Scottish Marine and Freshwater Science
Volume 6 Number 8

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Published by Marine Scotland Science

ISSN: 2043-7722
DOI: 10.7489/1618-1

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Effects of AC Magnetic Fields (MFs) on swimming activity in European Eels *Anguilla anguilla*

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Summary

Little is known about effects of magnetic fields (MFs, 50 Hz, measured in Teslas) associated with high voltage cables on behaviour of European eels. It has previously been shown in a field study that swimming speed of European eels in the Baltic Sea slowed when crossing a 130 kV AC power cable. However, no details of fish behaviour during passage over the cable were recorded in this study, and it is not known whether the observed reduction in swimming speed was due to the MF associated with the cable, or some other factor. The aim of the present study was to observe the response of European eels at the silver eel stage of their life-cycle to an AC MF of approximately 9.6 µT at a fine scale in a controlled laboratory setting. During 28 trials, each lasting 4 hours and using a single eel per trial, 10 eels (termed "swimmers") made between 1 and 43 passes through coils. There was no evidence of a difference in movement due to the MF nor observations of startle or other obvious behavioural changes associated with the magnetic fields. Level of movement decreased as the experiments progressed and increased with eel size. Eel passage through coils was unaffected by whether or not they were activated. In applying these results it must be kept in mind that the sample size was small, nocturnal behaviour was not tested and the field strengths were lower than might be encountered in the wild in some situations.

Key words: diadromous, MF, environmental impact assessment, magnetic field, migration, MREDs.

Introduction

The urgent need to reduce CO_2 emissions globally has led to a large impetus towards generating electricity from renewable energy sources (Gill, 2005; Inger *et al*., 2009; Boehlert & Gill, 2010; Frid *et al*., 2012). In Scotland, the Scottish Government aims to meet 100% of Scotland's electricity demand from renewable sources by 2020 (Scottish Government, 2011). Marine renewable energy developments (MREDs) that generate electricity from offshore wind, wave and tidal energy sources are therefore expected to increase rapidly around the Scottish coast over the next decades. As part of that sustainable development, it is important to consider potential effects of MREDs on animals (Gill, 2005; Frid *et al*., 2012).

An issue that is of some concern is the potential effect of electromagnetic fields (EMFs) associated with high voltage alternating current (AC) and direct current (DC) cables used to transmit electricity between adjacent generating devices and/or from the point of generation to the mainland (Gill, 2005; Gill *et al*., 2005, 2009, 2012; Öhman *et al*., 2007; Inger *et al*., 2009; Boehlert & Gill, 2010; Gill & Bartlett, 2010; Frid *et al*., 2012). An electromagnetic field is created when electrical current passes through a cable and consists of two constituent fields - an electric field and a magnetic field. Within an AC industry standard cable, the electric field is shielded and therefore retained within the cable, but the magnetic field is detectable outside the cable and induces a second electric field, known as the induced electric field, outside the cable (CMACS, 2003; Gill, 2005; Gill *et al*., 2005, 2012). Both the magnetic field and induced electric field have the potential to affect aquatic animals (Gill, 2005), for example *via* interaction between the magnetic field and magnetic material (magnetite) (Öhman *et al*., 2007), or *via* direct passage of the animal through the induced electric field. The movement of an animal through the magnetic field will also induce a further localised electric field (Gill *et al*., 2012). Magnetic fields generated by AC power cables are cyclical at 50 Hz (i.e. 50 cycles per second - UK mains power frequency), and marine organisms are likely to perceive these differently to the natural static (DC) geomagnetic field of the Earth (CMACS, 2003; Öhman *et al*., 2007), generally assumed to be approximately 50 µT. These AC magnetic fields (MF) can cause a range of behavioural changes in certain species of fishes, including pectoral fin flare, slowing or gliding, body spasms, attraction to the magnet, sudden stops, burst swimming (C starts), thrashing and tail spasms (Bevelhimer *et al*., 2013).

With a single conductor, the MF is proportional to the electric current and inversely proportional to the distance from the centre of the conductor. Cable burial or other cable protection measures reduce MF by increasing distance, as does having multiple conductors in close proximity which allows positive and negative currents to cancel, as with three-phase AC. The magnetic properties of armouring can also affect MFs. All these elements frequently apply in actual cable deployments, but modelling is complex, and there is often uncertainly over what the resulting field strengths will be and more values measured in field situations would be useful (Gill *et al*., 2014).

In the Scottish marine environment, European eel *Anguilla anguilla* (L.), is one of three diadromous fish species [along with Atlantic salmon *Salmo salar* (L.) and brown trout *Salmo trutta* (L.), commonly known as sea trout] for which potential effects of MFs are of particular concern (Malcolm *et al*., 2010; Gill & Bartlett, 2010; Gill *et al*., 2012). European eels are currently considered to be critically endangered (IUCN, 2009), listed under the "UK List of Priority Species" for the UK Biodiversity Action Plan (UK BAP) (JNCC, 2007) and listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). European eels are also subject to EC Regulation No 1100/2007, establishing measures for the recovery of the stock. Furthermore, it is thought that European eels are panmictic, part of a single breeding population (Als *et al*., 2011). Eels may live in fresh water for many years before they mature and migrate seawards as "silver eels" (Churchward & Shelley, 2004) at the beginning of their spawning migration to the Sargasso Sea. Silver eels may therefore be exposed to MFs associated with MREDs when inhabiting the coastal zone.

Migrating eels tend to leave European rivers in autumn and early winter, and most likely begin migrating to the Sargasso Sea immediately (Aarestrup *et al*., 2009). However, little is known about the behaviour of eels at this time, and for example in the Baltic Sea, eels may occupy the coastal zone for a significant period of time (Aarestrup *et al*., 2008). There are some direct field observations of the migratory behaviour of eels over sub-sea cables. Westerberg & Begout-Anras (2000) observed the orientation of silver eels in the vicinity of a high voltage DC power cable producing a MF of the same order of magnitude as the Earth's geomagnetic field at a distance of 10 m. Of the 25 female silver eels tracked, approximately 60 % crossed the cable and it was concluded that the cable did not act as a barrier to eel migration (Westerberg & Begout-Anras, 2000). In another study, Westerberg & Lagenfelt (2008) used acoustic tracking to study swimming speed of European eels crossing a 130 kV AC power cable in the Baltic Sea. Acoustic receivers were arranged in four curtains to create three intervals, the central interval where the cable was situated, and two adjacent intervals, one each to the north and south of the cable. It was found that the swimming speed of European eels was significantly slower when crossing the cable (i.e. through the central interval) than through the intervals to the north and south of the cable. The electric current in the cable at the time of the experiment varied from 140 to 300 A, although no measurements of MF strength were taken. No details of fish behaviour during passage over the cables were recorded in these studies and it is not known whether the reduction in swimming speed near the AC power cable was due to the MF, or some other factor.

The aim of the present study was to look in detail at the behaviour of European eels at the silver eel stage of their life-cycle when exposed to an AC MF in a controlled laboratory setting. A field intensity near 9.6 µT was used to reflect likely MF strengths eels might be expected to encounter in the vicinity of cabling between generators in developments in the Scottish coastal zone, this value representing an intermediate field strength based on current best estimates (e.g. CMACS, 2003; Gill *et al.*, 2005; Gill & Bartlett, 2010; Olsson *et al.*, 2010).

Materials and Methods

Experimental Animals

The experiment comprised 28 trials carried out in two phases (phase 1: 19 January 2012 to 9 February 2012, *n* = 12 trials; phase 2: 21 August 2012 to 16 October 2012, *n* = 16 trials; Table 1). Wild European eels (*n* = 28) were captured by traps in the Girnock and Baddoch Burns, tributaries of the Aberdeenshire River Dee in Scotland (phase 1: 18 August 2011, *n* = 9 fish; 14 September 2011, *n* = 2 fish; 20 September 2011, *n* = 1 fish; phase 2: 9 August 2012, *n* = 11 fish; 20 August 2012, *n* = 3 fish; 27 August 2012, *n* = 1 fish; 30 August 2012, *n* = 1 fish) and held initially in fresh water (2m diameter tanks) at the Marine Scotland Marine Laboratory, Aberdeen. The eels were then acclimated to full strength sea water by introducing them to 50 %, 75 % and 100 % sea water respectively in daily increments.

Experimental Arena

Trials were conducted in an annular tank (He & Wardle, 1988; Figure 1). In brief, a circular tank (9.78 m internal diameter) containing a central pillar (2.46 m external diameter) created a circular cruising channel 3.66 m wide and containing water to a depth of 0.98 m (Figure 1). To generate MFs, a bespoke system of four sets of Helmholtz coils were fitted in two arrays, each array comprised a pair of coils (nominally AB and CD) (Figure 1). Each pair of coils consisted of two hoops (1 m internal diameter) set facing each other and with 0.5 m between them, mounted within a framework made from grey plastic tubing (2.54 cm nominal bore). The outer surfaces of the framework and parts of the internal framework were covered with black knotless mesh (10 mm mesh size) to create four channels, each 0.5 m long, linking the two halves of the circular cruising channel (Figure 1). The strength of the generated MFs emitted by the coils could be varied and regulated remotely. The shape of the MF generated by a single coil set is shown (Figure 2). The MF diminished to approximately 50% of peak at 30 cm outside each coil face (Figure 2).

An array of four video cameras (two underwater and two overhead; Figure 1) were used to record swimming activity of fish passing through the coils. This configuration of cameras enabled an accurate assessment of when fish swam through the coils and thus through the generated MFs. To aid subsequent analysis, the footage from the four video cameras was multiplexed onto a single screen with a date and time display and recorded directly to the hard disk drive of a DVD recorder.

Experimental Protocol

On the day of each trial, a single eel was introduced to the annular tank at approximately 09:00 hours. At approximately 11:30 hours, overhead red lights were switched on, overhead green lights were switched off, the video cameras were switched on and recording began. Each trial took place between 12:00 and 16:00 hours. This 4-hour trial period was broken down into two, 2-hour periods, each of which was an exposure period during which a MF was presented from either coils A and B or coils C and D as follows. At 12:00 hours, either coils A and B or coils C and D were switched on. At 14:00 hours, the energised coil set was changed i.e. if coils A and B were energised first, coils A and B were switched off and coils C and D were switched on, and *vice versa*. Brief visual checks for activity were made at approximately 13:00 and 15:00 hours. Each trial ended at 16:00 hours when either coils A and B or coils C and D were switched off as appropriate.

The strength of the MF was determined by the input to the coils and was set at 1 V AC for all trials. This resulted in calibrated MF strengths of 9.6, 9.3, 9.8 and 9.8 μT for coils A, B, C and D respectively. Effective operation of coils was verified by measuring current from the voltage regulator and occasionally checking the fields directly between trials (lower and upper quartile values respectively for coils A, B, C and D: coil A: 9.2 and 10.0 μT; coil B: 9.1 and 9.6 μT; coil C: 9.4 and 10.1 μT; and coil D: 9.2 and 10.2 μT; n = 56 in each case).

The order in which coils A and B and coils C and D were energised was randomised such that coils A and B were energised first in 13 trials and coils C and D were energised first in 15 trials (Table 1). At the end of each trial, the eel was removed from the annular tank, killed, and total length (L_T, cm) of each fish was measured (L_T range: 31 to 96 cm, n = 28; Table 1).

Statistical Analysis

Eel activity was defined as the number of passes through a MF generator coil set in a two-hour period. Video footage was used to count the number of passes made by each eel through each coil set in each two-hour period, giving four measures of activity for each eel (Table 1). "Swimmers" were defined as eels that made at least one pass through a coil set, while "non-swimmers" were defined as eels that made no passes through a coil set. Only the data for the swimmers were used in the statistical modelling.

The relationship between eel activity and the explanatory variables was modelled by a generalised linear mixed model (GLMM) assuming a Poisson distribution and a log link. The following explanatory variables were considered:

id	(factor with a level for each fish)
phase	(factor with two levels distinguishing the first batch of eels from the second)
logL_T	(continuous measure of size)
coil	(factor: AB or CD - the coil the eel went through)
active	(factor: whether the coil was active or not)
time	(factor with two levels distinguishing the first two hours of observations from the second - when the active coils were switched)

A 'full' model was first fitted to the data with the following fixed and random effects structure:

Fixed ~ phase + logL_T + coil + active + coil.active + time + time.(phase + logL_T + coil + active + coil.active)

Random ~ id + id.time

This model allowed the number of passes to depend on any of the explanatory variables and allowed any relationship to change when the coils are switched. The model was then simplified in a backwards stepwise procedure based on Wald tests.

Results

Eel activity was highly variable among individuals. During the 4-hour period between 12:00 and 16:00 hours, 16 eels were never observed on video footage. For the other 12 eels, the total amount of time individuals were visible on video footage during this period ranged from 0.2 to 140.4 minutes (0.1 to 58.5 % of the time available). The median amount of time individuals were visible on video footage was 24.2 minutes (10.1 % of the time available) (lower quartile = 5.0 minutes or 2.1 % of the time available, upper quartile = 52.1 minutes or 21.7 % of the time available, n = 12). Of these 12 eels, 10 individuals were "swimmers".

"Swimmers" (n = 10) made between 1 and 43 passes through coils during the 4-hour period between 12:00 and 16:00 hours. These passes were distributed such that between 0 and 19 passes were made through active coils (mean ± S.D. = 5.5 ± 5.9 passes, n = 10; Table 1), and between 0 and 24 passes were made through inactive coils (mean ± S.D. = 5.4 ± 7.1 passes, n = 10; Table 1). No obvious behavioural responses to active coils were noted at any time during trials.

The fitted GLMM provided no evidence of a difference in movement due to the MF (Figure 3). There was strong evidence of a time effect (P = 0.008) with a reduction in movement during the second half of trials (after the active coils were switched). There was also weak but significant evidence of a size effect (P = 0.036; Figure 4) with an increase in movement due to size.

Discussion

Direct field observations have shown a significant reduction in the swimming speed of European eels crossing a 130 kV AC power cable in the Baltic Sea (Westerberg & Lagenfelt, 2008). However, silver eels exposed to an MF of approximately 9.6 μT in a controlled laboratory setting in the present study showed no discernible reaction. For the 10 "swimmers", the number of passes through active coils did not differ significantly from the number of passes through inactive coils. Furthermore, on no occasion was there any observation of unusual behaviour, such as fast-swim startle, near activated coils.

It was notable that eel activity was highly variable among individuals. Out of 28 eels, 16 fish were never visible on video footage, while the other 12 individuals were visible for between 0.1 and 58.5 % of the time available. Additionally, there was a greater propensity for larger fish to swim. It is possible that this relates to differences in the migratory stages of the fish. It is generally accepted that silver eels are more active than yellow eels (Tesch *et al*., 1992). Due to the capture method by which the eels in the present study were obtained, it is possible that some smaller eels not intending to make their migration downstream towards the sea were washed into the trap during times of high flow, as opposed to the larger eels which were destined for the sea.

There was strong evidence of a time effect with a reduction in movement during the second half of trials (when the active coils were switched). It is well documented from behavioural studies under controlled conditions that fish will often take some time to settle into a novel environment (e.g. Armstrong *et al*., 1997; 1999), and it seems likely that such settling behaviour explains why eels tended to reduce their movement over time in the present study. Randomising energisation state among coil pairs and switching state at the mid-point of trials controlled for changes in activity over time. However, in the absence of a comparison with a true control, we cannot say whether eels were discouraged from moving by their possible prior experience of an active coil earlier in the experiment.

It is possible that although eels did not respond to the MF intensity used in the present study, they would do so at higher field strengths. Likely values of MF strengths associated with MREDs reported recently (Olsson *et al*., 2010) are somewhat higher than those reported previously (e.g. CMACS, 2003; Gill *et al*., 2005; Gill & Bartlett, 2010). For example, modelling work of the magnetic field of five different AC power cables (10 - 145 kV, 100 - 500 A) showed a maximum MF of 35 μT immediately above a buried cable (Olsson *et al*., 2010). In the study by Westerberg & Lagenfelt (2008), the decrease in swimming speed of the eels passing over the cable was related to electric current in the cable, which varied from 140 to 300 A over the experimental period. Under the conditions of the lowest current (associated with a weaker magnetic field), swimming speed decrease was not apparent, and it was only at higher currents (associated with a stronger magnetic field) that a reduction in swimming speed was apparent. Although no measurements of magnetic field strength at the time of the study were reported by Westerberg & Lagenfelt (2008), Olsson *et al*. (2010) report the cable to emit a magnetic field of 200 μT at a distance of 1 m from the cable, a much higher field strength than that used in the present study. Furthermore, Bevelhimer *et al*. (2013) demonstrated a behavioural response of lake sturgeon *Acipenser fulvescens* (Rafinesque) to MF, but only above a threshold level of approximately 1000 to 2000 μT. There is hence little evidence to suggest that any species of fish respond to MF at the levels associated with most cabling currently proposed in MREDs.

It is also useful to consider physical effects on MF intensity. MF diminishes with distance from source according to an inverse square relationship. In the present study, the generated MF strength diminished to approximately 50 % of the maximum when 30 cm in front of or behind the coils and a similar effect would be expected around sub-sea cables. For example in relation to a 132 kV cable with an AC of 350 A emitting a MF of 1.6 μT on the surface of the cable and buried at a depth of 1 m, background MF levels are reached within 20 m (CMACS, 2003). Similarly, a maximum magnetic field strength of 35 μT immediately above a cable is reduced to 2.2 μT when 2 m from the cable (Olsson *et al*., 2010). Hence, any effect from high intensity MF will be highly localised and potentially resolved by burial or armouring of the cable. Indeed, while Westerberg & Lagenfelt (2008) noted a reduction in swimming speed of eels crossing a high voltage AC power cable, they too noted that any delay caused by this reduction in swimming speed (approximately 40 minutes on average), seemed unlikely to affect fitness in the context of a 7000 km migration.

From the data that are currently available, it appears that high voltage AC cables may be detected by eels but do not constitute a barrier to migration (Westerberg & Lagenfelt, 2008). In view of the absence of any large behavioural response at 9.6 μT in this study, it is possible that any threshold for a response to MF is higher and hence is likely to be a very localised phenomenon if indeed it exists. However, it must be acknowledged that many of the captive eels used in the present study were largely inactive. This may have indicated that they were unsettled in their environment and hence did not respond in the way that they would have done if unstressed. Furthermore, a power analysis showed that 10 large swimmers would be required to be confident (power > 80 %) of detecting a 50 % reduction in movement (if it existed), and 60 large swimmers would be required to be confident of detecting a 20 % reduction in movement. The relatively low number of swimmers in the present study resulted in low power to detect an effect.

Acknowledgements

We thank J. Godfrey, R. Glover, A. Thorne & R. McDonald for collecting the fish, C. Rycroft for helping to build and install the MF generator coils and B. Williamson, M. Paterson and L. Feehan for helping to install the MF generator coils, fish husbandry and assistance with the experimental work. We are grateful to R. Gardiner, J. MacLean, I. Malcolm, S. Middlemas, J. Gilbey, J. Godfrey and I. Davies for comments and helpful discussions. This work was funded by the Scottish Government.

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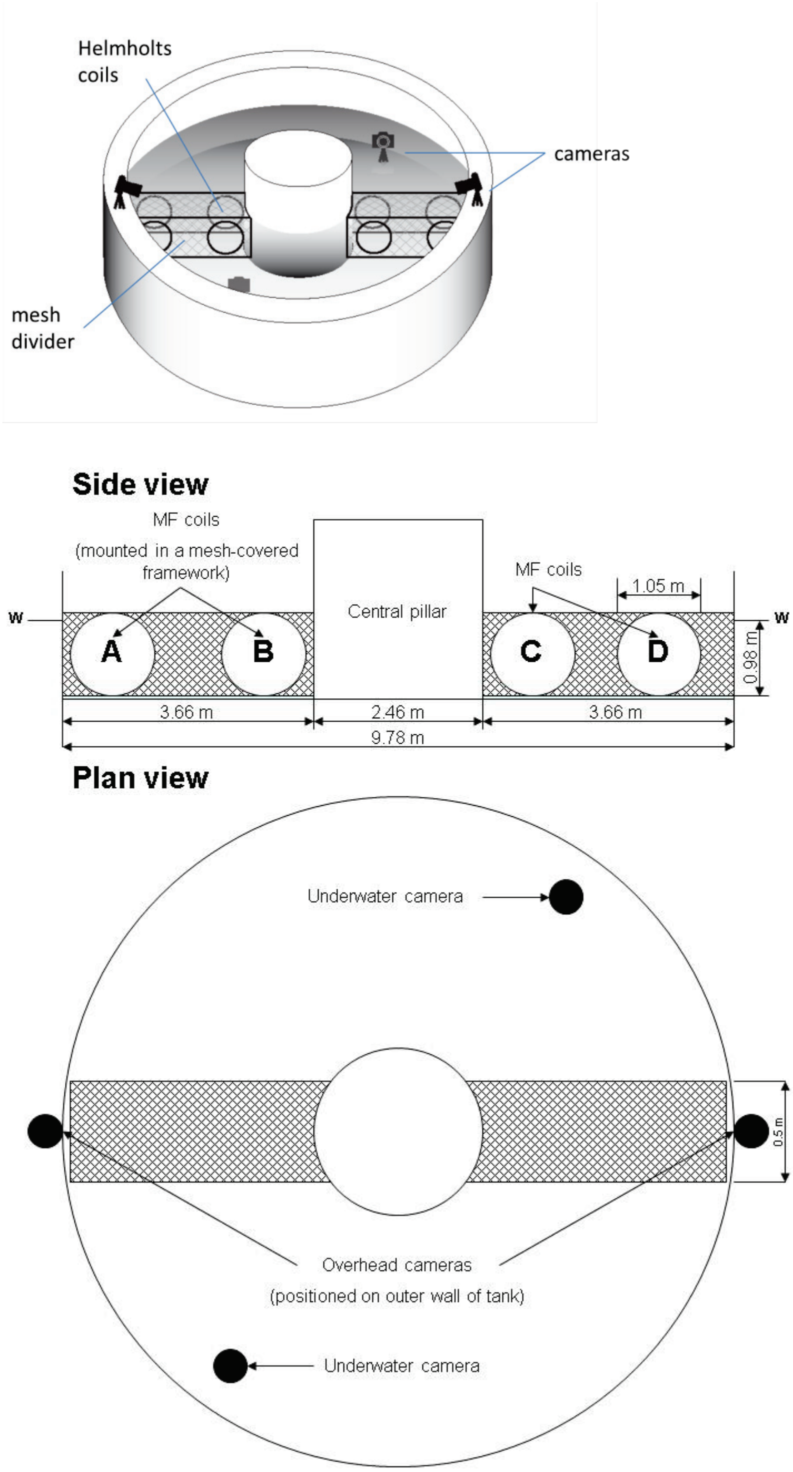

Figure 1 Schematic, side, and plan views of the annular tank in which the experiment took place. The tank was filled to a point just below the top of the mesh-covered framework (to the level marked "W") to ensure fish had to swim through one of the four MF coils in order to move around the tank.

(*a*)

9	15	38		59	10	8	10	59		38	15	9
10	18	29		33	21	18	21	33		29	18	10
10	17	23		27	24	21	24	27		23	17	10
11	15	21		23	23	22	23	23		21	15	11
11	15	20		22	23	23	23	22		20	15	11
11	14	19		22	23	23	23	22		19	14	11
11	15	20		22	23	23	23	22		20	15	11
11	15	21		23	23	22	23	23		21	15	11
10	17	23		27	24	21	24	27		23	17	10
10	18	29		33	21	18	21	33		29	18	10
9	15	38		59	10	8	10	59		38	15	9

(*b*)

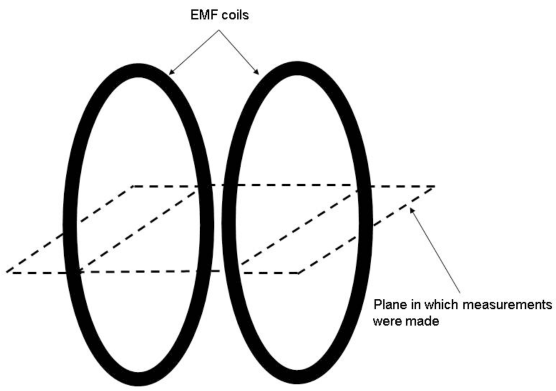

Figure 2 (*a*) Schematic top view of the shape of the MF generated by a single pair of coils. Numbers in squares show the MF strength measured in each 10 x 10 cm grid square relative to the positions of the MF generator coils (black vertical bars). Measurements were made in air and are given in µT using an AC input of 2 V (0.2 A) for calibration purposes at the time of installation. Measurements in (*a*) were made in the plane represented by the dashed lines in (*b*). Note that the MF extended in front of and behind the coils, and that MF strength diminished to approximately 50 % of the maximum when 30 cm in front of or behind the coils.

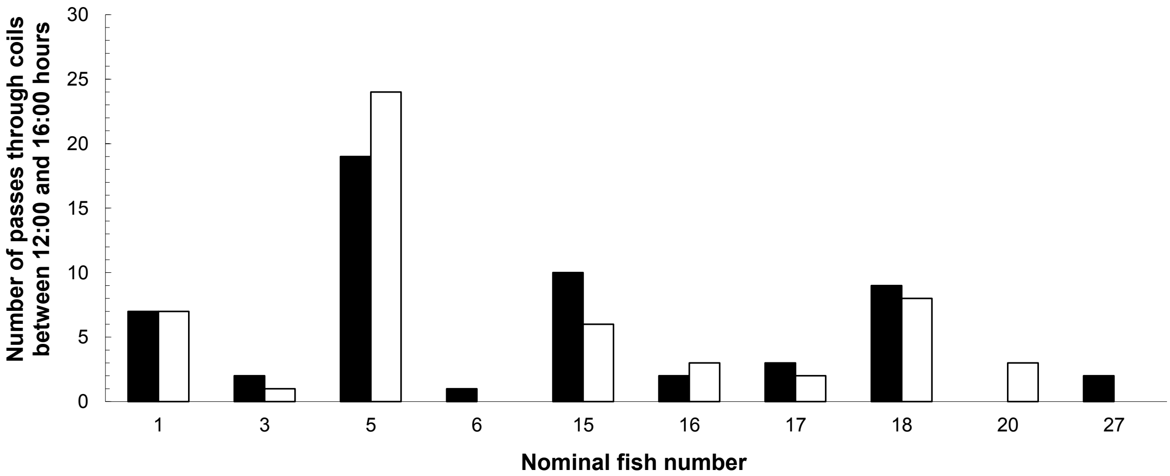

Figure 3 The number of passes made by “swimmers” (n = 10) through coils during the 4-hour period between 12:00 and 16:00 hours according to status of the coils (active ■; inactive □).

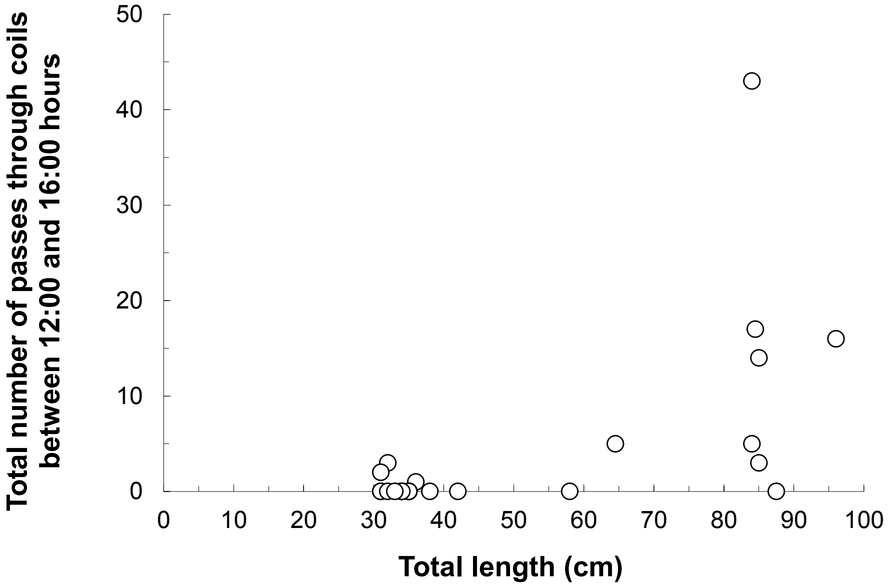

Figure 4 Scatterplot to show the relationship between the total number of passes through coils during the 4-hour period between 12:00 and 16:00 hours and eel size, expressed as total length (L_T, cm).

Table 1 Details of eels used in the experiment. Grey cells relate to non-swimmers.

						Coils A and B		Coils C and D	
Experiment phase	**Nominal fish number**	**Trial date**	**First coils activated**	**L_T (cm)**	**Swimming status**	**Passes when active**	**Passes when inactive**	**Passes when active**	**Passes when inactive**
1	1	19/01/2012	A and B	85	Swimmer	7	0	0	7
1	2	24/01/2012	C and D	58	Non-swimmer	0	0	0	0
1	3	25/01/2012	A and B	85	Swimmer	1	1	1	0
1	4	26/01/2012	C and D	42	Non-swimmer	0	0	0	0
1	5	27/01/2012	A and B	84	Swimmer	19	0	0	24
1	6	30/01/2012	C and D	36	Swimmer	1	0	0	0
1	7	31/01/2012	A and B	34	Non-swimmer	0	0	0	0
1	8	01/02/2012	C and D	31	Non-swimmer	0	0	0	0
1	9	02/02/2012	C and D	38	Non-swimmer	0	0	0	0
1	10	06/02/2012	C and D	35	Non-swimmer	0	0	0	0
1	11	07/02/2012	A and B	35	Non-swimmer	0	0	0	0
1	12	09/02/2012	C and D	35	Non-swimmer	0	0	0	0
2	13	21/08/2012	A and B	31	Non-swimmer	0	0	0	0
2	14	23/08/2012	C and D	34	Non-swimmer	0	0	0	0
2	15	28/08/2012	A and B	96	Swimmer	5	2	5	4
2	16	30/08/2012	C and D	84	Swimmer	0	3	2	0
2	17	04/09/2012	A and B	65	Swimmer	0	0	3	2
2	18	06/09/2012	C and D	85	Swimmer	0	8	9	0
2	19	13/09/2012	A and B	88	Non-swimmer	0	0	0	0
2	20	20/09/2012	C and D	32	Swimmer	0	3	0	0
2	21	26/09/2012	A and B	35	Non-swimmer	0	0	0	0
2	22	27/09/2012	C and D	34	Non-swimmer	0	0	0	0
2	23	02/10/2012	A and B	34	Non-swimmer	0	0	0	0
2	24	04/10/2012	C and D	35	Non-swimmer	0	0	0	0
2	25	08/10/2012	A and B	34	Non-swimmer	0	0	0	0
2	26	09/10/2012	C and D	32	Non-swimmer	0	0	0	0
2	27	10/10/2012	A and B	31	Swimmer	2	0	0	0
2	28	16/10/2012	C and D	33	Non-swimmer	0	0	0	0

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The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-78544-426-5 (web only)

Published by The Scottish Government, September 2015

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS51136 (09/15)