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Pulse trawling: Evaluating its impact on prey detection by small-spotted catshark (*Scyliorhinus canicula*)

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A B S T R A C T

Pulse fishing may pose a promising alternative for diminishing the ecosystem effects of beam trawling. However, concerns about the impact on both target and non-target species still remain, amongst others the possible damage to the electro-receptor organs, the Ampullae of Lorenzini, of elasmobranchs. The current study aimed to examine the role of pulsed direct current (PDC) used in pulse trawls on the electro-detection ability of the small-spotted catshark, *Scyliorhinus canicula*. The electroresponse of the sharks to an artificially created prey-simulating electrical field was tested before and after exposure to the pulsed electrical field used to catch flatfish and shrimp. No statistically significant differences were noted between control and exposed animals, both in terms of the number of sharks exhibiting an electroresponse prior to and following exposure as well as regarding the timing between onset of searching behaviour and biting at the prey simulating dipole. These results indicate that, under the laboratory circumstances as adopted in this study, the small-spotted catshark are still able to detect the bioelectrical field of a prey following exposure to PDC used in pulse trawls. However, to fully grasp the impact of PDC on elasmobranchs, further studies are imperative, including examining the effect on reproduction and young life stages, the longer-term and indirect influences and experiments under field conditions.

1. Introduction

In the North Sea, 90% of all demersal fish, shell and crustacean landings are caught with bottom trawls (STECF, 2014a). However, this type of fishery elicits well-known disadvantages for the ecosystem including consuming high amounts of fuel, disturbing the seabed and producing high discard levels due to poor selectivity (Jennings and Kaiser, 1998; Lindeboom and De Groot, 1998; Kaiser et al., 2000; Paschen et al., 2000; Piet et al., 2000; Depestele et al., 2014, 2015). The landing obligation under the Common Fisheries Policy (CFP) will be implemented stepwise between 2016 and 2019 for the demersal fisheries (STECF, 2014b, 2015). In order to meet the obligations imposed by the CFP and hence increase these fisheries' sustainability, electrical stimulation in fishing gear, beam trawls in particular, is considered a promising alternative resulting in reduced seabed disturbance, by-catch and fuel consumption and an increase in species selectivity (Boonstra and De Groot, 1974; Stewart, 1975; Polet et al., 2005b; Soetaert et al., 2015; van Marlen et al., 2014). Two major types of pulse gears may be discerned creating heterogeneous electrical fields. Firstly, a high frequency, 45–80 Hz, bipolar pulse with a conductor voltage of 45–60 V and pulsewidth of 100–270 μs is used to provoke a cramp reaction in flatfish (Stewart, 1977; de Haan et al., 2016). Secondly, a low frequency, 5 Hz, unipolar pulse with a 60 V conductor voltage and 500 μs pulsewidth induces a tail-flip in shrimps forcing them to jump up out of the seabed (Verschueren and Polet, 2009; Verschueren et al., 2012, 2014). In spite of fishing by means of electricity being prohibited by the EU since 1998, a derogation for the southern North Sea was manifested in 2009 (EU, 1998). Currently, each member state may equip 5% or 10% (the Netherlands) of their beam trawl fleet with pulse gears (EU, 2009, 2013). Consequently, 83 electrotrawlers using the flatfish pulse, targeting in particular sole (*Solea solea*) and plaice (*Pleuronectes platessa*), are operating in the southern North Sea. In addition, 8 ships are equipped with the electrotrawl for catching brown shrimp (*Crangon crangon*) (Pers. comm. Bart Verschueren). In order to provide sufficient basis for dispensing with the standing ban completely and implement this fishing technique on a broad commercial scale, one should clarify possible adverse ecosystem effects in accordance with the principles of the precautionary approach and responsible fishing (FAO, 2011). Despite the spinal injury encountered in cod (de Haan et al., 2008, 2011,

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2016; Rasenberg et al., 2013; van Marlen et al., 2014;), results of various studies substantiate a tentatively positive attitude towards electric fishing in terms of sustainability (Polet et al., 2005a; Smaal and Brummelhuis, 2005; van Marlen et al., 2009; Teal et al., 2014; Desender et al., 2016a, 2016b; Soetaert et al., 2014, 2016; de Haan et al., 2015). However, major gaps in knowledge on the impact of electric fishing still remain. Since 2006 "The international council for the exploration of the sea" (ICES) has urged investigation of the possible effects of pulse trawling on electro sensitive elasmobranchs (sharks, rays and skates) (ICES, 2006a, 2006b). In response to this question, De Haan et al. (2009) exposed dogfishes to the flatfish pulse under laboratory conditions. Only weak responses were noted and no increased mortality, macroscopic lesions nor aberrant feeding behaviour were observed. Despite these reassuring results, this does not demonstrate that the electro-receptor organs, the Ampullae of Lorenzini (AoL) are left undamaged as only dead fish pieces were provided as food. Indeed, benthic elasmobranchs especially rely highly upon their AoL to locate their prey buried in the seabed during the final moments of foraging (Dijkgraaf and Kalmijn, 1966; Kalmijn, 1971; Kajiura et al., 2010). Within close proximity, they can detect weak electric fields produced by living organisms, inanimate objects such as underwater electric cables, temperature gradients or the Earth's magnetic field (Kalmijn, 1972; Paulin, 1995; Gill and Kimber, 2005). In addition, electroreception not only plays a role in prey detection but is also important in courtship and reproduction, predator avoidance, orientation to local inanimate electric fields and possibly geomagnetic navigation (Kalmijn, 1978; Tricas et al., 1995; Tricas and Sisneros, 2004). The above leads to the research hypothesis that electric signals generated by the pulse trawl may affect the AoL, hence impacting the elasmobranch's individual fitness. Therefore, the intention of the current study was to assess the effects of electrical pulses, used in both flatfish and shrimp electrotrawling, on the functioning of the highly sensitive AoL. Small-spotted catsharks, formerly named lesser spotted dogfish (*Scyliorhinus canicula*), were employed as a representative for benthic electro sensitive elasmobranchs. For that purpose, the response towards an artificially created electrical field, mimicking the bioelectric field emitted by their prey, was observed prior to and following exposure to the electric field generated by an electrotrawl.

2. Materials and methods

2.1. Animals and housing

Fifty-three small-spotted catsharks were collected with beam trawls in the English Channel during commercial fishing practices and transported to the Institute of Agricultural and Fisheries Research (ILVO) in Ostend, Belgium. Eleven males and 42 females (52 ± 7 cm total length) were acclimatized for a minimum of three weeks in a 4200 L rectangular holding tank ($140 \times 600 \times 60$ cm) filled with aerated natural seawater and supplied with a mechanical and biological filter system. With regard to the water quality, the following values were recorded: 16 °C temperature; 34‰ salinity; 8 pH; 7.5 dH; <25 mg/L nitrate, <0.2 mg/L nitrite, <0.1 mg/L ammonia. The photoperiod matched natural conditions. During the acclimatization period, each fish was fed twice a week with 20 g (3% body weight) chopped whiting, herring, squids, shrimps or flatfish. The experimental protocol was approved by the ethical committee of ILVO (ID: 2012/171).

Seven 360 L polyethylene behavioural arenas ($110 \times 70 \times 60$ cm) supplied with natural sea water were utilized. The tanks were arranged serially and connected to one trickling filter, with animals not being able to move between aquaria. Individuals were housed in 9 mixed sex (one male, two females), 8 single sex groups of three females and one group with two males. Three different colors of floy-tags, inserted cranially to the first dorsal fin, enabled individual identification on subsequent video recordings. Prior to an experimental trial, an additional acclimatization period of one week was imposed following fish transfer, during which food was withheld. Thereafter, food rations were reduced to 13 g (2% of bodyweight) per week during the experimental trials.

2.2. Experimental design

Each experimental trial was divided into two periods as described below (Fig. 1). During the first period, the fish was allowed to acclimatize to the introduction of an acrylic plate (Fig. 2) connected to an electrical prey simulator whereby the food response (consumption of food) was observed during four consecutive days. Thereafter, the animals were deprived of food for two days, after which the second period started with the recording of the elicited electroresponse (biting towards the prey dipole electrical field). That same day the animal was exposed to an electrical field used to catch shrimp or flatfish at sea (Fig. 3). Following exposure, the electroresponse towards the prey simulator was again determined in its original behavioural arena during three consecutive days, with the first testing performed between 15 and 24 h following exposure to the trawl electrical field.

Period 1: food response prior to exposure to the electrical pulses.

After unplugging of all pumps and electrical devices in and around the tanks to eliminate background electrical fields, the acrylic plate connected to the prey simulating device was introduced. Five minutes following the introduction of the apparatus, the video camera was activated and one dipole was turned on, followed by the introduction of 1.3 g of chopped herring or whiting presented onto the active dipole. Once the food was consumed, the prey simulator was turned off. Once again, the simulator was switched on and off upon the provision and consumption of a new portion of food, respectively. This process was repeated until each individual received a maximum of 2.6 g of herring or whiting per day, or after ten minutes following the introduction of the food, the latter being the case if the animals did not exhibit a feeding response. Following, the unconsumed food was removed and the video camera and prey simulator were turned off and moved to the next randomly chosen experimental arena. Behavioural observations included i) the reaction time between food introduction and initiation of foraging behaviour, characterized by increased swimming activity and S-shaped turning close to the bottom (Kajiura and Holland, 2002; Kimber et al., 2009), and ii) the time to first feeding. These parameters were recorded during four consecutive days for each individual. The difference between these two parameters provided the delay time to elicit a bite response towards the provided food.

Period 2: exposure to the electrical pulse field and electroresponse.

The second period was initiated with the testing of the electroresponse of each individual towards the prey simulating dipole. For that purpose, the experimental procedure as described above was repeated, except that when the dipole was turned on, the foraging behaviour was invoked by the introduction of 20 mL of whiting juice through the odour delivery tube and no food was introduced. Once a particular shark had bitten at the prey simulating dipole, the dipole was turned off. The dipole electrical stimulus was turned on again when another shark entered the activity zone (10 cm radius circles centered around the dipole (Kimber et al., 2009)). The reaction time following scent introduction to exhibit food searching behaviour and to bite towards the dipole, were determined. The difference between these two parameters resulted in the delay time to bite towards the prey stimulus. Behaviour was monitored until all animals of one group had bitten the prey simulating electrode or ten minutes after the introduction of food derived scent should no bite response towards the dipole have occurred. Before moving the videocamera and prey simulator to the next randomly chosen arena, each shark received 2.6 g of chopped whiting or herring presented on the active dipole.

Following the evaluation of the first electroresponse for all sharks during one experimental trial, the animals were individually transferred to a treatment tank of 300 L ($110 \times 70 \times 45$ cm) where they were subsequently exposed to an electrical pulse field used to catch brown shrimp or flatfish. Sharks were orientated perpendicularly between

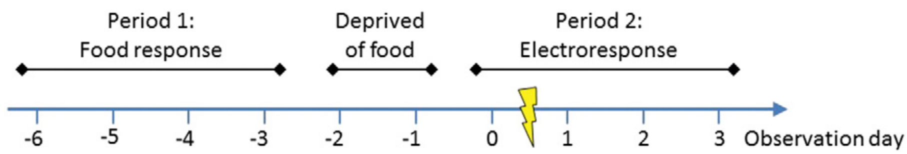

Fig. 1. Overview of an experimental trial divided in two periods wherein the food and electroresponse are recorded during four consecutive observation days. Exposure to a pulse trawl electrical field took place on day 0.

two electrodes, opposite the middle of the conducting elements, during exposure. They were positioned in a polyethylene netting (58 cm, 15 cm diameter, 1 cm^2 mesh size) with a cylindrical profile. Following transfer to the treatment tank, the pulse trawl generator was directly switched on during an exposure period of 5 s. The behaviour during exposure was observed.

In total 15 sharks were randomly exposed to the pulse to catch brown shrimp and 8 to the flatfish pulse. In addition, 30 controls were included and treated similarly, except for the exposure to the electrical field. After the exposure, the animal was released back in its original behavioural arena.

The following three consecutive days the electro response towards a prey stimulus subsequent to the scent introduction was observed as described above. The delay time to bite towards the dipole was calculated by subtracting the time following scent introduction to display food searching behaviour from the time to first bite towards the dipole.

2.3. Experimental equipment

2.3.1. The prey simulator

A 9 V battery-powered generator (Kajiura and Holland, 2002) was employed to deliver a direct current (DC) prey simulating electric field. The stimulus source supplied current (9 μA) via an underwater cable tightly sealed onto two seawater filled aquarium tubes (50 cm length, 3 mm internal diameter). The open ends of these salt bridges were attached through pre-drilled holes on a transparent acrylic plate (100 × 50 × 0.5 cm). The holes were spaced 1 cm apart, creating a dipole electric field that mimicked the size of naturally occurring prey. The acrylic plate was equipped with two dipoles, with the dipole centers spaced 35 cm apart (Fig. 2). A multimeter in series enabled monitoring of the current being applied between the electrodes of the active dipole. During each trial, only one of the dipoles was energized while the other dipole functioned as a control. An odour delivery polyethylene tube was also inserted into the center of one half of the acrylic plate from below, at 17.5 cm distance from both dipoles (Fig. 2). A syringe was used to introduce an odourant into the water surrounding the electrode array. The food derived scent consisted of a 20 mL seawater solution containing sieved whiting and squid rinse. The odour stimulus was required to invoke foraging behaviour and attract the sharks towards the electrical dipole. All tubing and connectors were shielded underneath the acrylic plate. Bricks arranged around the edges of the base prevented the acrylic plate from floating. The equipment was easily transferred between the seven experimental arenas wherein the dipole was randomly positioned.

2.3.2. Generating the shrimp and flatfish pulse trawl electrical field

To generate the same heterogeneous pulsed DC electrical field used to catch brown shrimp at sea, the exposure aquarium was equipped with two 50 cm long threadlike electrodes of 1.2 cm diameter, placed on the bottom of the aquarium (Fig. 3,A). Each electrode had a diameter of 12 mm and was composed of six stainless steel strands on the outside and a central solid copper strand inside. These conductors were placed in parallel at a distance of 65 cm and were electrically connected with an adjustable laboratory pulse generator (LPG, EPLG bvba, Belgium). Pulse parameter settings in the LPG were characterized by a unipolar square pulse shape and pulse duration of 500 μs generated at a frequency of 5 Hz, consequently building up an electrical pulse field with an interval of 200 ms. The applied voltage to the electrodes had a constant amplitude of 60 V (Verschueren and Polet, 2009, Verschueren et al., 2012).

To simulate the heterogeneous electrical field used to catch flatfish, two electrodes of 96 cm were adopted (de Haan et al., 2009). Each electrode was implemented with two conductors of 18 cm (32 mm diameter) with an isolated extension of 60 cm between both (Fig. 3,B). The

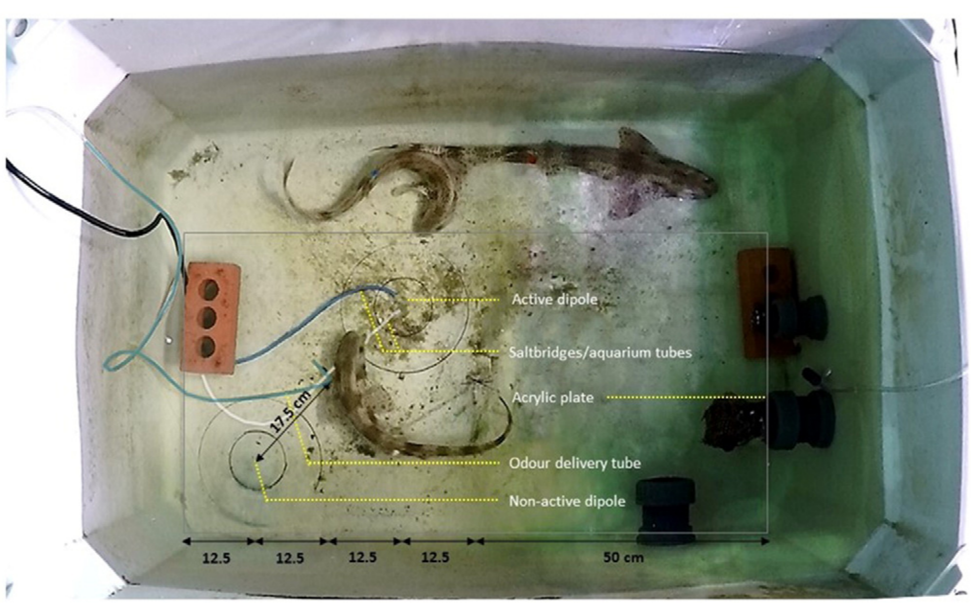

Fig. 2. Acrylic plate (100 × 50 cm) equipped with two dipoles spaced 35 cm from each other with the odour delivery tube attached in the middle between them at 17.5 cm from both dipoles.

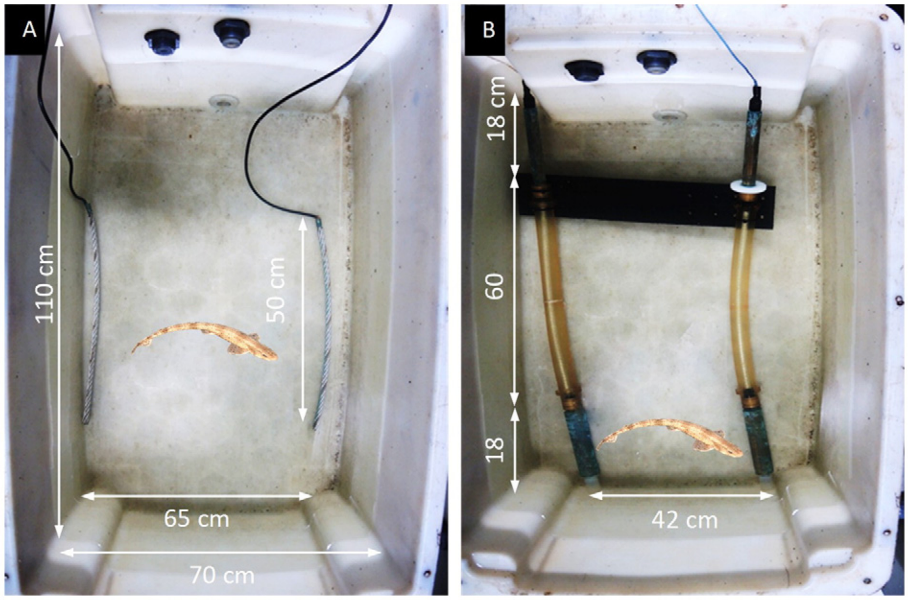

Fig. 3. A) Two 50 cm long electrodes spaced 65 cm apart used in electrotrawling for brown shrimp B) Two electrodes spaced 42 cm apart used to catch flatfish. Each electrode was implemented with two conductors of 18 cm and an isolated extension of 60 cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distance between electrodes was set to 42 cm. Pulse parameter settings generated in the LPG were characterized by a bipolar square pulse shape and pulse duration of 250 μs generated at a frequency of 80 Hz. The applied voltage to the electrodes had a constant amplitude of 60 V (Soetaert et al., 2016).

Pulse characteristics were closely monitored using a Tektronix® Oscilloscope type TDS 1001B.

2.4. Data analysis

A generalized linear mixed model (glmer function in R3.2.2, R Foundation for Statistical Computing, Vienna, Austria) was fitted to the data using treatment (control or exposed to shrimp or flatfish pulse), time and their interaction as categorical fixed effects and the animal as random effect. A binomial distribution with a logit-link function was used to compare the presence or absence of a food or electroresponse between control and exposed individuals during period one and two respectively. The differences in the evolution of the response before and after exposure between control and exposed were tested using a post-hoc linear contrast. Kaplan Meier plots were generated to visualize the electroresponse following exposure.

The delay time to bite towards the food or towards a prey simulating electric field was analysed with a similar linear-mixed effects model. The differences in the evolution of the delayed time to bite before and after exposure between control and exposed were tested using a post-hoc linear contrast. The analysed data were considered sufficiently normally distributed, based on the graphical evaluation (histogram and QQ-plot) of the residuals.

3. Results

No dead fish nor macroscopic injuries were observed throughout the whole experimental trial.

Representative data regarding food and electro response for period 1 and 2, respectively, are listed in Table 1.

Period 1: food response prior to the exposure to the electrical pulses.

Not all individuals exhibited searching behaviour following the introduction of food. Indeed, 6 days prior to exposure only 62% (31/50) commenced foraging and consequently took the food presented on the active dipole (Table 1). Three days before exposure, this number had increased to 71% (38/53). Over the four day observation period: 4 animals never ate, 6, 10 and 11 individuals consumed food on one, two or three days, respectively and 22 animals displayed a food response every day. Searching behaviour started 99 ± 121 s after the food was provided. The delay time to elicit a bite response towards the provided food over the four day observation period prior to exposure to electrical pulses was 79 ± 94 s (Fig. 4).

Period 2: exposure to the electrical pulse field and electroresponse.

Following two days of feed deprivation and before exposure to the electrical pulse field, the electroresponse amounted to 77%, whereby

Table 1
Data on the activity and food—or electroresponse behaviour. The treatment was given after testing of the first electroresponse on day 0. (C = control; S = exposure to the 5 Hz shrimp pulse; F = exposure to the 80 Hz flatfish pulse.)

				Food response													
				Day −6				Day −5				Day −4				Day −3	
Treatment	Length (cm)	Maximum # of animals	# Female	# Animals	# Active	# Bite	Delay time (s)	# Animals	# Active	# Bite	Delay time (s)	# Animals	# Active	# Bite	Delay time (s)	# Animals	# Active
C	51.5 ±7.2	30	24	27	15	15	81 ±93	30	18	17	48 ±46	30	22	22	74 ±81	30	25
S	54.2 ±5.9	15	12	15	12	12	63 ±54	15	15	14	137 ±109	15	13	12	96 ±113	15	11
F	51.8 ±7.9	8	6	8	4	4	88 ±143	8	7	7	56 ±80	8	5	5	58 ±32	8	5
Total	52.3 ±6.9	53	42	50	31	31	75 ±85	53	40	38	80 ±88	53	40	39	79 ±88	53	41

41 out of 53 individuals bit the prey stimulus (Table 1). Initiation of searching behaviour started at 57 ± 71 s following scent introduction and the delay time to bite towards the dipole electrical field was 105 ± 111 s (Table 1; Fig. 4).

During the exposure to both the shrimp as well as the flatfish pulse, all sharks displayed a cramp reaction which made the fish motionless during the 5 s pulse period. Simultaneously, the eyes closed. The control animals displayed active swimming behaviour in the net. On day one after exposure, following the introduction of a food-derived scent, an electroresponse was demonstrated in 66% (20/30), 73% (11/15) and 88% (7/8) of control and shrimp or flatfish exposed fish, respectively (Table 1; Fig. 5). Three days after treatment, 80% (24/30) of control animals and 87% (13/15) and 88% (7/8) of animals being exposed to the shrimp and flatfish pulse, respectively, bite at least once towards the prey simulating dipole (Fig. 5). Eight out of the nine sharks that never elicited an electro response following treatment (ID nr. 9, 11, 12, 29, 39, 45, 47, 52) did not display food searching behaviour (Table 2). The three not biting exposed animals (ID nr. 9, 11, 47) also exhibited a poor food response before treatment. Indeed, one animal came to feed two times and 2 sharks fed only once over the whole monitoring period. One control treatment shark (ID nr. 33) demonstrated food searching behaviour but did not bite. This behaviour, displaying food searching behaviour but not biting at the dipole, was sporadically observed sixteen times during the whole monitoring period in 10 controls and 5 exposed animals (ID nr. 1, 11, 24, 25, 15, 17, 30, 33, 36, 38, 41, 46, 48, 51, 52) (Table 2). No significant change of abnormal food or electroresponse behaviour could be distinguished in shrimp ($p = 0.222$) or flatfish pulsed ($p = 0.925$) animals compared to their control groups before or after exposure. The second, not active control dipole was never bitten. The reaction time between scent introduction and initiation of foraging behaviour was 68 ± 87 s. The delay time to bite between onset of foraging behaviour and the actual bite towards the simulated prey totalled on average 114 ± 102 s over the three day observation period after treatment and was not significantly influenced by being exposed to the shrimp ($p = 0.1315$) or flatfish pulse ($p = 0.0998$) relative to the control groups before or after exposure (Fig. 4).

4. Discussion

Elasmobranchs are affected by high bycatch rates and tend to exhibit a K-selected life history strategy which makes them especially vulnerable (White et al., 2012). They have become a focus for marine conservation action due to fishery driven global declines in many elasmobranch populations (Molina and Cooke, 2012; Jordan et al., 2013; Kynoch et al., 2015). Therefore, disturbing individual fish may have a serious impact on population levels and consequently top down effects through trophic cascades (Baum and Worm, 2009). There is a growing concern that these vulnerable fish may be affected by increasing occurrences of anthropogenic electric sources in many of the world's coastal, benthic habitats (Gill and Kimber, 2005; Normandeau et al., 2011). In response to questions put forward by ICES regarding the effect of pulse stimulation in commercial beam trawling on components of the marine ecosystem,

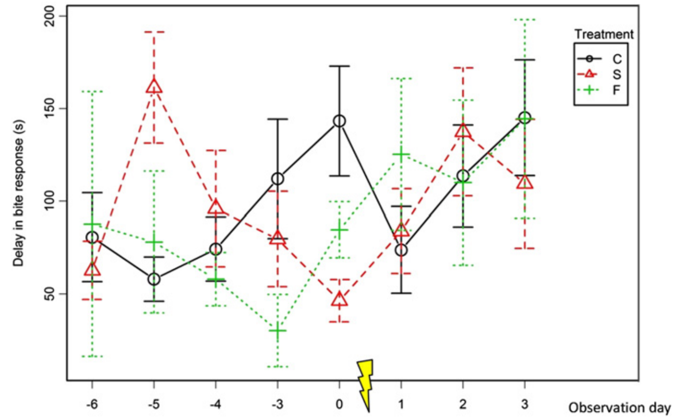

Fig. 4. The delayed time to elicit a bite response towards a food source or towards a prey simulated dipole for responding control (=C) and responding exposed (S = 5 Hz shrimp pulse; F = 80 Hz flatfish pulse) sharks per day. The treatment was given on day 0, after testing of the electroresponse.

the present study was conducted. These engendered data, as well as the results from the study undertaken by de Haan et al. (2009), did not reveal macroscopic injuries nor death as a result of exposure to the electrical pulse fields. The research group of de Haan et al. (2009) additionally did not note aberrant feeding behaviour in the 14 d observation period following exposure to the flatfish pulse. However, it needs to be kept in mind that in captivity sharks may easily find their daily chopped meal in the clean survival tanks without having to resort to their electro sensitive AoL. This is not the case in their natural habitat where these fish fully depend on their electro sensitive organs to detect the electrical field surrounding the prey burrowed in the seabed (Tricas and Sisneros, 2004). To our knowledge, this is the first study to examine the impact of PDC used in pulse trawls on the electro-detection ability of an elasmobranch. Small spotted catsharks were used as a model organism in the current study. Although this species encompasses rather robust animals with less conservation issues, sensitivity to electrical field strengths may be regarded as similar across species (Kajiura and Holland, 2002; McGowan and Kajiura, 2009; Jordan et al., 2011; Jordan et al., 2013). In addition, coastal species and those feeding on benthic prey, such as *S. canicula*, are most likely to rely heavily on the electrosensory system, warranting their inclusion as a model species in the current study (Tricas and Sisneros, 2004; Kajiura et al., 2010).

In our study, no statistically significant differences were noted between control and exposed animals, both in terms of number of sharks exhibiting an electroresponse to the dipoles prior to and following exposure, as well as regarding the delay time to bite to the prey simulating dipole. Nine animals, that is 6 controls (20%), 2 (13%) shrimp - and 1 (13%) flatfish pulsed, never bit the dipole electrical field after treatment, with 8 of these sharks not displaying active food searching behaviour. These animals laid on the bottom of the tank and did not move during the 10 min behavioural recordings. As a result, they did not encounter

Food response		Electroresponse															
Day −3		Day 0				Day 1				Day 2				Day 3			
# Bite	Delay time (s)	# Animals	# Active	# Bite	Delay time (s)	# Animals	# Active	# Bite	Delay time (s)	# Animals	# Active	# Bite	Delay time	# Animals	# Active	# Bite	Delay time (s)
22	97 ±139	30	24	21	143 ±139	30	22	20	74 ±105	30	17	15	119 ±111	23	12	12	145 ±108
11	65 ±76	15	14	12	47 ±34	15	11	11	84 ±76	15	12	12	126 ±116	8	7	7	109 ±92
5	30 ±44	8	8	8	85 ±43	8	7	7	65 ±108	8	6	5	110 ±100	8	5	4	144 ±107
38	80 ±116	53	46	41	105 ±111	53	40	38	86 ±97	53	35	32	120 ±108	39	24	23	134 ±100

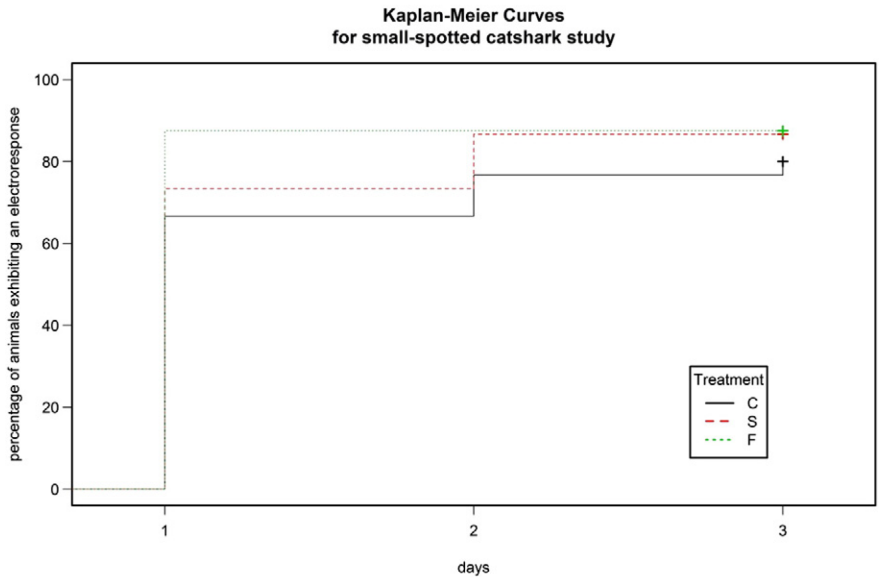

Fig. 5. Kaplan–Meier survival plot representing the percentage of animals exhibiting an electroresponse after one, two and three days following treatment. C = control; S = exposure to the 5 Hz shrimp pulse; F = exposure to the 80 Hz flatfish pulse.

the DC dipole fields. Up to 25% of non-responding sharks were encountered in other studies as well (Filer et al., 2008). This urges us to speculate that the failure to initiate a bite response may therefore not be rooted in the inability to detect the stimulus but because sharks were not hungry enough to be motivated to search for food. As motivational state changes between feeding, fasting, and refeeding, the best response, 77%, was noticed on day 0. This is the day following two days of food deprivation and before exposure to the electrical pulse field. The lowest response, 58%, was observed on day 3 after exposure to the electrical pulse field, the last day of the trial when the sharks had been fed on the preceding days.

In the present study only a single type of prey simulating electrical stimulus was tested. Sharks are able to detect and respond towards a variety of electrical fields such as fields of conspecifics to find a suitable mate (Tricas et al., 1995), prey (Kalmijn, 1972, Bedore and Kajiura, 2013), and predators (Sisneros et al., 1998; Kempster et al., 2013). They are also suspected to be able to detect electric fields induced by their movement with respect to the earth's magnetic field (Kalmijn, 1974, 2000; Paulin, 1995) and geomagnetic anomalies (Klimley, 1993; Montgomery and Walker, 2001). The prey-simulating electrical field chosen for the experiment is within the range shown to be attractive to catshark and comparable to those produced by a variety of species commonly found in their opportunistic diet (Kalmijn, 1971, 1972; Kajiura and Holland, 2002; Filer et al., 2008; Kimber et al., 2009, 2011, 2013). Different species emit varying and complex DC and AC bioelectrical fields. Prey-type DC electric fields have a magnitude of, e.g. 39 μV up to 500 μV for teleosts or up to 50 μV for crustaceans (Kalmijn, 1972; Bedore and Kajiura, 2013). According to Kalmijn (1972) and Haine et al. (2001), but in contrast with Bedore and Kajiura (2013) each species' field increases in strength with increasing specimen size. Furthermore if

Table 2
Individual data on the activity and food- or electroresponse behaviour. (NT = not tested; Red = absence of an electroresponse; Yellow = active food searching behaviour present but food or electro-response absent; C = control; S = exposure to the 5 Hz shrimp pulse; F = exposure to the 80 Hz flatfish pulse.)

			Food response																Electroresponse								
			Day -6			Day -5			Day -4			Day -3			Day 0				Day 1			Day 2			Day 3		
ID	length; cm	Sex	Active = 1	Bite = 1	Delay time (s)	Active = 1	Bite = 1	Delay time (s)	Active = 1	Bite= 1	Delay time (s)	Active = 1	Bite = 1	Delay time (s)	Active = 1	Bite = 1	Delay time (s)	REATM.	Active = 1	Bite = 1	Delay time (s)	Active = 1	Bite = 1	Delay time (s)	Active = 1	Bite = 1	Delay time (s)
1	55	F	0	0		1	1	71	0	0		1	0		1	1	9	C	0	0		1	1	28	NT	NT	NT
9	51	M	0	0		1	1	229	0	0		0	0		1	1	34	S	0	0		0	0		NT	NT	NT
11	58	F	0	0		1	0		0	0		0	0		1	1	69	S	0	0		0	0		NT	NT	NT
12	59	F	NT	NT	NT	1	1	NT	1	1	55	0	0		1	1	30	C	0	0		0	0		NT	NT	NT
24	50	F	1	1	24	1	1	28	1	1	16	1	1	12	1	1	33	C	1	1	210	1	0		1	1	238
25	56	F	1	1	54	1	1	45	1	1	23	1	1	5	1	1	41	C	1	1	196	1	0		0	0	
15	56	F	1	1	8	1	1	NT	1	1	96	1	1	199	1	0		S	1	1	164	1	1	244	0	0	
17	56	F	1	1	71	1	1	NT	0	0		1	1	20	1	0		C	1	1	3	0	0		0	0	
29	59	F	0	0		0	0		0	0		0	0		0	0		C	0	0		0	0		0	0	
30	65	F	1	1	26	1	1	30	1	0		1	1	NT	1	1	66	S	1	1	115	1	1	131	1	1	197
33	52	F	1	1	12	1	1	79	1	1	32	1	1	34	1	1	95	C	1	0		0	0		0	0	
36	47	F	0	0		1	1	NT	1	1	53	1	1	16	1	1	77	F	1	1	77	1	0		1	1	302
38	47	F	1	1	367	1	1	NT	1	1	158	1	0		1	1	111	C	1	0		0	0		1	1	394
39	66	F	0	0		0	0		0	0		0	0		0	0		C	0	0		0	0		0	0	
41	43	M	0	0		1	1	207	1	1	90	0	0		1	1	75	F	1	1	358	1	1	228	1	0	
45	48	M	1	1	185	0	0		1	1	6	1	1	305	1	1	9	C	0	0		0	0		0	0	
46	55	F	0	0		0	0		1	1	134	1	1	298	1	0		C	1	1	67	1	1	54	1	1	31
47	60	F	0	0		0	0		0	0		0	0		1	1	27	F	0	0		0	0		0	0	
48	39	M	0	0		0	0		1	1	341	1	1	10	1	0		C	1	1	4	1	1	116	1	1	161
51	60	F	0	0		1	0		1	1	199	1	1	15	1	1	273	C	1	1	428	0	0		1	1	139
52	39	F	0	0		0	0		1	1	41	1	0		0	0		C	0	0		0	0		0	0	

an organism is injured, the DC electrical field may dramatically rise up to >1250 μV for crustaceans (Kalmijn, 1972, 1974). Small-spotted catsharks attracted to fields around 0.1–1.5 μV cm^{-1} (Yano et al., 2000; Tricas, 2001; Kimber et al., 2011) and detection thresholds up to 5–20 nV cm^{-1} were observed (Dijkgraaf and Kalmijn, 1966; Peters and Evers, 1985; Tricas and New, 1998; Peters et al., 2007). These animals are able to distinguish different types of electrical fields with a clear preference for higher magnitude electrical fields of 9 or 90 μA compared to 0.9 μA (Kimber et al., 2011). However, when the current would increase much beyond 100 μA (Kraus and Fleisch, 1999) or when electrical fields of 4–10 μV cm^{-1} would be presented, catsharks are expected to avoid these fields (Gill and Taylor, 2001; Gill et al., 2014). As catsharks seem to be unable to discriminate between or show no preference for artificial and natural fields of a similar magnitude (Kimber et al., 2011), this may have implications when considering possible interactions with anthropogenic electrical fields such as underwater power cables (Gill and Taylor, 2001) or indeed pulse trawls. The latter should theoretically repel elasmobranchs away rather than attract them as the electrical field of an electrotrawl is at least 30 V m^{-1} when measured in the middle of two electrodes. This is at least 10,000 times higher than the 10 μV cm^{-1} that causes avoidance behaviour in sharks. According to Gill and Taylor (2001), an external uniform field of 1000 μV m^{-1} is reduced to 1 μV m^{-1} over a distance of 100 m. However, as the high frequency (45–80 Hz) electric field of the pulse trawl used to catch flatfish is outside the detection limits of electroreceptive organisms (<16 Hz) (Kalmijn, 1972; Tricas and New, 1998) only the low frequency (5 Hz) pulse trawl used to chase brown shrimp might be detectable by elasmobranchs. In the supposition that sharks, skates or rays sense this pulse trawl and in case it may be assumed that this results in avoidance behaviour, one might speculate that bycatch rates of elasmobranchs hence may be reduced. However, small spotted catsharks may be incapable of out-swimming an on-coming bottom trawl (Kynoch et al., 2015). That is almost certainly the case for skates that often bury into the seafloor. In case no avoidance behaviour is manifested in field situations and the dogfish consequently get caught in the electrical field of the pulse trawl, the animals may become entangled in the top panel of the pulse trawl. Indeed, a common behavioural response following exposure was to accelerate upwards when exposed <0.1 m distance from an electrode used in flatfish pulse trawling (de Haan et al., 2009). By-catch data of beam and pulse trawls might give more information on possible escape behaviour of elasmobranchs and rectify or disprove the above.

With regard to assessing the impact of electrical pulses on elasmobranchs, in addition to investigating the effect on the AoL, various other items need to be addressed. The research group of de Haan et al. (2008) observed that all exposed groups produced eggs in a period of 7 months following exposure. However, effects of pulse trawling on the reproduction and development of younger life stages remain uncertain. Furthermore, no long term studies have yet been conducted nor have possible other side-effects not measured in the present study such as stress, immune system impairment or behavioural alterations been examined. In addition, one needs to keep in mind that the current study was conducted under laboratory conditions which do not take into account the variable and dynamic character of the marine environment in which various parameters may change quickly at a specific site within a short time period. This renders field experiments imperative in which, as stated above, by-catch data for elasmobranchs are collected and behavioural alterations monitored.

5. Conclusion

The present study is the first to tackle the possible adverse effects of electrotrawls on vulnerable elasmobranchs and their electrosense organ involved in prey detection. Under the circumstances as adopted in this study, no altered foraging behaviour towards an electrically simulated prey was observed following exposure towards an electrical field used in shrimp and flatfish electrotrawls.

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