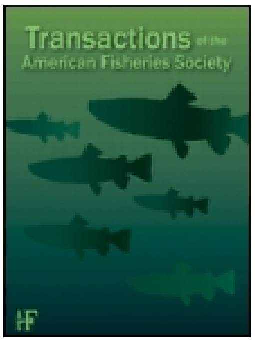

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ARTICLE

Behavioral Responses of Representative Freshwater Fish Species to Electromagnetic Fields

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Abstract

Hydrokinetic energy is proposed as an environmentally preferred means of generating electricity from river and tidal currents. To resolve environmental concerns, it is important to investigate potential effects on aquatic organisms from the electromagnetic fields (EMFs) that are created by underwater generators and transmission cables. We evaluated the behavioral responses of some representative freshwater fishes to static and variable EMFs in a series of laboratory experiments. Fish were exposed for 46 h to a static (DC) EMF with a permanent bar magnet or to a variable (AC) EMF with an electromagnet. Fish locations were recorded with a digital imaging system, and changes in activity level and distribution relative to the magnet position were quantified at 5-min intervals. Experiments with Fathead Minnow *Pimephales promelas*, Redear Sunfish *Lepomis microlophus*, Striped Bass *Morone saxatilis*, Lake Sturgeon *Acipenser fulvescens*, and Channel Catfish *Ictalurus punctatus* produced mixed results. Except for Fathead Minnow, there was no effect on fish activity level. Only Redear Sunfish and Channel Catfish exhibited a change in distribution relative to the position of the magnet, with both species showing an apparent attraction to the EMF source. In a separate experiment, rapid behavioral responses of Paddlefish *Polyodon spathula* and Lake Sturgeon to the onset of an AC field were recorded with high-speed video. Paddlefish did not react to a variable, 60-Hz magnetic field (i.e., like that emitted by an AC generator or cable), but Lake Sturgeon consistently responded with a variety of altered swimming behaviors. These results will be useful for positioning cables or generators to minimize interactions with EMF-sensitive species.

There is considerable interest in the development of marine and hydrokinetic (HK) energy projects in rivers, estuaries, and coastal ocean waters of the United States. Hydrokinetic technologies convert the energy of moving water in river or tidal currents into electricity without the impacts of dams and impoundments associated with hydropower or the extraction and combustion of fossil fuels. As of December 2012, the U.S. Federal Energy Regulatory Commission (FERC) had issued 54 preliminary permits to private developers to study HK projects in inland waters (FERC 2012), the development of which would total over 5,000 MW. Most of these projects are proposed for the lower Mississippi River. In addition, another 21 preliminary permits for tidal projects (totaling 1,688 MW) were under consideration by FERC. Although numerous HK designs are under

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development (see USDOE 2009 for a description of the technologies and their potential environmental effects), the most commonly proposed projects entail arrays of rotating devices that are positioned in high-velocity (high-energy) river channels.

The many diverse HK designs suggest a variety of environmental impacts, but a potential impact common to most is that the electromagnetic fields (EMFs) created by the projects may exert effects on aquatic organisms. Submerged electrical generators and electrical transmission cables will emit an EMF into the surrounding water. The cables' design, voltage, amperage, and type of electrical current (AC or DC) will be project specific. Short-distance cables used in rivers will likely carry AC, and long-distance marine cables will probably transmit high-voltage DC. Although cables will be insulated and armored to prevent leakage of electricity, the electric current moving through these cables will create magnetic fields in the immediate vicinity, which may affect the behavior or viability of fish and benthic invertebrates (Gill et al. 2005, 2009). In addition, movement of a conductor (e.g., aquatic animals or water containing dissolved minerals) through the magnetic fields can create an induced electrical field that can be sensed by some fish and aquatic invertebrates.

It is known that numerous marine and freshwater organisms are sensitive to electrical and magnetic fields, often depending on them for such diverse activities as prey location and navigation (USDOE 2009; Normandeau Associates et al. 2011). Despite the wide range of aquatic organisms that are sensitive to EMFs and despite the installation of increasing numbers of underwater electrical transmitting cables in rivers and coastal waters, little information is available to assess whether animals will be attracted, repelled, or unaffected by these new sources of EMFs. This knowledge gap is especially significant for freshwater systems, where electrosensitive organisms, such as Paddlefish *Polyodon spathula* and sturgeon, may interact with electrical transmission cables.

We carried out a series of laboratory experiments to test the sensitivity of freshwater fish to EMF levels that are expected to be produced by HK projects. The species were selected from a variety of taxonomic groups and are all common to the large rivers that will support HK technologies. Although prolonged exposure to EMFs could potentially lead to physiological changes, we assumed that exposure of motile aquatic organisms to EMFs in a river would be relatively brief and nonlethal; thus, we focused our investigations on detecting changes in behavior that might signal consequent effects on distribution, activity, or migration.

In laboratory experiments, we exposed fish to a range of EMF values that were representative of field strengths likely to be created by HK projects. Because values for the EMFs associated with operating HK projects have not yet been published (USDOE 2009; Normandeau Associates et al. 2011), we carried out a literature search of other electrical cable designs and contacted HK developers and researchers to ascertain the likely strengths of the magnetic fields.

The British Centre for Marine and Coastal Studies (CMACS 2003) surveyed cable manufacturers and independent investigators to compile estimates of the magnitudes of magnetic and electrical fields. Most agreed that the electrical field can be completely contained within the cable by metallic shielding (and by the sediments if the cable is buried). On the other hand, magnetic field emissions cannot be reduced by shielding, although multiple-stranded cables can be designed so that the individual strands cancel out a portion of the fields emitted by the other strands. Estimates of the magnetic field strength produced by the current-carrying cable ranged from 0 μT (by one manufacturer) to 1.7 and 0.61 μT at distances of 0.0 and 2.5 m, respectively, from the cable. By comparison, the Earth's geomagnetic field strength ranges from approximately 20 to 75 μT (Bochert and Zettler 2006).

Slater et al. (2010) derived models to predict the EMFs from energized DC monopole, DC bipole, and AC cables and compared their predictions with measurements of EMFs from an offshore wind farm. The predicted maximum strengths of the magnetic fields at the surface of the 1,000-A cables were approximately 1,000 μT for DC monopole cables, 3,000 μT for DC bipole cables, and 900 μT for single-phase AC cables. For all cables, the maximum magnetic field strength decreased rapidly with distance, dropping to nearly the background levels for the Earth's magnetic field at 10 m from the axis of the cable. Based on a comparison with field measurements of a power cable in the River Clwyd (North Wales), Slater et al. (2010) concluded that their models will reasonably predict the electrical and magnetic fields generated around the specific cable designs being considered for subsea power transmission.

Normandeau Associates et al. (2011) used design characteristics of 24 undersea cables to model the expected magnetic fields to which marine organisms may be exposed. For both AC and DC cables, the predicted strength of the magnetic fields was greatest at the surface of the cable and declined rapidly with vertical and horizontal distance. Maximum levels for the 10 modeled AC submarine cables were about 18 μT. Magnetic fields for the DC cables peaked at about 160 μT, although the average maximum field strength for the nine modeled cables was about 80 μT. Magnetic field strengths were predicted to decrease to near-background levels at a distance of 10 m from the cable.

The predicted values summarized above were made for underwater transmission cables associated with offshore wind energy production or other applications. None of the HK developers or researchers whom we contacted had measured or predicted the EMFs from their generators or electrical transmission cables, but they provided information about the types of transmission cables that they had installed or expected to use. From physical dimensions, voltage, and amperage of the electrical cables, estimates of the strength of magnetic fields at various distances from the cable were calculated using Ampere's Law applied to a long, straight wire:

$$B = (2.0e^{-7}) \times (I/R),$$

where B is the magnetic field strength (T), I is the electrical current (A), and R is the radius (m) from the center of conduction. For a variety of cable configurations carrying currents ranging from 105 to 500 A, the resulting estimates of magnetic field strength ranged from 460 to 8,000 μT at the surface of the cable and from 20 to 100 μT at 1 m from the cable's surface (Cada et al. 2011). Compared with estimates from this simple equation, the magnetic fields of more complicated cable configurations (e.g., steel-armored or multicore cables) would be expected to decrease more rapidly with distance (i.e., in a polynomial rather than linear relationship). Consequently, in the absence of measurements, our predicted magnetic field strengths almost certainly encompassed the full range of magnetic flux densities that fish are likely to encounter from HK devices.

METHODS

Because underwater power transmission cables may carry either AC or DC, we designed experiments with magnets that produced both static (DC) and variable (AC) EMFs. We selected magnets with a maximum magnetic strength that was within or above the range estimated from data gathered in an industry survey (Figure 1). Trials with DC magnets included 46-h exposures, with the endpoints of interest being a change in fish activity and location relative to the magnet's position. Trials with AC magnets included two types: (1) 46-h exposure trials with the same endpoint of interest as for the DC magnet trials; and (2) trials involving brief exposures of a few seconds, with the endpoint of interest being changes in fish swimming behavior. Experimental details are provided below.

Direct current static-field experiments.—Adult Fathead Minnow *Pimephales promelas* and juvenile Redear Sunfish *Lepomis microlophus*, Channel Catfish *Ictalurus punctatus*, and Striped Bass *Morone saxatilis* were used to investigate fish attraction to or avoidance of a DC (static) magnetic field. Because our experimental setup was dependent on fish exhibiting a preference for or against the EMF, we chose species for these trials that are not continuous swimmers and that are often associated with some form of cover, as this was used to maximize exposure. Fathead Minnow were obtained from stock maintained at the Oak Ridge National Laboratory's Aquatic Ecology Laboratory and were housed in aquaria for at least 3 d prior to each experiment. The juvenile Redear Sunfish (TL ranging from 60 to 82 mm), Channel Catfish (TL ranging from 28 to 42 mm), and Striped Bass (TL ranging from 32 to 45 mm) were obtained from the Eagle Bend Fish Hatchery (Tennessee Wildlife Resources Agency, Clinton). The fish were transported from the hatchery to the laboratory in aerated, insulated coolers and were held in aquaria at a water temperature of 25°C for at least 3 d before testing. Fish were fed Tetramin fish flakes or defrosted brine shrimp *Artemia* spp. daily before and between experiments but not during experiments.

Test and control tanks were standard, glass-sided aquaria (51 cm long × 26.5 cm wide × 31.5 cm high) with nonmetallic sealant and plastic rims. A rectangular, permanent bar magnet

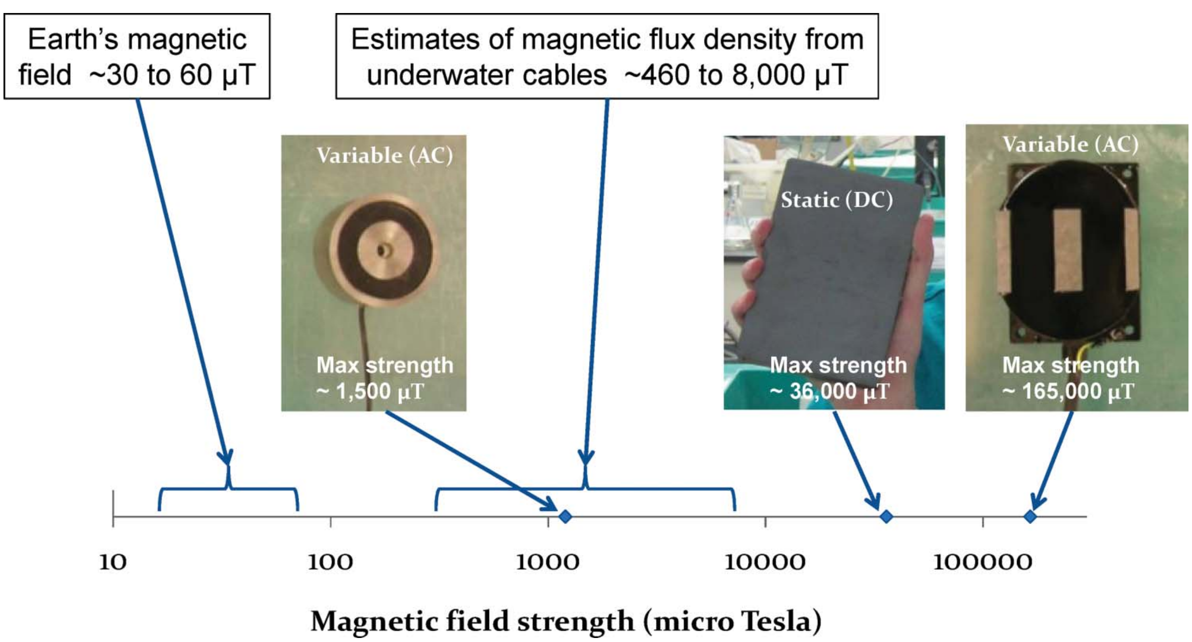

FIGURE 1. Maximum field strengths (μT) measured at the surface of the AC and DC magnets used in this study, presented in comparison with the Earth's natural field strengths and with field strengths predicted for underwater transmission cables. [Figure available online in color.]

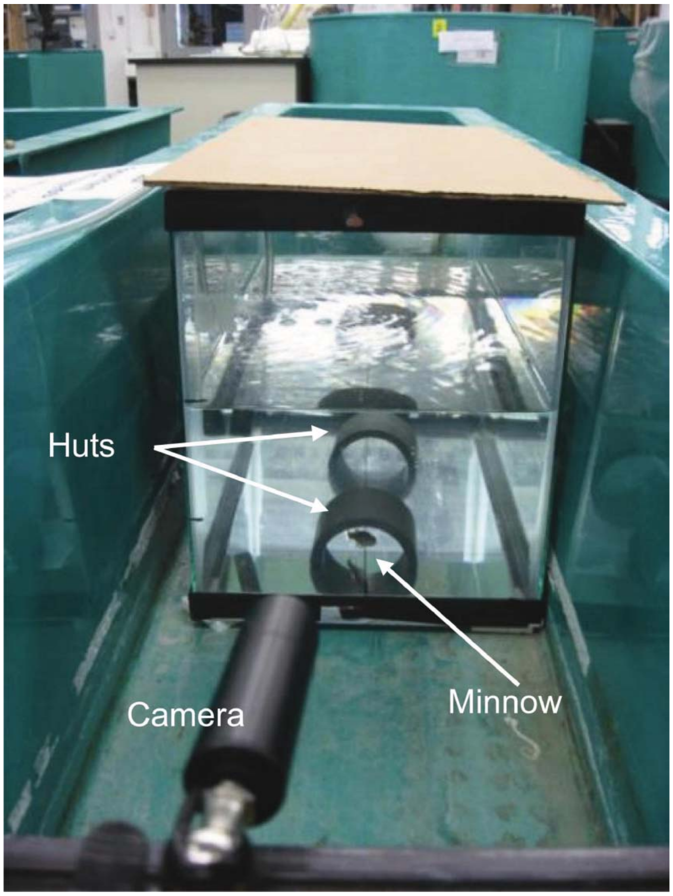

FIGURE 2. Experimental setup for the 46-h electromagnetic field exposure experiments. [Figure available online in color.]

was placed under each test tank by elevating the tank corners with tiles so that the magnet's surface was close to but did not touch the glass bottom of the aquarium (Figure 2). Control tanks (those without magnets) were similarly elevated. Test and control tanks were filled to a depth of 9 cm with dechlorinated tap water and were held at room temperature (23–25°C). Lighting was provided throughout the laboratory by overhead fluorescent lights on a daily schedule of 12 h on and 12 h off. Dissolved oxygen (DO) concentration and temperature were measured in each tank.

The static magnetic field in each test tank was created by a ceramic (ferrite) bar magnet (10.4 × 15.5 × 2.5 cm), and the field was measured with a Gauss meter (Model GM-2; AlphaLab, Inc., Salt Lake City, Utah). Magnetic field strength measurements were converted from Gauss to microTeslas (μT) in this paper for purposes of comparison and discussion. The field created by the magnet was strongest at the magnet's surface (∼36,000 μT) but rapidly decreased with vertical and horizontal distance (Figure 3). The magnetic field readings on the opposite side of the test tank from the magnet dropped to near-background levels (∼90–190 μT within the building).

Up to four test tanks and four control tanks were used simultaneously. Test tanks and the tank end that was used for magnet placement were selected randomly. There were no sediments or other substrate in the glass-bottomed aquaria, but the underside of each tank was covered by opaque paper to prevent the magnet from being seen by the fish. Because some fish prefer to remain under cover as part of normal behavior (e.g., male Fathead Minnow), opaque, polyvinyl chloride (PVC) half-cylinders (henceforth, "huts"; 76 mm long, 30-mm inside radius) were placed in the center of each half of each tank to encourage the fish to experience the maximum magnetic field if present. One of the huts was placed directly over the magnet, and the other hut was placed on the opposite side of the tank (Figure 2). The fish were free to move from one hut to the other and were free to select a preferred location or to remain outside of the huts. The top of each aquarium was covered, and the aquaria were placed inside empty, opaque fiberglass flumes to minimize external disturbance. Video cameras were positioned between the tanks such that fish inside of huts were easily observed, and the cameras continuously provided digital images for storage to an Image Vault (New Albany, Indiana) security system.

The experiments were started in the morning by placing a single fish in each tank without the huts present. After the fish had acclimated to the test tanks for 55 min, two huts were placed in each tank. Five minutes later, we began recording the locations of the fish, with an image of each tank stored every 1–2 s. After a 46-h experiment, magnets were switched from the test tanks and placed under the control tanks; huts were removed for approximately 50 min and then replaced for a second 46-h experiment with the same fish. Hence, each fish was exposed alternately to the magnetized (test) and control treatments; half of the fish were randomly chosen for the test treatment first, and the other half were given the control treatment first.

After experiments concluded, we reviewed the recorded images and noted the location of each fish every 5 min during the lighted period of the day (0620–1820 hours). The video images from each test and control tank were examined to determine whether the fish were (1) in the north half or south half of the tank and (2) inside or outside of the PVC hut.

A movement index (MI) was calculated to compare each fish's level of activity in the test and control tanks. The MI was calculated as the total number of times a fish was recorded on the opposite side of the tank relative to the location that had been recorded for the previous observation (i.e., 5 min earlier). The MI would be higher for a fish that changed sides frequently (indicating a high level of activity) than for a fish that remained on one side (e.g., inside of a hut) for much of the time.

Because of the possibility that other factors in the laboratory (such as the position of overhead lights) might contribute to the distribution of fish in the tanks, we used a paired *t*-test to determine differences in distribution and activity between experiments with and without a magnet in place. For all species, paired *t*-tests were used to evaluate (1) whether the number of occurrences on the magnet side during trials with a magnet in

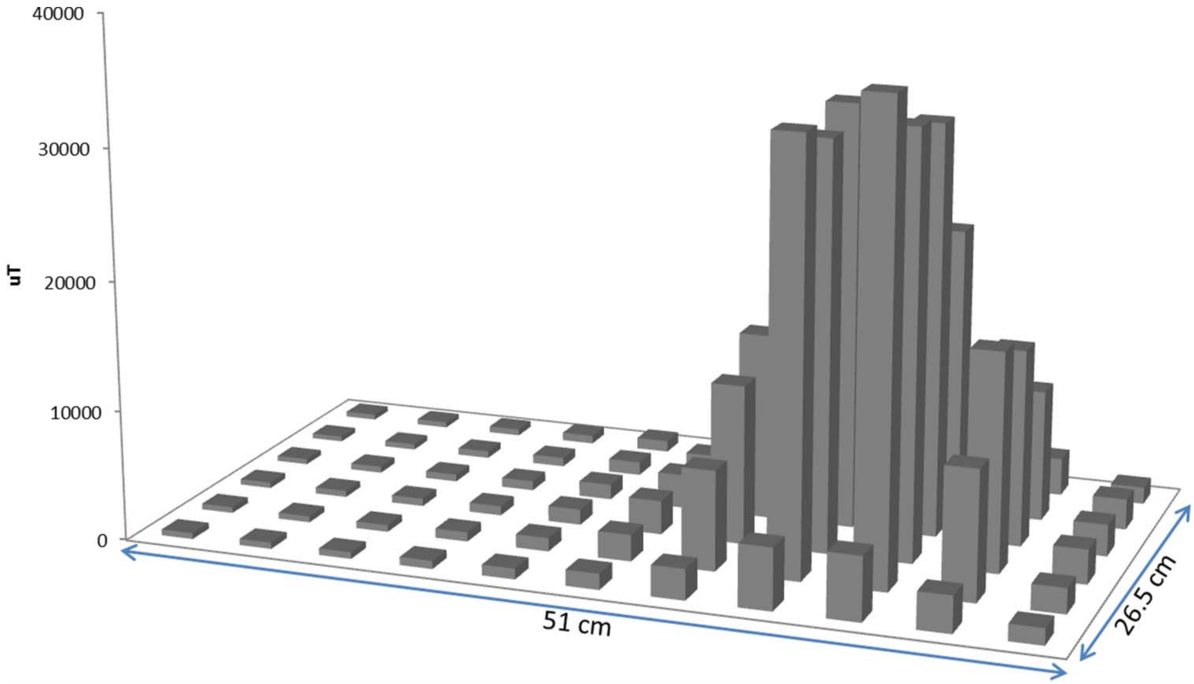

FIGURE 3. Strength (μT) of the static magnetic field created within each aquarium when placed over a permanent bar magnet. The maximum field strength was 36,410 μT. [Figure available online in color.]

place differed from the number of occurrences on the same side during the control (no-magnet) trials, (2) whether the number of occurrences under the hut on the magnet side differed from the number of occurrences under the hut on the same side during control (no-magnet) trials, and (3) whether activity (MI) differed between test and control treatments.

Alternating current variable-field experiments.— Experiments using AC electromagnets were conducted with juvenile Redear Sunfish, Lake Sturgeon *Acipenser fulvescens*, and Paddlefish to detect their reactions to variable magnetic fields like those that will be produced by HK generators and other AC-transforming or transmitting components. These experiments were of two types: (1) the aquarium attraction/avoidance studies that were carried out with the DC bar magnets were repeated with AC electromagnets (for Redear Sunfish and Lake Sturgeon only); and (2) a strong, variable magnetic field was created inside a circular test arena by using an AC electromagnet to assess immediate behavioral responses to an instantaneous EMF exposure.

The design of the trials in the circular arena required species that would swim continuously around the periphery of the tank, which is why only Paddlefish and Lake Sturgeon were used in those trials. Paddlefish are widely distributed throughout the Mississippi River basin, including slow-flowing water of the Mississippi River and its major tributaries and main-stem reservoirs. The Paddlefish rostrum is very sensitive to weak electric fields, such as those produced by their planktonic prey but also by submerged metal rods (Wojtenek et al. 2001; Wilkens and Hofmann 2007). Thus, Paddlefish are likely to encounter HK projects on large rivers in the USA, and because of their electrosensitivity, Paddlefish may be affected by the EMFs that are generated by these projects.

The Lake Sturgeon is found in large lakes and rivers of eastern North America, in the upper and middle Mississippi River basin, in the Great Lakes and Hudson Bay drainages, and in the upper Coosa River system. This large, bottom-oriented species is likely to be exposed to EMFs from HK projects in rivers—particularly the EMFs emitted by electrical transmission cables on the riverbed. Sturgeon can utilize electroreceptor senses to locate prey and may exhibit varying behavior at different electric field frequencies (Basov 1999, 2007). The potential effect of EMFs on this species (e.g., altered swimming behavior or altered ability to find prey) is a concern because Lake Sturgeon are likely to encounter HK projects and submerged electrical cables during their migration in large rivers.

Juvenile Lake Sturgeon (TL ranging from 13.8 to 18.3 cm) were obtained from the Cohutta Fish Hatchery (Cohutta, Georgia), and juvenile Paddlefish (TL ranging from 25.2 to 30.0 cm) were obtained from the Aquila International, Inc., hatchery (Versailles, Kentucky). Fish were maintained in 500-L, round fiberglass tanks with dechlorinated freshwater inflow at the Aquatic Ecology Laboratory and were fed defrosted brine shrimp daily.

The glass aquarium experiments conducted with AC magnets were of the same design as described for the ferrite bar magnet experiments except that we used an AC-powered electromagnet (Model EM400-24-212; 24 V, 20 W, 290.3-kg [640-lb] lifting force; APW Company, Rockaway, New Jersey) as the source of the magnetic field. These experiments were performed with 20

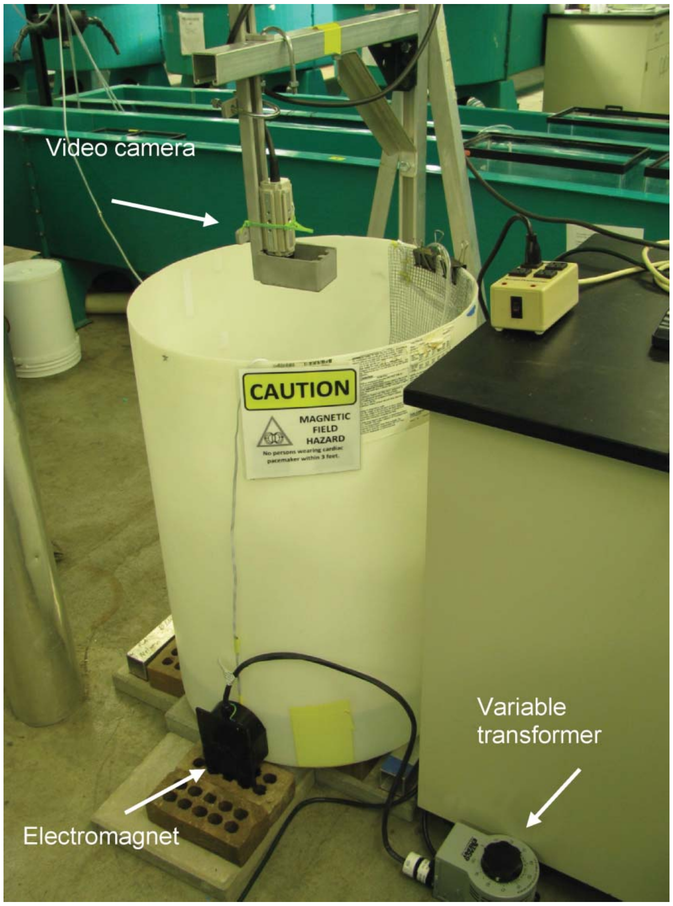

FIGURE 4. Experimental tank used to test the responses of juvenile Paddlefish and Lake Sturgeon to a 4-s burst of electromagnetic field created by an AC electromagnet. [Figure available online in color.]

juvenile Lake Sturgeon and 8 Redear Sunfish; all fish were tested individually. Based on preliminary observations indicating that Lake Sturgeon would not utilize huts, the PVC huts were not placed in the tanks for experiments with this species. Otherwise, data collection and analysis were the same as described above for the DC magnets.

The second set of experiments, which were designed to assess short-term responses to an immediate exposure, was conducted in an opaque white, cylindrical Nalgene polyethylene test tank (83 cm high, 56 cm in diameter) containing 30 L of water at a depth of 11 cm (Figure 4). A Photron Fastcam PCI (Photron USA, Inc., San Diego, California) high-speed camera was suspended above the tank and was interfaced to a PC with Photron Fastcam Viewer software. Video analysis was conducted using Visual Fusion software (Boeing-SVS, Inc., Albuquerque, New Mexico). Video files were saved immediately to the PC hard drive and were later transferred to an external hard drive for long-term storage.

An AC electromagnet (Model FDE-1; 120-V AC, 7 A, 60 Hz; Magnetech Corp., Novi, Michigan) was placed against the outside of the experimental tank at the base so that the magnet's height spanned the depth of the water in the tank (see Figure 4). The 60-Hz electromagnet was connected to a variable transformer (Model 3PN1010B; Staco Energy Products Co., Dayton, Ohio), which allowed the intensity of the magnetic field to be altered for different treatments. Prior to the experiment, the resulting magnetic field inside the tank (Figure 5) was measured with a Gauss meter at 1-cm spacing on the inside tank wall. During experiments, the Gauss meter's probe was fixed to the outside of the tank between the tank and the electromagnet, and the meter was affixed to the inside of the tank above water level so that the digital readout was in view of the camera. This allowed the observer conducting the postexperiment analysis to ascertain from the video recording the frame and exact time at which the EMF was activated in the tank and the frame at which the fish began to respond. The magnetic field was strongest directly over the magnet (~155,000 μT at full strength) but decayed rapidly with distance (Figure 5). In addition to measuring the maximum strength at any location on the magnet, we also calculated the average magnet strength across the face of the magnet, as we believed that this metric better represented the level experienced by the test fish. Temperature and DO were monitored in the experimental tank prior to each experiment, and freshwater was added as needed to match the temperature and DO in the holding tank. Fish were allowed to acclimate to the experimental tank for approximately 15 min before treatments were initiated. Fish were initially tested with the electromagnet set at full power. In subsequent tests, a variable transformer was used to reduce the strength of the magnetic field to 50, 25, 5, 4, and 1% of full power in order to determine response thresholds. The average strength across the face of the magnet for the six levels tested was 50,834 μT at 100% power; 25,499 μT at 50% power; 12,831 μT at 25%; 2,697 μT at 5%; 2,190 μT at 4%; and 670 μT at 1%.

After acclimating to the circular experimental tank, the fish normally swam in a predictable manner around the wall of the tank. Watching on the Fastcam Viewer, the observer began a video recording as the fish approached the magnet, and the observer then used an external switch to activate the electromagnet just as the fish was swimming over it. A control (nonmagnetized) test was carried out in an identical fashion except that the electromagnet was unplugged and thus no magnetic field was created.

The reactions of an individual fish to the treatment or control exposures were video-recorded 9 or 10 times, spaced 5 min apart. Treatment and control tests were randomly assigned. For each video, 1,088 frames were recorded at a rate of 250 frames/s for a total of approximately 4.3 s.

From the video recordings, we noted (1) the frame at which the electromagnet switch was activated, (2) the proportion of the fish's body that was over the magnet when the switch was activated, (3) the total duration of the reaction (if any) exhibited by the fish, and (4) any behaviors that were apparent in the recording. Eleven distinct behaviors were identified, and the presence of any of these behaviors during the 4.3-s

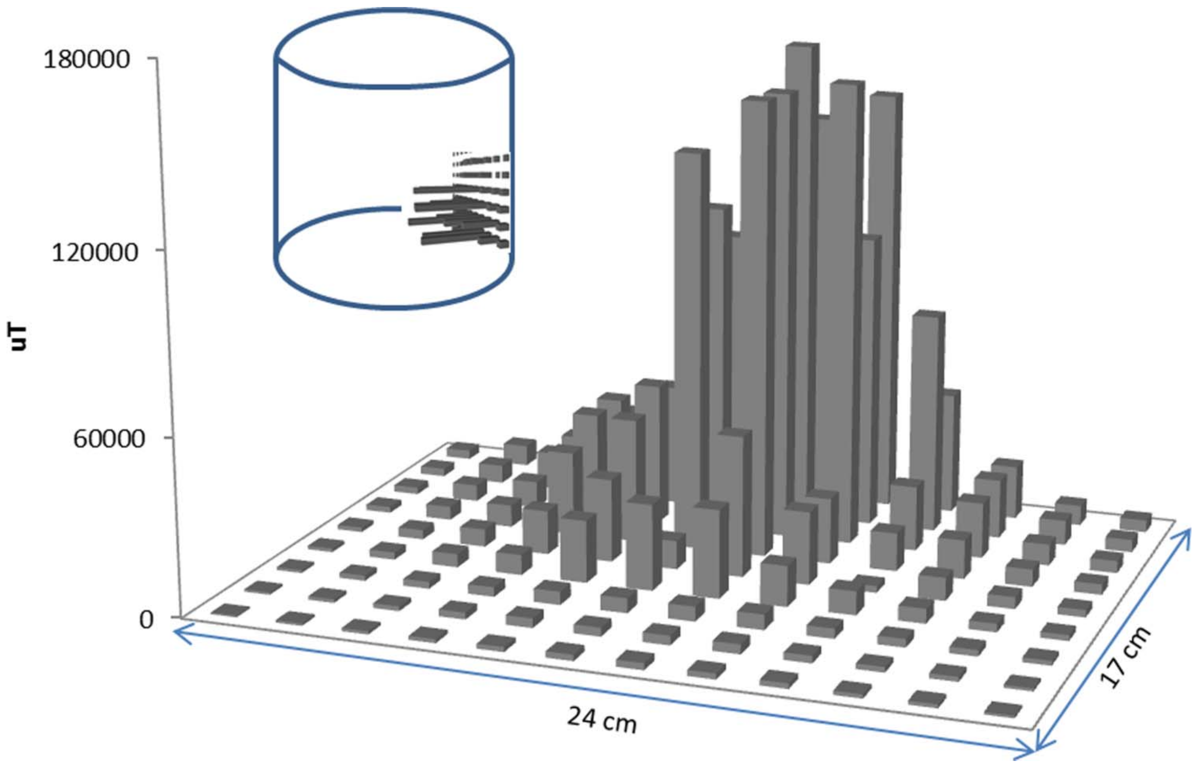

FIGURE 5. Magnetic field (μT) produced at the inside wall of an experimental tank (i.e., as depicted in Figure 4) by an AC electromagnet at the strongest (100%) setting. The far row represents the bottom of the inside of the tank, and the embedded schematic of the experimental tank shows the placement of the field as the fish would have experienced it. [Figure available online in color.]

recording was noted. For consistency, a single observer initially viewed all of the videos and assigned all of the observed behaviors. Because some of the behavioral changes that occurred near the electromagnet were subtle (e.g., fin flares, slight acceleration, or slight deceleration), a second observer (independent to the first) rescored all of the Lake Sturgeon videos to provide another judgment about whether the fish's behavior had changed in response to activation of the magnet. The second observer used the same video files and video analysis software as before, but the viewing field was reduced in size so that the observer could not see the screen of the Gauss meter; thus, the second observer did not know whether the recording was from a control or a test exposure.

Durations (s) of the reactions exhibited by fish in test and control trials were compared by means of *t*-tests and ANOVA (SigmaPlot version 12; Systat Software, Inc.). Data were first square-root transformed and tested for normality by using the Shapiro–Wilk normality test. If the square-root-transformed data were nonnormal, a Mann–Whitney rank-sum test (for experiments with one treatment plus control) or a Kruskal–Wallis one-way ANOVA on ranks followed by Dunnett's test (for experiments with multiple treatments plus control) was conducted to compare median values of reaction duration among the groups.

RESULTS

Fish Responses to Chronic Exposure in a Direct Current Static Field

The four species used in the DC magnet experiments exhibited different behaviors during the 46 h in the test aquaria. Striped Bass regularly moved about the tanks and occupied the PVC huts infrequently (∼1% of the time on average). Redear Sunfish were usually inside the huts (78% of the time), and Fathead Minnow and Channel Catfish also spent a majority of their time in the huts (64% and 67% of the time, respectively). Only for Redear Sunfish did we detect a difference between the total amount of time spent at the side of the tank with the magnet and the time spent at that same side of the tank during control trials, when no magnet was present (paired *t*-test, $\alpha = 0.05$; Table 1). When considering only the amount of time spent in the huts, which placed fish in closest proximity to the magnets when present, we found that Redear Sunfish and Channel Catfish spent significantly more time in huts with magnets under them than in the same huts when magnets were absent (48% versus 32% of observations for Redear Sunfish; 43% versus 25% of observations for Channel Catfish; Table 2). In all three of these cases, the presence of the magnet appeared to result in an increase in time spent at that side of the tank.

TABLE 1. Mean number of observations (percent occurrence in parentheses) in which fish were on the side of the tank where magnets were located during treatment trials (Treatment) and number of observations in which fish were on that same side during control trials (Control; i.e., when magnets were absent) in the 46-h exposure experiments (N = mean number of individual fish observed). The P-values for two-tailed paired t-tests are presented.

Species	N	Magnet	Treatment	Control	P
Fathead Minnow	12	DC	89 (49.3)	111 (61.5)	0.20
Redear Sunfish	16	DC	105 (57.9)	86 (47.6)	0.05
Striped Bass	12	DC	142 (50.4)	148 (52.3)	0.63
Channel Catfish	12	DC	152 (54.3)	127 (45.2)	0.40
Redear Sunfish	8	AC	99 (54.6)	68 (37.6)	0.12
Lake Sturgeon	20	AC	184 (49.4)	195 (51.9)	0.12

TABLE 3. Mean movement index for fish that were exposed to either DC or AC magnets during 46-h treatment trials and for fish in paired control (no-magnet) trials. The P-values for two-tailed paired t-tests are presented.

			Movement index		
Species	N	Magnet	Treatment	Control	P
Fathead Minnow	12	DC	48.7	38.8	0.02
Redear Sunfish	16	DC	25.1	29.3	0.09
Striped Bass	12	DC	81.6	86.3	0.48
Channel Catfish	12	DC	11.0	9.1	0.65
Redear Sunfish	8	AC	17.1	17.3	0.98
Lake Sturgeon	20	AC	151	153	0.68

Redear Sunfish and Channel Catfish were the less active of the four species, and Striped Bass were the most active. Fathead Minnow were intermediate with respect to activity level and were the only species that had a significantly different (i.e., increased) level of activity during exposure to a magnetic field than during control treatments (Table 3).

Fish Responses to Chronic Exposure in an Alternating Current Variable Field

The two species used in the 46-h AC magnet experiments exhibited different behaviors during the tests. Lake Sturgeon regularly moved about the tanks and rarely stayed in any one location, while Redear Sunfish usually spent their time inside the huts (73% of the time on average). Neither species displayed a significant difference between the amount of time spent at the side of the tank with the magnet and the time spent at that side of the tank during control trials with no magnet present (paired t-test, $\alpha = 0.05$; Table 1). When we considered only the amount of time the fish spent in huts (i.e., resulting in close proximity to magnets when the magnets were present), we found that Redear Sunfish spent significantly more time in huts with magnets under them than in the same huts without magnets under them (Table 2). Redear Sunfish were less active than Lake Sturgeon and had a significantly different (increased) level of activity when exposed to a magnetic field relative to control treatments (Table 3).

TABLE 2. Mean number of observations (percent occurrence in parentheses) in which fish occupied the hut on the side of tank where magnets were located during treatment trials (Treatment) and number of observations in which fish occupied the hut on that same side during control trials (Control; i.e., when magnets were absent) in the 46-h exposure experiments (N = mean number of individual fish observed). The P-values for two-tailed paired t-tests are presented.

Species	N	Magnet	Treatment	Control	P
Fathead Minnow	12	DC	55 (30.7)	73 (40.7)	0.33
Redear Sunfish	16	DC	87 (48.0)	58 (32.1)	0.01
Striped Bass	12	DC	2.0 (0.6)	2.0 (0.6)	0.87
Channel Catfish	12	DC	120 (42.9)	70 (24.9)	0.05
Redear Sunfish	8	AC	82.0 (45.6)	46.0 (25.2)	0.02
Lake Sturgeon	20	AC			

Fish Responses to Burst Exposure in an Alternating Current Variable Field

The variable magnetic fields created by the AC electromagnet are depicted in Figure 5. The maximum value of the field at full power was approximately 165,780 μT; the strength of the field decreased rapidly from the peak value in both horizontal and vertical directions such that background levels were restored approximately 28 cm away from the wall, or about halfway across the tank. Normal background levels in the laboratory were approximately 100–200 μT. The strength of the magnetic field decreased in proportion to the percentage of power applied to the electromagnet by the variable transformer. The maximum value of the field at 50% power was approximately 103,020 μT, and background levels were detected at 19 cm away from the tank wall. At 5% of full power, the maximum strength of the magnetic field was approximately 11,030 μT, and background levels were measured at approximately 10 cm from the tank wall. Finally, at 1% of full power, the magnetic field inside the tank peaked at approximately 3,510 μT, and background levels were measured at approximately 5 cm from the tank wall.

Results of the second observer's quality control evaluation suggested that in nearly all cases, the changes in fish behaviors (or lack thereof) in the vicinity of the AC electromagnet were clearly distinguishable from normal swimming movements when evaluated by independent observers. The first and second observers agreed on 271 of 280 video observations (97% agreement) for Lake Sturgeon in control and test exposures.

During control trials without an EMF present, individuals of both Paddlefish and Lake Sturgeon typically swam in a circle around the periphery of the tank at a uniform velocity. Observed behaviors other than normal swimming were classified into 10 types ranging from a subtle slowing to more obvious responses, like thrashing and flaring of fins (Table 4). The incidence of various altered swimming behaviors exhibited by Lake Sturgeon in the video recordings is summarized in Table 5.

TABLE 4. Summary of Paddlefish and Lake Sturgeon behaviors that were observed during 4-s exposures to variable (AC) magnetic fields.

Behavior	Description
1. Normal swimming	No change from normal swimming (varies by species)
2. Speed slows or gliding	Stops actively propelling body forward but still moves forward
3. Sudden stop over magnet	No movement; stops directly over the stimulus area
4. Speed increases	Swimming speed gradually accelerates, or the fish exhibits burst swimming
5. C-shape without escape	Forms a C-shape but does not use it to leave the area of the magnet
6. C-shape with escape	Forms a C-shape and leaves the area of the magnet
7. Body spasm	Entire body shakes or quivers
8. Thrashing	More pronounced than a spasm; shaking, often breaking the surface or splashing
9. Tail shake or spasm	Only the tail exhibits spasms as described above
10. "Jumps" away	Entire body moves away from the stimulus area without being propelled by fins; looks like a vertical hop or jump
11. Pectoral fin flare	Pectoral fins are extended wider

Paddlefish.—Juvenile Paddlefish showed little reaction to the variable magnetic field, exhibiting some altered behavior in 8% of the trials when the magnet was activated. The most common Paddlefish responses to the EMF were formation of a C-shape or thrashing, but these behaviors were also observed in 2% of the control trials. When the duration of the reaction (altered behavior) was considered, the differences between the test and control trials were not statistically significant ($P = 0.169$).

Lake Sturgeon.—In contrast to juvenile Paddlefish, juvenile Lake Sturgeon showed a variety of reactive behaviors to the magnet, with 96% of the 50 trials (i.e., observations) including some type of reaction to the sudden appearance of the full-strength magnetic field (Table 5; Figure 6). At a reduced field strength, Lake Sturgeon again showed a variety of reactive behaviors; 100% of the trials involved some reaction by the fish at both 25% and 50% of full magnetic field strength. When field strength was reduced further, the reaction rates dropped, with Lake Sturgeon reacting in only 47% of trials at 4% of maximum field strength and in 60% of trials at 5% of maximum field strength (Figure 6). A substantial decrease in the reaction of juvenile Lake Sturgeon occurred at 1% of maximum magnetic field strength (i.e., at a peak field strength of ~3,510 μT; average field strength of ~670 μT across the face of the magnet), with fish showing a change in behavior in only 7% of the trials. Some control Lake Sturgeon exhibited altered behaviors as well; 8% of the 110 control trials (experiments LS1, LS2, LS3, and LS4 [see Table 5] combined) involved some response by the fish when they swam in the area of the unenergized electromagnet.

Overall, the juvenile Lake Sturgeon behaviors that were observed most frequently in response to the variable magnetic field included pectoral fin flare (30.5% of all observations), slowing or gliding (22.6%), body spasms (20%), remaining in the area of the magnet (15.5%), and sudden stops near the magnet (14.2%).

TABLE 5. Summary of reactions (altered swimming behaviors) of juvenile Lake Sturgeon to 4-s exposures from a variable (AC-generated) magnetic field. See Table 4 for definitions of the numeric codes (2–11) representing altered behaviors.

Experiment	Number of fish	Percent of maximum magnetic field	Number of observations	Number of reactions	Mean duration (s) of reactions	Altered behavior observed: 2	3	4	5	6	7	8	9	10	11
LS1	10	100	50	48	1.86	29	17	0	10	4	22	9	8	6	36
		0	50	4	0.18	4	0	0	1	0	1	0	0	0	0
LS2	10	25	30	30	2.03	17	12	0	5	0	17	4	0	9	23
		50	30	30	1.95	15	13	1	5	2	21	5	2	8	26
		0	30	5	1.09	2	0	0	1	0	2	0	0	1	2
LS3	5	4	15	7	1.68	6	1	0	2	0	1	2	0	0	7
		5	15	9	1.99	5	4	0	2	1	3	0	0	1	9
		0	15	0	0	0	0	0	0	0	0	0	0	0	0
LS4	5	1	15	1	2.56	0	0	1	0	0	0	0	0	0	0
		4	15	15	1.91	8	7	0	0	0	9	2	0	1	13
		0	15	0	0	0	0	0	0	0	0	0	0	0	0

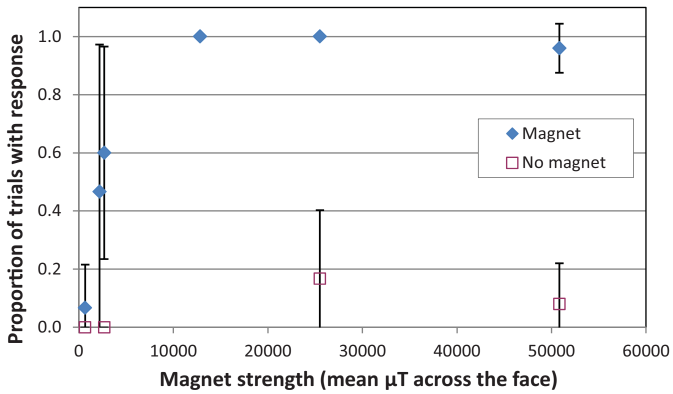

FIGURE 6. Proportion of trials in which juvenile Lake Sturgeon responded to sudden exposure to variable electromagnetic fields. Control results (open squares) are positioned at the magnetic strength (μT; averaged across the face of the magnet) of the treatment exposure with which they were paired, but no magnetic field was generated during the control trials. [Figure available online in color.]

Behaviors that were observed less often included C-starts without escaping the stimulus area (7.6%), "jumping" away from the stimulus area without swimming (7.1%), thrashing (6.8%), spasms of the tail only (2.6%), C-start reactions followed by escape from the area of the magnetic field (2.1%), and increases in swimming speed (0.5%). Some of these behaviors were also seen in the control fish (experiments LS1 and LS2), albeit at a much lower incidence than observed among EMF-exposed Lake Sturgeon. In all cases, Lake Sturgeon recovered immediately after the magnets were turned off, and they resumed normal swimming behavior. There were no apparent lasting effects from the exposures to magnetic fields, and all Lake Sturgeon were healthy several months after the experiments concluded.

Comparisons of the reaction durations by means of one-way ANOVA on ranks revealed statistically significant differences among test and control groups. For experiment LS1, the reaction duration was significantly different between test and control groups (Mann–Whitney rank-sum test: $P < 0.001$). For experiments LS2, LS3, and LS4, we used Kruskal–Wallis one-way ANOVA followed by Dunnett's test to discern differences among treatments. In experiment LS2, the reaction durations in both treatments (25% and 50% of maximum magnet strength) were significantly different from those of the controls ($P < 0.05$ for both). In experiment LS3, the reaction durations were significantly different overall ($P = 0.002$); when multiple comparisons were conducted, a difference was revealed between the 5% magnet strength treatment and the control ($P < 0.05$) but not between the 4% magnet strength treatment and the control. In experiment LS4, the reaction durations were again significantly different overall ($P < 0.001$). However, when multiple comparisons were conducted, the reaction duration for the 4% magnet strength treatment significantly differed from that of the control ($P < 0.05$), but the reaction duration at 1% magnet strength did not significantly differ from that observed for the control.

DISCUSSION

Experiments examining the reactions of freshwater fish to EMF exposures produced mixed results. The 46-h exposure experiments with six combinations of five species and two magnet types found some evidence that fish respond behaviorally to elevated EMFs. Based on the amount of time spent under huts in close proximity to the magnets, Redear Sunfish appear to be attracted to both DC- and AC-generated magnetic fields. The only other positive response in 46-h exposures was an increase in Fathead Minnow activity when DC magnets were present.

Rapid behavioral reactions to the sudden appearance of an AC-generated magnetic field were distinctly different for the two species tested. The variable EMF created by an AC electromagnet elicited little or no behavioral effects in Paddlefish, a species that is known to be highly sensitive to weak electrical fields. However, another species of known EMF sensitivity, the Lake Sturgeon, consistently displayed altered swimming behavior when exposed to the variable magnetic field. By gradually decreasing the magnet strength, we were able to identify a threshold level (average strength ∼ 1,000–2,000 μT) below which short-term responses disappeared. For the EMF strengths we tested, the threshold of no impact was equivalent to being 10–20 cm from the full-strength magnet. If a fish in the wild were to swim across a transmission cable in flowing water and then exhibit a response like those observed in the present study, that individual would be swept quickly away from the cable and would recover almost instantly. Such a response would be unlikely to have any lasting health effects on the fish, but it could delay or impede normal movements (e.g., upstream migration) if cables crossed much of the river bottom and were positioned perpendicular to the migration route.

Passive electroreception is widespread among fish, occurring in numerous orders of cartilaginous and non-teleost bony fishes (Collin and Whitehead 2004), although this capability has not been reported for most teleosts (Wilkens and Hofmann 2005). Of the species we tested, Paddlefish and members of the sturgeon and catfish families are known to be electrosensitive. The absence of consistent responses to the magnetic field or the consequent induced electrical field among Fathead Minnow, Redear Sunfish, or Striped Bass is perhaps not surprising because there is no indication from the literature that these taxa have specialized magnetosensitive or electrosensitive tissues. However, the lack of response among Paddlefish to the strong, variable EMF was unexpected. This species is extremely sensitive to very small electrical fields produced by the movement of prey items such as *Daphnia* (Wojtenek et al. 2001; Wilkens and Hofmann 2007), and Paddlefish are known to avoid metal rods placed in the water because of the rods' electrical field potential (Gurgens et al. 2000). Because of this sensitivity, we expected that Paddlefish would react to the induced electrical field created by their swimming through the strong AC-generated magnetic fields in the test tank. Wojtenek et al. (2001) noted that the zooplankton prey of Paddlefish produced both DC and oscillating AC electrical fields containing multiple frequencies and amplitudes, and those authors found that Paddlefish feeding behavior varied with frequency and amplitude. It is possible that the frequencies and intensities of the induced electrical signals created by the strong, 60-Hz electromagnet in our experiments were beyond the range that is readily detected by Paddlefish. A variety of combinations of magnet type and exposure scenario could be applied to fish; thus, the lack of an observed response to the combination we tested does not preclude the possibility that Paddlefish would respond to a different type of EMF exposure scenario.

Similarly, because Brown Bullheads *Ameiurus nebulosus* are known to be sensitive to very weak DC electrical fields (Roth 1968; Peters and Bretschneider 1972; Peters and van Wijland 1974; Eeuwes et al. 2001), it might be expected that other members of the Ictaluridae (e.g., Channel Catfish) would also have this sensory ability. In the cited studies of Brown Bullheads, the DC field was generated in experimental arenas by using electrodes, whereas in our experiments the Channel Catfish were exposed to an electrical field that was created by magnetic induction. An induced electrical field is the more likely potential stimulus for fish that are present in the vicinity of an HK project with well-shielded electrical components, but an induced field may not be detected in the same way as electrical currents that pass directly through the water between electrodes. Nonetheless, Brown et al. (1984) demonstrated the stimulation of electroreceptors in Turkestan Catfish *Glyptosternon reticulatum* both from DCs and from movement of a permanent bar magnet over the fish. Although the amount of time spent under huts by the Channel Catfish in our experiments increased when a magnet was present, this was probably not a response to an induced electrical field since the fish were not moving relative to the magnetic field when under the huts.

The observed reactions of Lake Sturgeon in this study are consistent with the results of related studies of Asian sturgeon species. Basov (1999) exposed Sterlet *Acipenser ruthenus* and Russian Sturgeon *Acipenser gueldenstaedti* to weak electrical fields with frequencies ranging from 0.1 to 50.0 Hz. At low electrical field intensities, the sturgeon exhibited orientation and search responses (i.e., they were attracted to the field). At higher field intensities, the fish attempted to escape from the area of the electrodes; behaviors reported by Basov (1999) included quivering of the pectoral fins, strong excitation, and sudden escape from the electrode zone. In a subsequent field study of a river below a hydroelectric dam, Basov (2007) observed the movements of sturgeon in an area where an AC field had been induced by 50-Hz overhead power lines. Three species of sturgeon (Sterlet, Russian Sturgeon, and Great Sturgeon *Huso huso*) were found to congregate in areas below the overhead powerlines where measured fields exceeded that which was determined to be perceptible by sturgeon in Basov (1999). Although other environmental factors may have accounted for the distribution of sturgeon below the dam (e.g., hydraulic and bottom substrate features or food availability), the low-intensity induced electrical field did not appear to elicit an avoidance response.

Laboratory studies have shown that the electrosensitivities of fish are related to both field intensity and the frequency of ACs. Depending on the species, the maximum reactions to an EMF may occur at intermediate values of frequency and intensity and will drop off at both higher and lower values. The static and variable magnetic fields tested in our experiments were likely stronger than fields that would be experienced by fish near an HK project, although there is uncertainty about this owing to a lack of published measurements of HK technologies and their associated transmission cables. Further studies of freshwater fish responses to EMFs produced by HK technologies await a better definition of the nature and strength of the emitted fields. If these parameters are found to be outside the range of values that are detectable by fish, then concerns about the constraints posed by EMF emissions on the development of riverine HK projects may be resolved.

In addition, our biological response experiments used simple fields issuing from a single source, as might be created from an underwater cable. Different configurations of cables and other electricity-generating and transmitting components could create very different fields in terms of field strength and shape (Kadomskaya et al. 2005; Slater et al. 2010; Normandeau Associates et al. 2011). Some cable configurations may produce weaker magnetic fields than those predicted for a simple, straight wire. For example, armoring with high magnetic permeability can attenuate the field from an AC cable by shunting, and high-conductivity sheathing materials can partially cancel the magnetic field (Normandeau Associates et al. 2011). On the other hand, more complex and potentially stronger EMFs will be emitted from multiple parallel or overlapping cables or other interconnected components of the HK device; in large HK projects, these types of fields could be expressed over significant areas of a river channel. Additional studies of multiple HK generators and multiple cables are needed, beginning with model predictions of various EMF conformations, field site measurements of EMFs at an operating HK prototype, and monitoring of the responses of aquatic organisms to the complex fields. Whereas it will be difficult to reduce the EMFs from HK generators, the mitigation of cables' EMF effects on aquatic organisms might be accomplished by using different cable configurations, burying the cables in sediments, or a combination of strategies (CMACS 2003; Kadomskaya et al. 2005).

The results of these and similar studies will be useful for determining whether the cables and generators associated with marine and HK projects and offshore wind energy production pose an environmental concern for fish species that might interact with these projects. Our preliminary results suggest that if sensitive species are present, cable placement and installation might need to include (1) burying the cables to take advantage of the rapid decline in the magnetic field with distance and (2) positioning the cables in a way that minimizes their crossing of fish migratory pathways or corridors. Future studies should be conducted to evaluate different EMF sources and strengths, additional species, and the ability of simple mitigation measures to minimize any response and subsequent effects. Ultimately, studies that are designed to observe the responses of fish to live power lines in realistic field settings will provide more definitive results.

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