DIRECTIONAL RESPONSE OF THE ATLANTIC SALMON (*SALMO SALAR* L.) FRY TO A MAGNETIC FIELD

Adam Tański[1], Małgorzata Bonisławska[2], Agata Korzelecka-Orkisz[1], Joanna Szulc[1], Krzysztof Formicki[1]

[1] Department of Hydrobiology Ichthyology , Biotechnology of Reproduction, West Pomeranian University of Technology in Szczecin, 71-550 Szczecin, Poland
[2] Department of Aquatic Sozology, West Pomeranian University of Technology in Szczecin, 71-550 Szczecin, Poland

Abstract

The directional response of Atlantic salmon (*Salmo salar* L.) fry to a magnetic field was studied. In an experimental unit, larvae were able to choose their direction of movement and swim to chambers with a generated magnetic field (0.2 mT or 1.0 mT) or with only geomagnetic field. There was no directional response of larvae to the magnetic field of lower intensity (0.2 mT). The higher intensity magnetic field, at 1.0 mT, had a significantly greater number of larval responses. The results show that directional response of the fish to the magnetic field starts at early stages in ontogenesis.

Keywords

Fish fry, magnetic field, orientation, salmon, *Salmo salar*

INTRODUCTION

The phenomenon of orientation of living organisms in a given space has received attention over many years. For a long time, however, it was not associated with an effect of the Earth's magnetic field.

In the last few decades many advanced studies have been conducted on insects, shellfish, fish and birds in attempts to explain the ability of animals to undertake regular seasonal journeys by detection of the geomagnetic field (Keeton 1971; Gould 1980; Quinn and Brannon 1982; Lohmann et al. 1995; Yano et al. 1996). Animals have adapted significantly to the permanently present geomagnetic field, which has been a constant element in the environment during the process of evolution. Migration of animals, including fish, which are easily capable of route-finding, has received intensive study. The orientation and navigation abilities of animals are believed to be based on a variety of senses that detect various components of the habitat, e.g. presence of smell, water currents, stars or, as recently emphasized, geomagnetic field (Groot 1965; Wiltschko and Wiltschko 1972; Quinn 1980; Quinn et al. 1981; Zoger et al. 1981; Quinn and Brannon 1982; Quinn and Groot 1983).

Both natural and artifical magnetic fields not only affect the sense of orientation of the young and mature fish during their migration but also significantly affect the development of gametes and the early stages of ontogenesis.

In the case of fish eggs, a decrease in egg shell resistance to external factors was observed after application of an increased magnetic field (Formicki 1986). Other studies on fish eggs showed that an increased magnetic field can slow down absorption of water during the process of hydration (Winnicki et al. 1992). Studies on two species of fish, Danube salmon (*Hucho hucho* L.) and Atlantic salmon (*Salmo salar* L.), showed that a static magnetic field increased the duration of sperm viability and motility, thus increasing the chance of successful fertilization (Formicki et al. 1990, 1991; Formicki and Winnicki 1993). Embryos of Atlantic salmon, brown trout (*Salmo trutta* L.), northern pike (*Esox lucius* L.), rainbow trout (*Oncnrhynchus mykiss* Walb.) or rudd (*Scardinius erythrophthalmus* L.), incubated in an artificial magnetic field in a fixed position from the fertilization stage to the blastopore closure stage showed orientation significantly different from the random orientation in the control. Their head-tail axes tended to orientate in the geographical north-south direction (Formicki et al. 1997; Formicki and Tański 2000).

Brown trout fry, placed in an experimental unit that allowed changes in direction of movement in reaction to stimuli, were found to respond to a magnetic field. Fish mostly entered chambers exposed to a weak, static generated magnetic field (Formicki et al. 2002, 2003, 2004 a, b). Fish caught by trapping in a natural body of water also responded to the magnetic field. They mostly entered traps that had a magnetic field generated at their entrances (Formicki et al. 2001, 2002, 2004b). Similar reactions were observed during studies on two species of fish from the Adriatic Sea, European seabass (*Dicentrarchus labrax* L.) and gilt-head (sea) bream (*Sparus aurata*) (Tański et al. 2011).

A static magnetic field also caused physiological changes in the exposed fish. These were acceleration of heart rate in older embryos and larvae and acceleration of the motility of the pectoral fins in hatched larvae (Winnicki and Formicki 1990; Winnicki et al. 1994).

The aim of the present research was to study the behaviour of Atlantic salmon larvae in an experimental unit in which they were given the opportunity to choose their direction of movement in response to a gradient in a generated magnetic field.

MATERIALS AND METHODS

The experiments were carried out in March 2008 in the laboratory of the Division of Fish Anatomy and Embryology, Agricultural University of Szczecin. The material for study included developing eggs obtained from the spawn of mature adults of Atlantic salmon caught in the River Rega in Trzebiatów (Northern-west of Poland, 54°3′26″N 15°16′43″E). The spawn was incubated in classical California appliances in the hatchery of the Polish Angling Association in Goleniów with a permanent water supply derived from a natural reservoir, the River Wiśniówka. The larvae were reared through the early life stages in nurseries. At the stage of resorption of 2/3 of the yolk sac, the fish were transported in isothermal containers, with aeration, to the laboratory, where they were placed in 450-liter water tanks with closed circuit water circulation, aeration and external biological filtration (Fluval filters). The tanks were equipped with an additional cooling system for maintaining a stable and optimal temperature for salmon development, close to 8^{o} C. The experiment began 2 days after acclimation.

A specially constructed experimental unit in the shape of a square, with sides measuring 100 cm in length and 10 cm in high, with a circular arena at the centre, was used for studying the behaviour of larvae in response to a static magnetic field (Fig. 1).

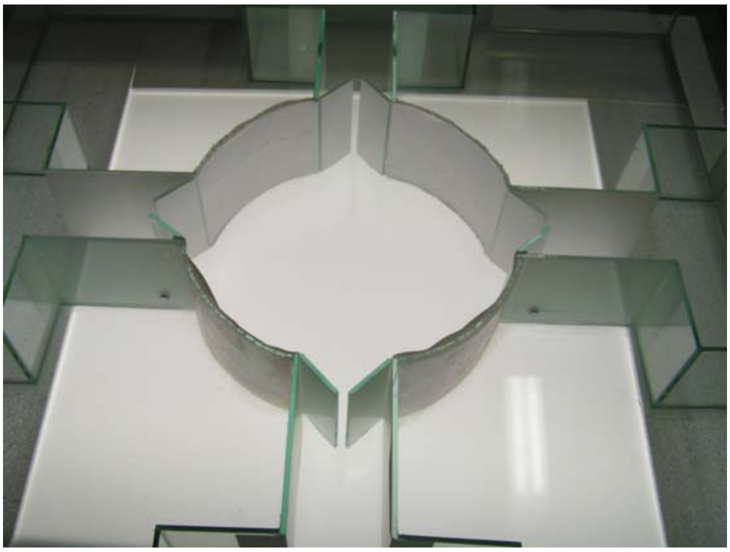

Fig. 1. An experimental unit for studying orientation of salmon larvae

The 40-cm-diameter arena was attached to four passages, 15 cm wide. To prevent reversal of larval movement, gaps of only 1.5 cm wide were made in the walls of the arena where it connected with the passages. The unit was built of glass covered with non-transparent foil. During experiments, a constant temperature of 8°C was maintained by the exchange of water. Water was supplied from tanks used for the cultivation of salmon. The whole unit was covered with opaque black foil to eliminate any possible effect of other physical stimuli (e.g. light). The bottom of the unit was lit by homogeneous light at low intensity and without shadows. A magnetic field of 0.2 mT (treatment I) or 1.0 mT (treatment II) at the area of the gaps was generated by four permanent magnets. Two of them were placed at each of two opposite sides of the arena, at both sides of each passage, near the gaps and facing in an east-west direction (Fig. 2). Such positioning of the magnets generated a magnetic field in parallel to the geomagnetic field. Dummy rubber magnets were placed at each of the two other, opposite, sides of the arena to act as a control. Magnetic field intensity was measured with a hallotron gaussmeter HTM-12m (Institute of Telecommunications and Acoustics, Wrocław University of Technology, Poland).

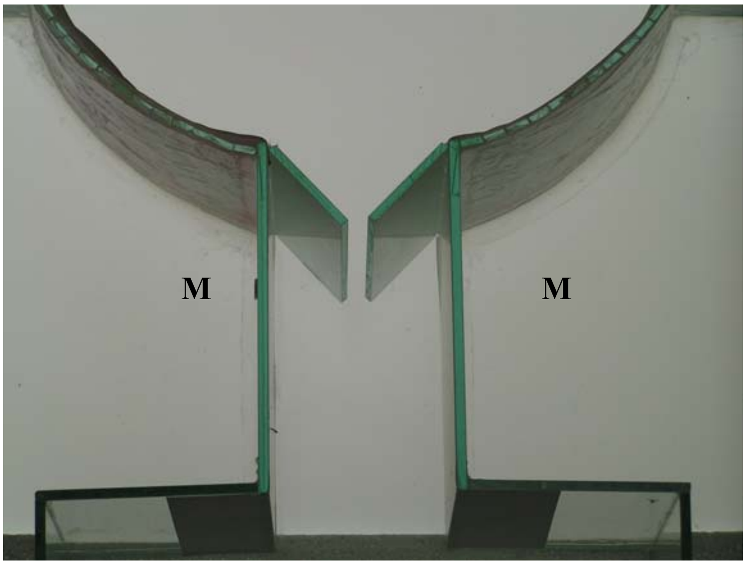

Fig. 2. Location of magnets (M) at both sides of the passage, near the gaps in the arena

Five salmon larvae were transferred from the tank to a bottomless cylinder placed in the arena of the experimental unit and allowed to acclimate for 15 min. The experiment was then started by lifting the cylinder to liberate the fish. The larvae entering the treatment or control passages or staying in the arena were counted after 30 min. There were 20 replicates of each treatment. One hundred larvae were observed in each treatment. Larvae from each replicate were transferred to a separate tank to avoid their repeated participation in the experiment. At the end of the experiment the fish were transferred to natural conditions. The behaviour of the fry was observed continuously and recorded using an imaging system (CCD Sony) mounted 2 m from the unit and connected to a monitor and computer. Recorded images were used for further detailed analyses.

The results obtained were analysed statistically by Pearson chi-square test for qualitative variables and observed and expected frequencies, using Statistica PL v. 9.0 software.

RESULTS

Thirty two larvae (= 32%) moved to the passage exposed to the lower intensity magnetic field (0.2 mT, treatment I). Fifty seven larvae (= 57%) moved to the passage exposed to five times greater magnetic field intensity (1.0 mT, treatment II).

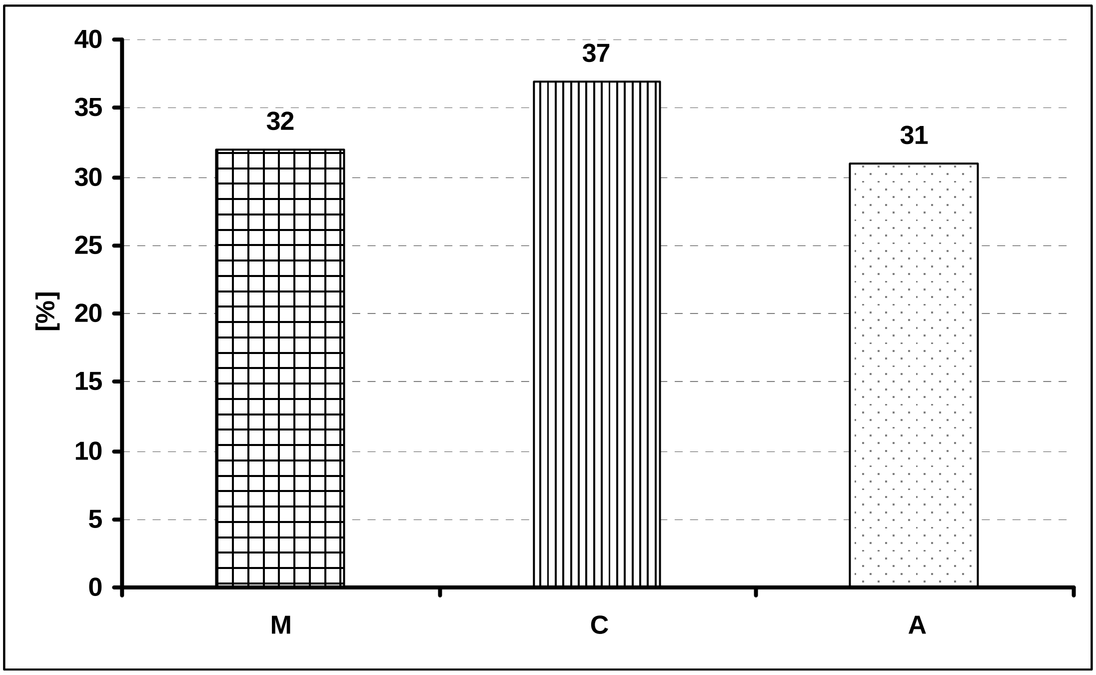

Fig. 3. Orientation of Atlantic salmon larvae in response to a generated magnetic field. M – in magnetic field with intensity of 0.2 mT, C – in control, in geomagnetic field only, A – in arena located at the centre of the experimental unit. Chi-square test = 0.6208479, df = 2, P = 0.733136

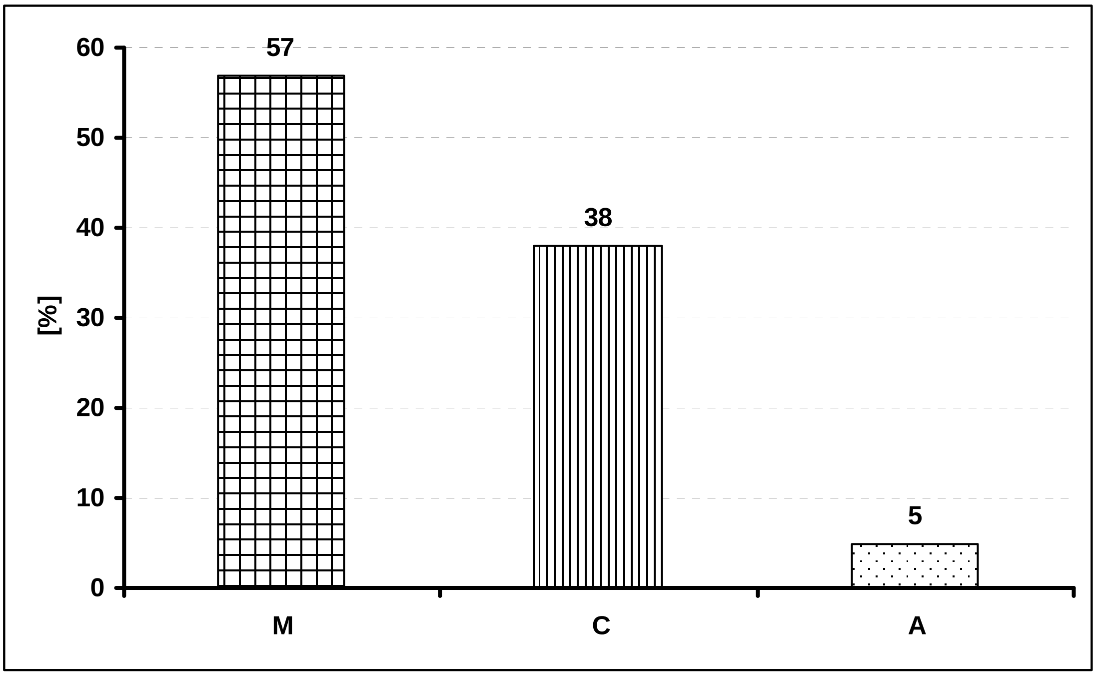

Fig. 4. Orientation of Atlantic salmon larvae in response to a generated magnetic field. M – in magnetic field with intensity of 1.0 mT, C – in control, in geomagnetic field only, A – in arena located at the centre of the experimental unit. Chi-square test = 41.52492, df = 2, P<0.001

Thirty seven (37%) and thirty eight (38%) larvae moved to the control passage in treatments I and II, respectively. Thirty one (31%) and five (5%) larvae stayed in the arena in treatments I and II, respectively (Figs. 3, 4). The differences in numbers of larvae that moved to the treatment passage (exposed to the generated magnetic field) and to the control passage (exposed to geomagnetic field only) or stayed in the arena were statistically significant only for treatment II, in which the higher magnetic field intensity (1.0 mT) was applied.

DISCUSSION

The results show that a magnetic field with intensity of 1.0 mT generated at the entrance to passages in the experimental unit created a directorial response in Atlantic salmon fry towards the magnetic field. The application of a lower intensity magnetic field (0.2 mT), however, did not affect the orientation of the fry, since similar numbers of larvae entered passages exposed to the generated magnetic field and to the geomagnetic field. The number of larvae staying in the arena at the centre of experimental unit was also similar.

The behaviour of young fish and mature adults from the family Salmonidae, i.e. sockeye salmon (*Oncorchynchus nerka*), chum salmon (*Oncorchynchus keta*), Atlantic salmon (*salar*) and rainbow trout (*Oncorhynchus mykiss*), in geomagnetic and generated magnetic fields were observed by Chew and Brown (1989). They concluded that these species of fish can also respond to a magnetic field and utilize it for navigation and orientation in space.

Results of advanced studies in the 1980s and 1990s showed that some migratory fish species contain particles of compounds with magnetic properties. They have been detected in the head of yellowfin tuna (*Thunnus albacares* Bonn.) (Walker et al. 1982), in the bodies of chinook salmon (*Oncorhynchus tschawytscha* (Walb.)) and chum salmon (*O. keta* (Walb.)) (Kirschvink et al. 1985; Ogura et al. 1992), in the skull of European eel (*Anguilla anguilla* L.) (Hanson et al. 1984), and in the lateral line of Atlantic salmon (Potter and Moore 1991). These compounds, particularly magnetite (a natural magnet) may contribute to the orientation of fish in space. Experiments of Potter and Moore (1991) confirm this hypothesis. So far, the response of salmon fry to a magnetic field can not be associated with the presence of magnetite because it is still not known when its synthesis starts, whether at embryonic and larval development or at later stages in ontogenesis. Since the fish did not respond to the lower intensity of the generated magnetic field (0.2 mT), and moved in equal numbers to the exposed and non-exposed passages or stayed in the centre of the unit, the directional response seems to be determined by the intensity of the magnetic field. It is probable that exposure of larvae to even greater intensity of magnetic field would further increase the effect.

According to Cleary (1993), effects of magnetic fields on biological systems occur in specific 'windows' of field strength. The 'windowed' nature of these effects implies that even when there is no effect at some field values there may be effects at other, lower or higher values. Although Cleary (1993) applies 'the window effect' to explain effects in electromagnetic fields it seems that it can also be applied in explanation of effects in a magnetic field. Increasing intensity of the generated magnetic field seemed to affect the orientation of salmon fry.

New techniques applied in biological studies serve to broaden our understanding of magnetoception. Magnetic stimuli seem to be recognized by the nervous system, the structure of which is rather complex (Walker et al. 1997; Lohmann and Johansen 2000). Moreover, it seems that magnetic stimuli may affect the directional response of animals by induction of certain chemical changes in biological molecules in their bodies. These changes may be induced by magnetic fields with intensity equal to the intensity of the geomagnetic field (Johnsen and Lohmann 2005).

It seems that changing the magnetic field gradient can induce certain reactions in animals and these may be followed by directional responses similar to those observed in fish caught in natural bodies of water using fish traps equipped with magnets (Formicki et al. 2004 b). The action of the magnetic field causes anxiety in the fish, curiosity and a 'searching response', which seems to make them determined to swim in the direction of the cage in the trap.

Similar reactions were observed in sea trout (*Salmo trutta m. trutta*) (Formicki et al. 2004a) and in adults of belica (*Leucaspius delineatus* (Heckel, 1843) (Formicki et al. 2003), when they were kept in special experimental units which offered them the choice of direction of movement.

It seems that the magnetic field at intensity of 1.0 mT, generated in the experimental unit at the passage entrance, caused a similar reaction of ‘curiosity’ and this was followed by entry into the passage. Lower intensity of the generated magnetic field (0.2 mT) did not cause such response.

The newest theory to explain the mechanism of response to magnetic fields concerns the existence of mechanical connections between crystals in the cell and ion channels in the cell membrane. The positioning of both helps in recognizing the direction and intensity of the magnetic field (Walker et al. 1982, 1997; Diebel et al. 2000, Formicki 2008). The magnetic active components in the cell seem to be able to open or close the ion channels in the cell membrane and thus transfer the signal, which results from changes in the position of these active components in response to the magnetic field (Walker et al. 2002).

The results reported here will be used as a basis for further studies in the natural habitat. They will contribute to application of static magnetic fields of low intensity in practical fishing and to hydro-technical enterprises aimed at facilitating the migration of fish.

References

1. Chew G. L., Brown G. E. 1989. Orientation of rainbow trout (*Salmo gairdneri*) in normal and null magnetic field. Can. J. Zool., 67: 641 – 643.

2. Cleary S.F., 1993: A review of in vitro studies: low-frequency electromagnetic fields. Am. Ind. Hyg. Assoc. J., 54: 178–185.

3. Diebel C. E., Proksch R., Green C. R., Neilson P., Walker M. M. 2000. Magnetite defines a magnetoreceptor. Nature., 406, 299–302.

4. Formcki K., Winnicki A. 1993. Wpływ stałego pola magnetycznego na ruchliwość plemników i zapłodnienie u ryb. In. VII Sympozium Nauk Radiowych. Komunikaty. Politechnika Gdańska str: 201 - 204.

5. Formcki K., Winnicki A., Sobociński A. 1990. Motility of spermatozoa of danube salmon (Hucho hucho L.), expose to magnetic field prior to activation. Pol. Arch. Hydrobiol. , 37, 3: 439-447.

6. Formcki K., Winnicki A., Sobociński A., Mongiało Z. 1991. Effects of fertilizing sea trout (*Salmo salar* L.) eggs spermatozoa exposedto magnetic field. Acta Ichth. Piscat., 21, 1: 99-104.

7. Formicki K, Sadowski M, Tański A, Korzelecka-Okisz A, Winnicki A., 2004b, Behaviour of trout (*Salmo trutta* L.) larvae and fry in a constant magnetic field. Journal of Applied Ichthyology. Berlin, 20: 290-294.

8. Formicki K, Tański A, Sadowski M, Winnicki A., 2004a, Effects of magnetic field on fyke net performance. Journal of Applied Ichthyology. Berlin, 20: 402–406 .

9. Formicki K. 1986.The effect magnetic field on resistance of eggs membran es In same salmonid Fish Pol. Arch.Hydrobiol., 33, 1: 105 -114.

10. Formicki K., 2008. Chapter 14: Magnetoreception. In: Fish Larval Physiology [R.N. Finn,. B.G. Kapoor (eds.)], Science Publisher, USA: 461–491. ISBN: 978 – 1-57808-388-6.

11. Formicki K., M. Bonisławska, M. Jasiński, 1997: Spatial orientation of trout (*Salmo trutta* L.) and rainbow trout (*Oncnrhynchus mykiss* Walb.) embryos in natural and artificial magnetic fields. Acta Ichth. Piscat., 27, 2, 29–40.

12. Formicki K., Tański A., 2000: Wpływ pola magnetycznego na ułożenie osi symetrii rozwijających się zarodków troci (*Salmo trutta* L.) i pstrąga tęczowego (*Oncorhynchus mykiss* Walb.) Krajowe Sympozjum Telekomunikacji – KTS 2000 w Bydgoszczy, PAN, ATR Bydgoszcz, I T. Politechnika Wrocławska, Prace D, str. 328–334

13. Formicki K., Tański A., Sadowski M., Winnicki A., 2002: Wpływ pola magnetycznego na preferencje kierunkowe larw i narybku ryb.

14. Formicki K., Tański A., Sobociński A., Winnicki A., 2001: A directional response of fish to changes in magnetic field in natural environment. The 10th European Congress of Ichthyology – ECI X Prague, September 3–7, 2001 "In the heart of Europe!", 119.

15. Gould J.L., 1980: The case for magnetic sensitivity in birds and bees (such as it is). Amer. Sci., 68: 256–267.

16. Grot, C., 1965, On the orientation of young sockeye salmon (Oncorhynchus nerka) during their seaward migration out of lakes. Behav. Suppl. 14, 1–198.

17. Hanson M., Karlsson L., Westerberg H., 1984, Magnetic material in European eel (*Anguilla anguilla* L.). Comp. Biochem. Physiol., 77 A, 2: 221–224.

18. JohnsenS., Lohmann K. J., The physics and neurobiology of magnetoreception. Neuroscience. Vol. 6. 706-7012.

19. Keeton W.T., 1971: Effects of magnets on pigeons homing. Proc. Nat. Acad. Sci., 68: 102–106.

20. Kirschvink J.L., Walker M.M., Chang S.-B., Dizon A.E.,. Peterson K.A, 1985: Chains of single domain magnetite particles in chinook salmon, Oncorhynchus tshawytscha. J. comp. Physiol., 157: 375–381.

21. Lohman K.J., Johansen S., 2000: The neurobiology of magnetoreception in vertebrate animals. Trends Neurosci., 23: 153–159.

22. Lohmann K.J., N.D. Pentcheff, G.A. Nevitt, G.D. Stetten, R.K. Zimmer-Faust, H.E. Jarrard, L.C. Boles., 1995: Magnetic orientation of spiny lobsters in the ocean: Experiments with undersea coil systems. J. Exp. Biol., 198: 2041–2048

23. Ogura M., M. Kato, N. Arai, T. Sasada, Y. Sasaki, 1992: Magnetic particles in chum salmon (*Oncorhynchus keta*): Extraction and transmission electron microscopy. Can. J. Zool. Review., 70, 5: 874–877

24. Potter T., Moore A., 1991: Salmon migration mystery: Scientists magnetic navigation theory. Fishing News, 4030: 3.

25. Quinn T.P., 1980: Evidence of celestial and magnetic compass orientation in lake migrating sockeye salmon fry. J. Comp. Physiol., 137A: 243–248.

26. Quinn T.P., Brannon E.L., 1982: The use of celestial and magnetic cues by orienting sockeye salmon smolts. J. Comp. Physiol., 147: 547–552.

27. Quinn T.P., Groot C., 1983: Orientation of chum salmon (*Oncorhynchus keta*) after internal and external magnetic field alteration. Can. J. Fish. Aquat. Sci., 40: 1598–1606.

28. Quinn T.P., Merrik R.T., Brannon E.L., 1981: Magnetic field detection in sockeye salmon. J. exp. Zool., 217: 137-142.

29. Tański A., Korzelecka-Orkisz A., Grubišić L., Tičina V., Szulc J., Formicki K., 2011: Directional responses of sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) fry under static magnetic field. Electronic Journal of Polish Agricultural University. EJPAU Vol. 14 (4) #8.

30. Walker M.M., A.E. Dizon, J.L. Kirschvink., 1982: Geomagnetic field detection by yellowfin tuna. Ocean, 8: 755–758.

31. Walker M.M., Diebel C.E., Haugh C.V., Pankhurst P.M., Montgomery J.C., Green C.R., 1997: Structure and function of the vertebrate magnetic sense. Nature, 390: 371–376.

32. Walker, M. M., Dennis, T. E., and Kirschvink, J. L. (2002). The magnetic sense and its use in long!distance navigation by animals. Curr. Opin. Neurobiol. 12, 735–744.

33. Wiltschko W., Wiltschko R., 1972: Magnetic compass of European robins. Science, 176: 62–64.

34. Winnicki A., Formcki K., Sobociński A. 1992. Water uptake by trout (*Salmo salar* L.) eggs exposed aferactivation to magnetic field. Acta Ichth. Piscat. 22, 2: 155-161.

35. Winnicki A., Formicki K., Korzelecka A., Sobociński A., 1994: Cardiac responses of pike (*Esox lucius* L.) embryos and larvae to constant magnetic field. Arch. Ryb. Pol., 1: 87–93.

36. Winnicki A., Formicki K.,1990: Effect of constant magnetic field on myocardium activity in larvae of trout (*Salmo trutta* L.). Bull. Pol. Acad. Sci. Ser. Biol. , 38 (1-12); 57–60.

37. Yano A., M. Ogura, A. Sato, Y. Sakaki, M. Ban, K. Nagasawa, 1996: Development of ultrasonic telemetry technique for investigating the magnetic sense of salmonids. Fisheries Science, 62 (5): 698–704.

38. Zoger J., Dunn J.R., Fuller M., 1981: Magnetic material in the head of the common Pacific dolphin. Science, N.Y., 213: 892–894.

Рецензент проф. Юзвяк З.