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Reactions of fry of Siberian sturgeon (*Acipenser baeri* Brandt, 1869) to magnetic field

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ABSTRACT

The objective of the study was to trace directional reactions of the fry of Siberian sturgeon (*Acipenser baeri* Brandt, 1869) to magnetic field of 0.2 and 0.9 mT superimposed on geomagnetic field according to the geomagnetic force lines. In the experimental setup the fish could enter chambers oriented to the N, S, E and W. At the entrance to the chambers the value of magnetic field was increased or only geomagnetic field was active (control sample). The fish reactions were recorded with CCD cameras and analysed. The water temperature in the experimental setup was 17.0 ± 0.2 °C, pH 7.4 ± 0.2, and oxygen content 8.2 ± 0.3 mg/dm^3. The whole setup was isolated from any external stimuli that could affect the fish behaviour. A total of 400 individuals were subject to two series of experiments. A significant majority ($p < 0.05$) entered the chambers of the experimental setup where the value of the generated magnetic field was higher than the natural background, indicating a directional reaction of the Siberian sturgeon to magnetic field. No difference was observed in the fish reactions to magnetic field of 0.2 mT and 0.9 mT.

Keywords: *Siberian sturgeon*, magnetic field, magnetic orientation, fish reactions.

INTRODUCTION

In recent years, numerous studies have focused on the sensitivity to and perception of magnetic stimuli in various systematic groups. Among others, influence on fungi, plants, insects, crustaceans, fishes, or birds, and on their ability to return to definite places using magnetic field during their migrations (Bochert and Zettler, 2004; Wiltschko and Wiltschko, 2005; Lohmann et al., 2007; Formicki, 2008; Fey et al., 2019; Vasilyeva et al., 2021; Rutkowska-Narożniak and Pajor, 2022).

Magnetic field affects both behaviour of adults and directional reactions of fish embryos and larvae. Incubation of embryos of salmon (*Salmo salar* L., 1758), sea trout (*Salmo trutta* m. *trutta* L., 1758) and of fishes regarded as non-migrating, such as pike (*Esox lucius* L., 1758) or rudd (*Scardinius erythrophthalmus* L., 1758), in unchanged position from fertilisation till the closing of blastopore has shown that the symmetry axes of the embryos are usually oriented in the north-south plane (N–S) (Formicki, et al., 1997; Tański, et al., 2005). The effect of generated magnetic field has also been found to cause physiological changes in the fish. In the case of embryos and larvae of pike and sea trout the static magnetic field causes acceleration of heartbeat and movements of pectoral fins (Formicki 2008; Formicki et al., 2019).

Sea trout larvae and adult sun bittern (*Leucaspius delineatus* Heckel, 1843) in an experimental setup with free choice of swimming direction show directional reactions to changes in magnetic field. They most often enter the chambers with weak, static, generated magnetic field (Formicki et al., 2004b). A similar reaction is displayed by fishes (mainly cyprinids) trapped in a lake with fyke nets. More fish are caught in nets with magnetic field of higher values at the entrance than in those of geomagnetic field only (Formicki et al., 2004a).

Observations on directional reactions of juvenile chum salmon (*Oncorhynchus keta* Walbaum, 1792) from the Conuma river have shown that individuals placed in special containers move in accordance with their natural migration route. Darkening of the containers causes no change of direction, but placing magnetic plates near the fish head disturbs the natural directional reaction (Quinn and Groot, 1983). Experiments of Yano et al. (1996) on adult chum salmon from the Kuril Islands show that the navigation in that species depends on many factors. Attaching magnetic plates with changed poles and five times exceeding geomagnetic field values around the head does not disturb the migration route in the northern Pacific. Probably inducing magnetic field around the whole body, not only around the head, would affect the migration route. Experiments with sockeye salmon (*Oncorhynchus nerka* Walbaum, 1792) also confirm their ability of orientation in magnetic field. Their smolts placed in round containers in geomagnetic field show orientation in accordance with the migration direction in the wild (Quinn and Brannon, 1982).

According to Chew and Brown (1989) rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792), placed in a zero magnetic field in water current, shows no directional preferences. The individuals irrespective of age, placed in geomagnetic field, orient themselves mainly to north-west (NE).

A wide spectrum of research on "magnetic migration" of juvenile forms and adult individuals of salmonids, ie. Pacific salmon, pink and sockeye salmon, and Chinook salmon, in the natural environment, was conducted by Putman et al., 2013; Putman et al., 2014a; Putman et al., 2014b; Putman et al., 2018.

Studies on homing in European eel (*Anguilia anguilla* L., 1758) show that the direction of swimming of "silver" eel toward the open sea and "yellow" eel toward freshwaters is affected not only by geomagnetic field but also by other factors, such as changes in salinity, movements of water layers as well as the season of the year (Tesch et al., 1992). Eel caught in the North Sea, but still not migrating to the spawning grounds, are able to return to the place from which they were removed from a distance of a few hundred kilometres (Deelder and Tesch, 1970).

Later it was found that a magnetic map leads juvenile European eels to the Gulf Stream (Naisbett-Jones et al., 2017).

Also Siberian sturgeon (*Acipenser baeri* Brandt, 1869) belongs to the group of long distance migrants; it is a potamomorphic species inhabiting both middle and upper sections of the catchment areas of the rivers Ob, Yenisei, Lena, Yana, Indygirka and Kolyma (forming freshwater populations), and estuary parts of marine waters (Kirschbaum, 2010). Males become mature at the age of 13–14 years, females at 17–18 years. There is a variety of factors inducing sturgeon migrations and affecting their direction. The sturgeon spawns at temperatures not below 8–9 °C, and mass migrations of adult fish to their spawning grounds start at water temperature of 12–14 °C (Sokolov and Malyutin, 1977). Besides the water temperature, other external factors stimulating migrations of adult sturgeon are water level and turbidity. Moreover, the timing of migration is affected by the state and maturity of the gonads (Ryabova et al., 2006), increased activity of neurosecretory and endocrine systems and increased metabolism geomagnetic field plays an important role in governing the fish migration routes (Krylov et al., 2014). The start of sturgeon spawning migration falls on June, and the spawning takes place only next year. The spawning grounds are located ca. 1300 km of the river mouth. They are usually deep places with gravelly bottom. The species is endangered within its natural distribution range and is intensively bred (Rosenthal and Gessner, 1992; Rosenthal et al., 2006).

Research on the impact of magnetic fields on the direction of fish migration is important because in the era of strong anthropogenic pressure and the expansion of transmission networks, the problem of the impact of magnetic fields generated by power cables (SPCs) may significantly affect the functioning and the disruption of fish migration (Krzystolik et al., 2024; Verhelst et al., 2025; Cresci et al., 2023; Cieślewicz et al., 2025).

To our knowledge there were no studies on the directional reactions of juveniles of Siberian sturgeon to magnetic field, either natural or generated. Because of this we decided to check if the fry of Siberian sturgeon, which in the wild migrates toward river estuaries, reacts to generated magnetic fields – a capacity which the sturgeon might use during its migrations.

MATERIAL AND METHODS

The material included fry of Siberian sturgeon: 400 individuals of mean body length 52 ± 1.32mm, purchased in the breeding centre Oleśnica in north-western Poland (N52°59'34'', E16°51'7''). The fish were brought to the laboratory in 60 litre plastic bags containing 1/3 water and 2/3 oxygen. Additionally, the bags were placed horizontally in thermo-isolation containers which ensured constant temperature during transport (17.0 ± 0.2 °C). The fry was transported early in the morning which facilitated maintaining constant temperature during the three-hour journey. Once in the laboratory, the fish were placed in a 600 litre container with specially prepared water (thermal conditions as in the breeding centre – 17.0 ± 0.2°C, well oxygenated water of 8.2 ± 0.6 mg/dm^3, continuous filtration in closed system with FLUVAL 403 filters (Hagen Fluval Aquatic Products, USA) with biological cartridge). The container was additionally lit with day fluorescent lamps LF 36W/54-765 (Philips, Poland), light: dark cycle 12:12 hours. The light intensity measured above the water table in the container was 1024 lux (luxmeter LXP - 2, Meraserw, Poland). The fish were fed granulated feed (*Dana*-ex, *Dana Feed* A/S. Horsens, Denmark) used earlier in the breeding centre in Oleśnica, with doses and frequency as in the breeding cycle (daily dose 3% of stock mass, feeding frequency every 8 hours). The fish were kept in the container in such conditions during 7 days.

Experimental setup

To study the behaviour of sturgeon fry in static magnetic field we used a specially constructed experimental setup in the form of a square, side length 100 cm and wall height 10 cm. A circular arena was placed in the middle of the setup, of 40 cm diameter and with four corridors departing from it, each 12 cm wide and ending with a chamber. Screens at the entrances to the corridors formed 3 cm slits which made it difficult for the fish to back away (Figure 1).

The setup (walls, bottom, screens) was made of glass (Pilkington IGP, Poland), covered with opaque white foil (Fol- Poz, Poland).

During the experiment the whole setup was surrounded with a black, opaque round foil curtain (Fol-Poz, Poland) which hung from the ceiling of the room, in order to eliminate other stimuli (e.g. light) which could affect the fish movements (Figure 2). The curtain had an entrance which could be closed and was used to place the

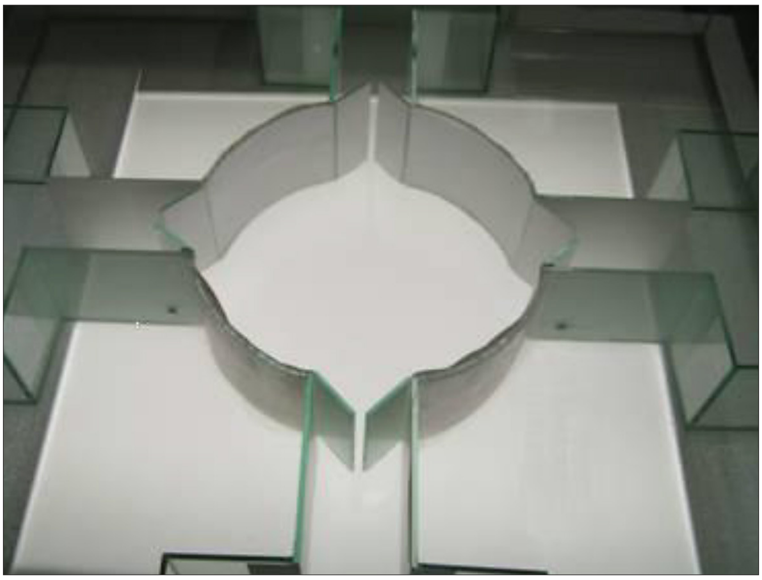


Figure 1. Experimental setup made of glass in the form of 100 x 100 cm square, wall height 10 cm for studying directional reactions of sturgeon: a – arena of 40 cm diameter, b – corridors 12 cm wide, c – chamber, d – screens preventing fish from backing away, e – magnets generating magnetic field on both sides of entrances to corridors

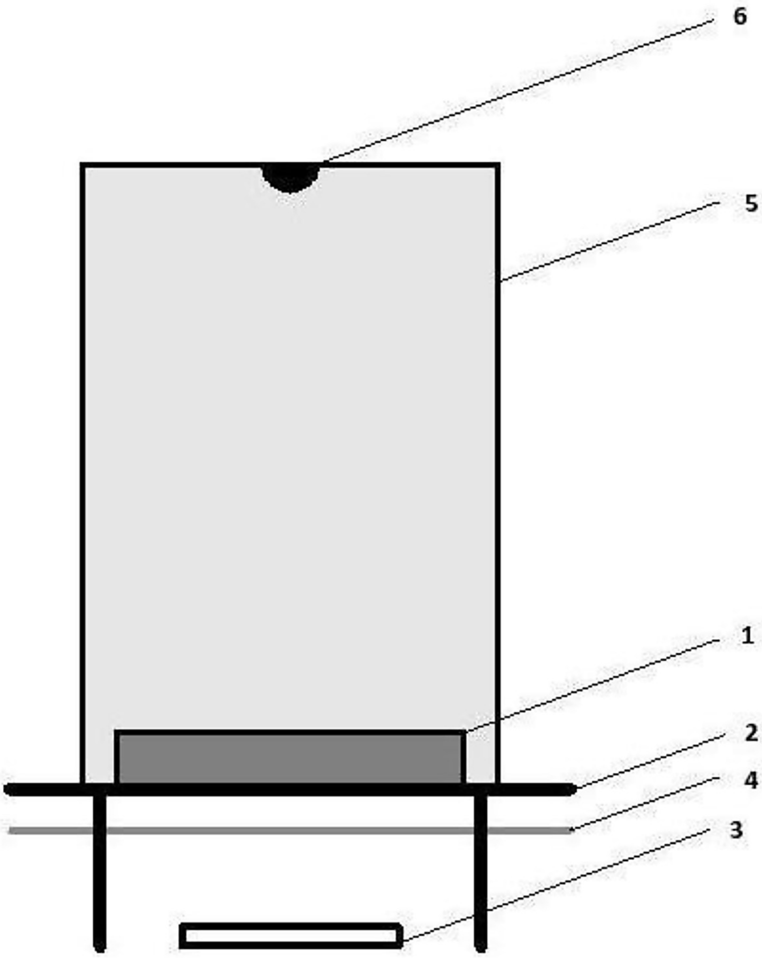


Figure 2. Diagram showing placement of experimental setup: 1 – experimental setup (Figure 1), 2 – white light-diffusing perspex plate, 3 – lighting (4 fluorescent lamps evenly distributed under experimental setup), 4 – additional light-diffusing perspex screen, 5 – external curtain, 6 – computer–coupled camera

fish in the setup. The entrance was always tightly closed during the experiment. The bottom of the setup rested on a white perspex plate (Heko, Polska), which was lit with a uniform, shade-less light (4 day fluorescent lamps LF 36W/54-765 (Philips, Poland) evenly distributed under the whole setup). A white perspex plate (Heko, Poland) was placed above the light source, 60 cm from the setup bottom, to ensure additional even diffusion of light. All the setup was placed on a wooden (no metal elements) glued base. Digital camera CCD (Nikon DS-Ri2, Nikon Imaging, Japan Inc.) synchronised with PC computer was mounted ca. 2.2 m above the setup, to monitor the fish behaviour and save the image on the disc for further analysis.

During the experiment the water temperature in the setup and its surroundings was maintained at a constant level of 17.0 ± 0.2 °C; pH (7.4 ± 0.2) (pH-meter CX401, Elmetron, Poland) and oxygen content (8.2 ± 0.3 mg/dm^3) (oxygen-meter CX401, Elmetron, Poland) were also monitored.

Magnetic field

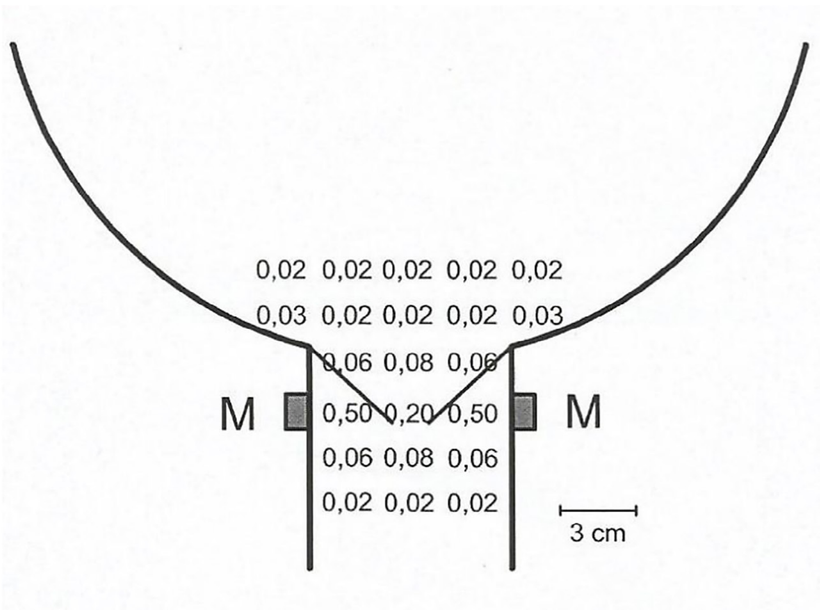
Magnetic field was generated using permanent ferrite magnets MW 5.2 × 3/F30. At the entrance to the corridors, on the opposite sides of the circular arena, magnetic field value was increased through placing two permanent magnets at each so that magnetic field at the entrance used by the fish was 0.2 mT (variant I) and 0.9 mT (variant II) (Figure 3a, b). The remaining two corridors were regarded as control, with rubber imitations of magnets at their entrances.

The experimental setup was within the background geomagnetic field and was positioned in such a way that lines of force of the field generated by the magnets matched the natural geomagnetic lines of force. The intensity of magnetic field was measured with hallotrone tesla-meter HTM-12m (Institute of Telecommunication and Acoustics, Wrocław Technical University); the distribution of values of the field generated in both variants of the experiment is presented in Figure 3.

Course of experiment

Twenty replicates were done for each variant (Series I and II). In each variant 100 individuals were examined. For variants I (0.2 mT) and II (0.9 mT) the experiment was repeated twice (series 1 and 2) with one-month interval (April and May 2015) in identical conditions. On each occasion sturgeon fry (5 individuals) was transferred in glass crystallizer of 600 ml volume from the container to the experimental setup, where they were acclimated to the surroundings in a special, cylindrical vessel without bottom, placed in the centre of the setup arena. After 10 minutes – time of fish acclimation – the cylinder was very carefully lifted to release the fish. The fish behaviour

a)



b)

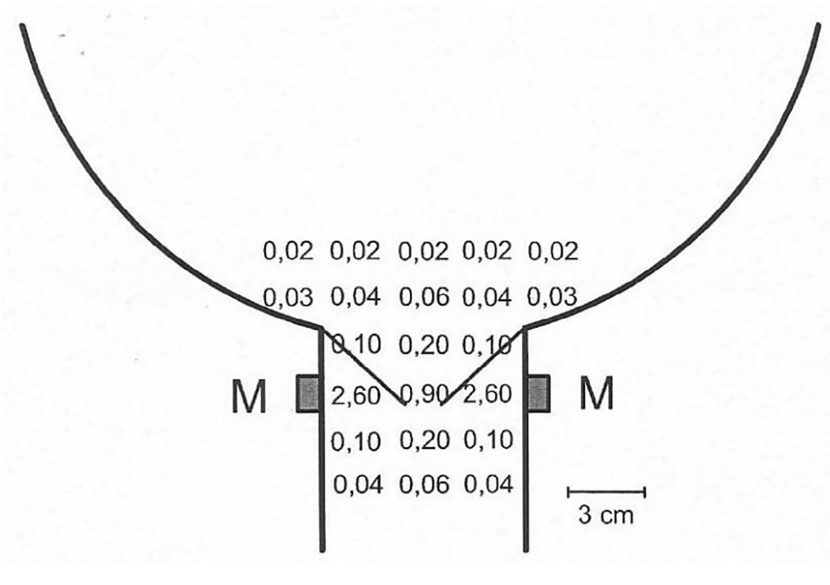


Figure 3. Entrance to corridor in experimental setup with screens (preventing fish from backing away) and distribution of lines of force of magnetic field marked; values in two variants, a) variant I – 0.2 mT, b) variant II – 0.9 mT

was continuously registered on the computer disc and constantly observed on the computer screen.

In each experiment we used different individuals of Siberian sturgeon brought from the breeding centre.

After 30 minutes from the fish release in the centre of the arena in both variants the number of fry was counted:

- In the chambers in which magnetic field was generated at the entrances to the corridors (MF),
- In the chambers in which no magnetic field was generated at the entrance - control (C);
- In the centre of the arena – (A).

After the experiment the fish were placed in a separate container and returned to further breeding.

Statistical analysis

The results were subject to statistical analysis using STATISTICA 12.0 PL (Toolsa OK., USA) with ANOVA, and post hoc Duncan test.

RESULTS

The results of the experiment on juvenile Siberian sturgeon using magnetic field of 0.2 and 0.9 mT indicate distinct directional preferences (Figure 4 a–f).

In variant I, series 1 (experiments conducted in April) the chamber with magnetic field of 0.2 mT generated at the entrance was entered by as many as 68 fish which was 68% of the examined individuals. The control chamber was entered by only 26 fish, i.e. 26% of the examined group (difference statistically significant, ANOVA, p = 0.000151). The remaining 6 fish stayed in the central part of the arena (6%) (Figure 4a). Similar results were obtained for variant I, series 2 (May experiment). The chamber was entered by 80 fry which was 80% of the fish, the control chambers (without magnets) by 17 fish i.e. 17%, while 3 individuals i.e. 3% stayed in the centre of the arena (Figure 4c). Also in this series the number of fish in the chamber with generated magnetic field was statistically significantly higher compared to the control (ANOVA, p = 0.000146) and the arena centre (ANOVA, p = 0.000063).

In variant II, series 1 and 2, more numerous fish entered the chambers with magnetic field of 0.9 mT, than the control chambers or the arena centre (Figure 4 b, d). In series 1 the number of fish in the chamber with generated magnetic field was statistically significantly greater compared to the control (ANOVA, p = 0.000149) and to the arena centre (ANOVA, p = 0.000056) (Figure 4b). Likewise, in series 2 the chambers with generated magnetic field attracted a statistically significantly greater number of fish (71 individuals i.e. 71%) than the chambers with no magnetic field - control (24 individuals) (ANOVA, p = 0.000147) or the arena centre (5 individuals; ANOVA p = 0.000051) (Figure 4d).

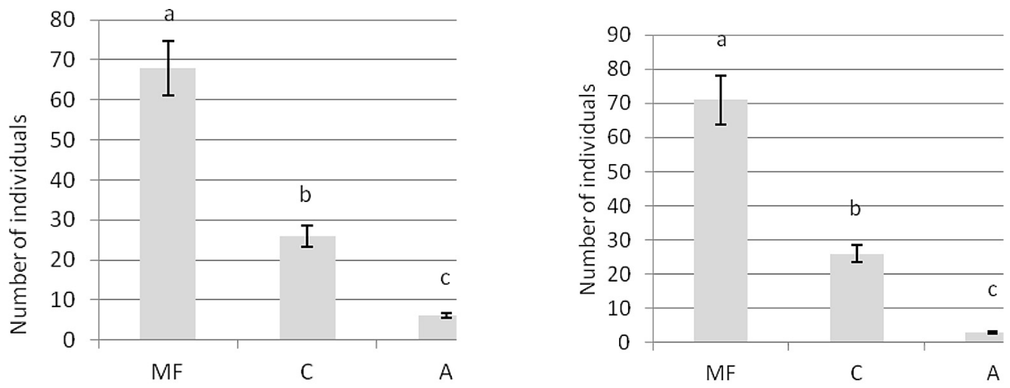
Overall, in variant I with magnetic field of 0.2 mT, in both series 1 and 2, the chambers under the effect of magnetic field were entered by 148 fish i.e. 74% of the examined individuals, the control chamber by 43 fish i.e. 21.5% of the examined fish; 9 individuals (4.5%) stayed in the arena centre (Figure 4e).

In variant (0.9 mT), similarly, the total number of fish which entered the chambers with generated magnetic field (MF) was 142 i.e. 71%, whereas the control chambers were entered by 50 fish (25%), and 8 remained in the arena centre (4%) (Figure 4f).

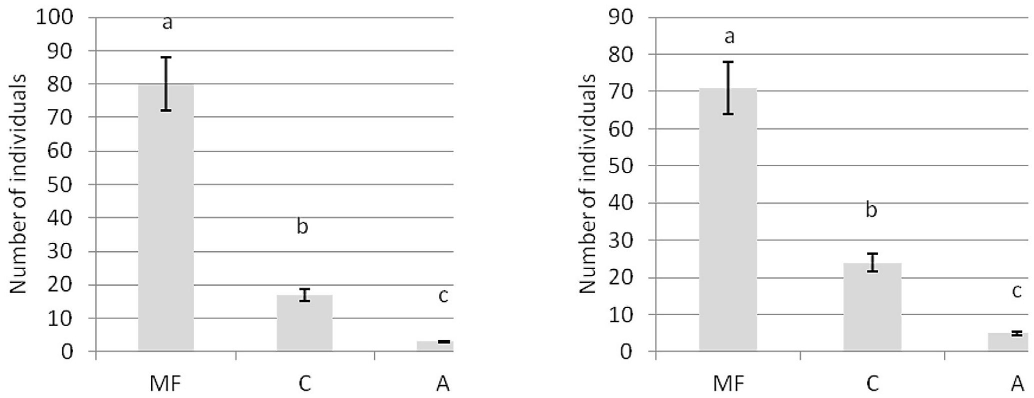
The statistical analysis of the numbers of fish in the two variants showed that magnetic field of both 0.2 mT and 0.9 mT affected the directional reaction of the juvenile Siberian sturgeon, and the results were statistically significant (ANOVA, $p < 0.001$). Considering the two variants together it was noted that the number of fish in the chamber with magnetic field of 0.9 mT was slightly higher than in the variant with 0.2 mT (ANOVA, p = 0.03496).

DISCUSSION

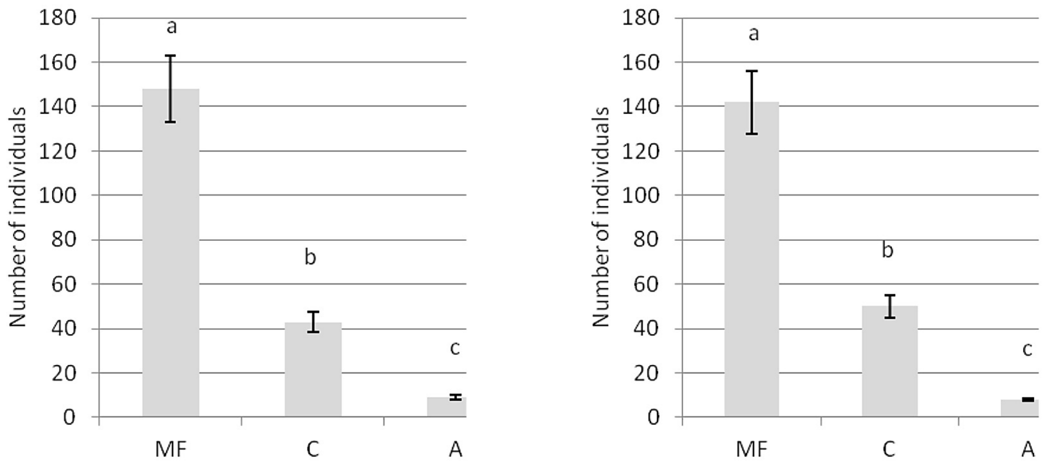
The results show that static magnetic field generated at the entrance to the corridors (chambers) causes a directional reaction in the examined fish. It is noteworthy that a similar number of fish entered the chambers with weaker magnetic field at the entrance (variant I – field value 0.2 mT) and those with stronger field (variant II – field value 0.9 mT). In both variants the analysis showed statistically significant differences in the number of fish entering the chambers with generated magnetic field and those choosing the chambers without generated magnetic field or remaining in the arena. Magnetic field generated at the entrance to the chambers in each variant caused a reaction (”interest”) of the fry which were within the range of the generated field, resulting in the fish entering



Series 1



Series 2



Overall results for series 1 and 2

Figure 4. Directional reactions – selection of direction of movement by fry of Siberian sturgeon in the experimental setup with generated magnetic field of 0.2 mT (variant I) and 0.9 mT (variant II) (MF – magnetic field, C - control, A - arena); Values marked with different letters are statistically significantly different at $p < 0.05$ (Duncan test). a – Series 1, variant I – value of generated magnetic field 0.2 mT ($p = 0.000151$); b– Series 1, variant II – value of generated magnetic field 0.9 mT ($p = 0.000149$); c – Series 2, variant I – value of generated magnetic field 0.2 mT ($p = 0.000146$); d – Series 2, variant II – value of generated magnetic field 0.9 mT ($p = 0.000147$); e – Series 1 and 2, variant I – value of generated magnetic field 0.2 mT ($p = 0.000149$); f – Series 1 and 2, variant II – value of generated magnetic field 0.9 mT ($p = 0.0000148$)

the chamber. The studies however do not justify any conclusions about a constant proportional dependence between the field value and the number of fish entering the chamber. The concept of the so called "window effect" (Cleary 1993) is associated with the effect of magnetic field on living organisms. The phenomenon consists in susceptibility of the organism to magnetic fields within a certain range of values. Below and above that range of values the organism may not react to the stimulus at all, or else display a different reaction.

The behaviour of Siberian sturgeon in magnetic field may be explained by the fact that the changed value of magnetic field induces reactions of the organism which in turn cause changes of direction of its movement in space. Similar reactions were observed in the studies on juvenile salmonids (Formicki et al. 2004b; Putman et al., 2014a; Putman et al., 2018). The phenomenon was also noted in adult cyprinids and percids whose directional reactions were studied in the wild – in a lake, using traps provided with magnets. In those cases magnetic field disturbed the adult fish or made them curious, so that most individuals did not move away but entered the trap's cage (Formicki et al., 2004a).

The sturgeon's ability to choose the direction of movement in the water column is based, among other things, on their perception of electric or magnetic field. Elasmobranch fishes, while moving in the water column, cross the lines of force of magnetic field and thus induce electric field which is perceived with electroreceptors – Lorenzini organs. The fishes use the phenomenon to find food and perceive the direction of movement (Kalmijn, 1982). In the case of Siberian sturgeon such induction is however unlikely, since – contrary to elasmobranch fishes – the species has no electroreceptors. Besides, during their migrations the sturgeon move in both saline (sea) and freshwaters (rivers) while perception of electric field with electroreceptors – Lorenzini organs – requires increased electric conductivity which occurs in salt water only.

Migrations of juvenile sturgeons, especially anadromous – downstream, are important from the point of view of behavioural and physiological adaptations to sea water environment. Siberian sturgeon as well as two other Asian species: Chinese sturgeon (*A. sinensis)* (Zhuang et al., 2002) and Amur sturgeon (*A. schrenckii)* (Zhuang et al., 2003), start their migration downstream as hatchling embryos (Gisbert et al., 1996) using swim-up and drift. Kynard et al. (2002) suggest that the phenomenon is also associated with the high predation pressure on the sturgeon spawning grounds, resulting in small chances of survival of juveniles. Migrating away from spawning grounds reduces not only predation pressure on hatchling embryos, but also competition for food which on spawning grounds is available in limited quantities (Zhuang et al., 2002). However, it is only at the stage of fingerlings that the juveniles exceed the distance of 400 km downstream of spawning grounds, and the velocity during migration of various species of acipenserids ranges from 0.17 to 2.16 km/h (Kirschbaum et al., 2011). During migration sturgeons, like lampreys and salmonids, use geomagnetic field to orient themselves and choose the direction of movement, and each change in the value or direction of the field may cause disorientation (Krylov et al., 2014). For example, recent studies have demonstrated that the ocean migratory pathways of sockeye salmon (*Oncorhynchus nerka)* around Vancouver Island, Canada are influenced by decadal changes in the earth's geomagnetic field (Putnam et al., 2013).

Studies on the effect of magnetic field on reactions of European eel (*Anguilla anguilla)* done on yellow juveniles showed no typical directional reaction, as opposed to the silver forms which migrate to their spawning grounds. However, the juvenile eel perceive the effect of increased value of generated magnetic field, which is manifest as delayed motor reaction compared to the control (Tański, 2014). This means that the fish are capable of reacting to changes in magnetic field, but depending on the advancement of their development and on the environmental conditions they may use or not use the ability. A similar situation may be suspected in the case of fry of Siberian sturgeon which, when swimming downstream, may already be capable of reacting to magnetic field but do not have to use the ability.

The fish capability of orientation in magnetic field has for a long time been explained by the presence of magnetite (Fe_3O_4) crystals in the bodies of some migratory fishes. It has been detected, among other species, in the head of yellowfin tuna (*Thunnus albacares*) (Walker et al., 1982), body of chinook salmon *(Oncorhynchus tschawytscha*) and chum salmon (*Oncorhynchus keta*) (Ogura et al., 1992, Naisbett-Jones et al., 2020), in rainbow trout (Walker et al., 1997), in the eel skull (Hanson et al., 1984) and in the eel lateral line (Potter and Moore, 1991). The presence of magnetic material has also been observed in fish species which do not migrate for long distances, such as perch (*Perca fluviatilis*) and carp (*Cyprinus carpio*) (Hanson and Westerberg, 1987). Though to date there have been no attempts at detecting magnetic material in sturgeon body, it can be assumed that, since magnetic material and magnetite are known to occur in many species, both migratory and non-migratory, they may also be present in Siberian sturgeon – an anadromous species.

On the other hand, according to recent studies, perception of magnetic stimuli does not necessarily have to be associated with definite specialised structures. The ability to perceive changes in the value of magnetic field can be explained based on connection crystals – single domain magnetite (Fe_3O_4) – with ionic channels (Diebel et al., 2000; Walker et al., 2002, Naisbett-Jones and Lohmann 2022). Explanation of the mechanism of perception of magnetic field by organisms assumes that the localisation of crystals in cells and tissues is based on micromechanical – microtubules – connections between the crystals and ionic channels in the membranes. Magnetic field penetrates living tissues, so that receptors or sensitive organs can be located in various body parts and do not require direct contact with external environment. Ferromagnetic molecules behave like miniature magnets and under the effect of magnetic field their individual magnetic moments may become identical. A chain of single domain particles may be connected by microtubule-like strands with the number of openings of ion channels and the channels may be mechanically opened and closed when the direction or intensity of ambient magnetic field is changed. Opening or closure of the trans-membrane ion channels significantly changes the cell's membrane potential, which is translated onto perception of the direction and intensity of ambient magnetic field (Formicki et al., 2021).

The results of our experiments on the behaviour of fry of Siberian sturgeon in generated magnetic field confirm that magnetic field affects directional reactions of the fry. It can be thus surmised that the ability to perceive changes in magnetic field occurs in various fish species which undertake different kinds of migrations, and is not attributable only to long-distance migrants, such as eel or salmon.

CONCLUSIONS

In the presented work, the aim of the research was to investigate whether Siberian sturgeon (*Acipenser baeri*) fry are able to show directional reactions in an artificially generated magnetic field with higher values than the Earth's magnetic field. It was shown that the artificial magnetic field significantly influenced the choice of the direction of movement in a specially constructed research set. It can therefore be assumed that in natural conditions, juvenile Siberian sturgeon individuals floating towards the sea, in addition to following the river current, are also sensitive to changes in the values of magnetic fields of anthropogenic origin. The conducted research expands the state of knowledge about the behavior of migratory fish in the magnetic field.

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