 1758) embryos in the geomagnetic field (a): analysis of variance (ANOVA) F-test(5, 60) = 1.2970; confidence interval (CI) = 99.96–100.09; variance (p) = 0.27730 and in magnetic fields: 1 mT (b): ANOVA F-test(5, 60) = 7.6882; CI = 90.61–134.77; p = 0.00001, 3 mT (c): ANOVA F-test(5, 60) = 0.96219; CI = 70.33–88.09; p = 0.44821, 5 mT (d): ANOVA F-test(5, 60) = 2.5475; CI = 77.05–108.19; p = 0.03716.

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that microtubule responses in melanophores are involved in magnetic field-effected changes in membrane permeability. If microtubules, sensitive to magnetic field effects, are involved in shifting the pigment particles within the melanophores, then the melanin transport becomes altered and the pigment is concentrated in the melanophore centre. This explains the effect of static magnetic field on the melanin translocation and melanophore responses in whitefish and vendace embryos during early ontogenesis.

The influence of magnetic field on the melanophores of fish is significant, and results can be extrapolated to other, higher organisms and in the future will allow us to widen the knowledge on pigment cell magnetoreception in vertebrates.

References

Alexander G, Sweeting R, McKeown B. 1998. The effect of thyroid hormone and thyroid hormone blocker on visual pigment shifting in juvenile coho salmon (Oncorhynchus kisutch). Aquaculture 168: 157–168. doi:10.1016/S0044-8486(98)00346-9
Bruno L, Echarte MM, Levi V. 2008. Exchange of microtubule molecular motors during melanosome transport in Xenopus laevis melanophores is triggered by collisions with intracellular obstacles. Cell Biochemistry Biophysics 52: 191–201. doi:10.1007/s12013-008-9034-3
Brysiewicz A, Formicki K, Winnicki A. 2007. Effects of magnetic field on pigmentation of embryos and juveniles of pike (Esox lucius L., 1758). XII European congress of ichthyology, ECIXII, 9–13 Sep 2007, Cavtat, Croatia: Book of abstracts. 64 pp.
Burton D. 2002. The physiology of flatfish chromatophores. Microscopy Research and Technique 58: 481–487. doi:10.1002/(ISSN)1097-0029

Figure 9. Melanophores (indicated by arrows) on the head of vendace Coregonus albula (Linnaeus, 1758) embryos (220 D°) in magnetic field (3 mT): (a) acclimation (geomagnetic field), (b) 1 minute, (c) 3 minutes, (d) 5 minutes, (e) 30 minutes and (f) 60 minutes in magnetic field.
Wannitikul P, Winnicki A, Formicki K. 1993. Effect of constant magnetic field on fish melanophores in vivo and in vitro. In: Blank M, editor. Electricity and Magnetism in Biology and Medicine. San Francisco: San Francisco Press. pp. 849–850.

Wiltschko R, Wiltschko W. 2005. Magnetic orientation and magnetoreception in birds and other animals. Journal of Comparative Physiology A 191: 675–693. doi:10.1007/s00359-005-0627-7

Winnicki A, Formicki K. 1993. Activation and motility of spermatozoa of vendace (*Coregonus albula* L.). Acta Ichthyologica Et Piscatoria 23: 147–152. doi:10.3750/AIP

Winnicki A, Korzelecka-Orkisz A, Sobociński A, Tanski A, Formicki K. 2004. Effects of the magnetic field on different forms of embryonic locomotor activity of Northern pike, *Esox lucius* L. Acta Ichthyologica Et Piscatoria 34: 193–203. doi:10.3750/AIP

Zagal’Skaya EO, Gnyubkin VP, Maksimovich AA. 2005. Morphological characteristics of the retinomotor response in salmon trout (*Oncorhyncus masou*) fry in a magnetic field and red light. Neuroscience and Behavioral Physiology 35: 903–907. doi:10.1007/s11055-005-0143-9