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Can sawfish bycatch within the Northern Prawn Fishery be mitigated using an electric field?

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Acknowledgments

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Executive Summary

This project aimed to test the effect of electric fields on sawfish behaviour and to assess the potential for electric pulses to mitigate sawfish bycatch in prawn fisheries. The project was developed in collaboration with the Northern Prawn Fishery Industry Projects Manager Adrianne Laird and Dr Peter Kyne, principal investigator of National Environmental Research Programme/National Environmental Science Program Marine Biodiversity Hubs projects specialised in Northern Australia threatened species, including sawfishes.

Sawfishes are among the most threatened family of marine fishes and are particularly vulnerable to incidental capture in trawl and gillnet fisheries. In northern Australia, their distribution range overlaps with that of several commercial fisheries, including the Northern Prawn Fishery. Given the inefficiency of current bycatch reduction devices in reducing sawfish bycatch, there is a pressing need to develop new approaches to minimise sawfish interactions with fishing gear. Ideally, those would involve mechanisms that prevent contact with the fishing gear, i.e. that affect the behaviour of sawfish, preventing them from entering the nets, without affecting catches of target species.

Elasmobranchs (sharks and rays) have the ability to detect minute electromagnetic fields using highly sensitive electroreceptors. This sensory capability has been used to develop repellent technologies and the use of electric fields has been proposed as the method with the highest potential to reduce sawfish bycatch. The present project was developed to test the effect of electric fields on sawfish behaviour, to determine if a strong electric field can overwhelm their electrosensory system and dissuade them from approaching its source and/or elicit a fleeing behaviour. If successful, this technology could be incorporated into a device and attached to commercial fishing nets to reduce sawfish bycatch.

The project consisted of tank experiments conducted at the Biopixel/James Cook University Aquarium facilities in Cairns (Queensland). The experimental tank was 4.6 × 6.0 m and had a 1200 L capacity. The apparatus that produced the electric field consisted of two 40 cm long electrodes suspended in-line and 112 cm apart, halfway through the water column. This setup was placed perpendicular to and against one side of the tank, across the swimming path of sawfish, and was connected to a laboratorial pulse generator by power leads. The generator used produces electrical pulse stimuli and allows the user to independently adjust the different pulse parameters including voltage, frequency, pulse duration, and pulse shape. Sawfish were subjected to electric pulses with different waveform characteristics, and to a control treatment with no electric pulse produced. The initial selection of the waveform parameters was guided by the electric field characteristics of commercially available products, which are personal shark deterrents previously shown to affect shark behaviour. This resulted in the selection of a ‘Baseline’ waveform that seemed to best deter sawfish based on preliminary observations. Sawfish behaviour was tested in presence of the ‘Baseline’ pulse stimulus and five variations of that pulse, where only one parameter (polarity, voltage, frequency, pulse shape, pulse duration) was changed at the time to identify which change in pulse characteristics is most likely to improve the deterrent effect. Two Largetooth Sawfish individuals were tested, a 1.02 m (sawfish 1) and a 1.65 m (sawfish 2) total length, both males. Experiments were recorded with a video camera placed above the tank, and sawfish behaviour was coded using an event-logging software coupled with direct observations. Recorded behaviours included activity (swimming/resting), direction of approach in relation to the electrodes, reaction distance, reaction type, and presence/duration of twitching. Data was analysed using conditional inference trees to identify the effects of individual, treatment, treatment day, session number, trial number, approach number, and time of the day on 1) reaction distance, 2) inter-approach times (i.e. time between two consecutive approaches), 3) reaction type, 4) twitching presence, and 5) duration.

Sawfish clearly sensed and reacted to all electric fields tested, but only when they were very close (typically within 1.2 m) to the electrode setup. Reactions included 'twitching' and rapid changes in swimming direction and speed. Upon swimming towards the electrode setup, four different behaviours were observed. Two of these were considered as desirable for the development of a sawfish repelling device: when the sawfish turned back after sensing the electric pulses, and when the sawfish changed swimming direction and continued on a path parallel to the electrodes, not crossing the strongest part of the electric field. These behaviours confirm that the sawfish can sense the electric field and is repelled by it. Two undesirable behaviours were also observed, including when the sawfish continued its path, swimming between the two electrodes and when the sawfish entered the electric field but lost the ability to swim away (freezing). These behaviours would lead to the sawfish entering the nets. Sawfish reacted differently and from further away following the first experimental sessions, suggesting that the animals are capable of learning to avoid an unpleasant stimulus. The two sawfish showed somewhat different reactions to the different treatments, and the treatments that best worked for the smaller individual were not as favourable for the larger individual, and vice-versa. This could be related to animal size or to intraspecific behavioural differences.

Although sawfish reacted and were repelled by electric fields, they did not display a fleeing behaviour from a distance far away enough to avoid entering trawl nets. None of the waveforms used could repel from distances likely to be sufficient to deter sawfish from entering trawl nets (3–4 m). Additionally, exposure to the electric fields tested did not consistently lead to reactions conducive to escaping. This suggests that the electric pulses tested are unlikely to be useful to reduce sawfish bycatch in prawn trawlers. Increasing pulse voltage, frequency or duration could potentially improve the usefulness of an electric field repelling sawfish, but higher energy waveforms would (i) be more challenging to implement (as larger units would be necessary to produce the electric field, which would be more expensive and have higher power consumption), (ii) increase potential stress and harmful side-effects in sawfish and other non-target species, and (iii) be more dangerous to humans. We suggest that the use of electric fields as sawfish deterrents should be revisited if/when technological advances allow for electric field propagation to be increased to elicit fleeing behaviour from greater distances. Until then, other mitigation measures that can reduce sawfish interactions should be investigated alongside an assessment of post-release survival and means to increase post-release survival if capture cannot be avoided and post-release survival is low.

Keywords

Bycatch reduction devices, electric repellents, Largetooth Sawfish, prawn fisheries, prawn trawl, *Pristis pristis*.

Introduction

In recent decades, the incidental capture of bycatch species has become an important issue in trawl fisheries worldwide (Hall et al. 2000, Hall & Mainprize 2005), and impacts of fishing activities on the marine environment (including bycatch interactions) have been increasingly scrutinised (Davies et al. 2009, Roda et al. 2019). There has also been an increased focus towards ecosystem-based fishery management, due to increased environmental concern for marine resources (Brodziak & Link 2002, Pikitch et al. 2004, Trochta et al. 2018). Of all gear types, trawl fisheries produce the highest bycatch rates (Zeller et al. 2018). This led to the development of a range of gear innovations such as bycatch reduction devices (BRDs) and turtle excluder devices (TEDs).

The Northern Prawn Fishery (NPF) is the largest Australian prawn trawl fishery and the most valuable Commonwealth managed fishery. The annual gross value of production of this fishery was $119 million in 2016–2017, contributing to 29% of the Commonwealth fishery gross value of production (Mobsby et al. 2019). Much of its prime fishery regions overlap the ranges of several threatened species such as turtles (Riskas et al. 2016), sea snakes (Milton 2001), and elasmobranchs (sharks and rays) (Peverell 2005, Salini et al. 2007), including sawfish (Stevens et al. 2008). This has led to resources being expended on designing, implementing, and monitoring technologies to reduce bycatch (e.g. TEDs and BRDs) (Brewer et al. 2006, Campbell et al. 2020), while maintaining high catches of the targeted species. Although these mechanisms have successfully reduced bycatch of several species, including Threatened, Endangered and Protected (TEP) species, many of those species, such as sawfishes, are still regularly caught during routine fishing activities (Griffiths et al. 2006, Jaiteh et al. 2014).

Due to their life-history characteristics and morphology, sawfishes are highly susceptible to anthropogenic mortality (Simpfendorfer 2000, Stobutzki et al. 2002), leading to sawfishes being among the most threatened family of marine fishes globally (Dulvy et al. 2016). They are nationally and internationally recognised as being at risk from fishing activities, with all sawfish species having experienced dramatic population declines, reduced geographic ranges, and being likely to take several decades to recover from reduced populations (Simpfendorfer 2000, Dulvy et al. 2016). Incidental capture, particularly in trawl and gillnet fisheries worldwide, is one of the primary threats to elasmobranchs (Oliver et al. 2015) in general, and to sawfishes (Dulvy et al. 2016) in particular.

Australia's northern coastline is one of the few remaining places in the world where viable sawfish populations occur. Current protected areas cover a limited percentage of the sawfish species' distributions and are therefore not sufficient to ensure recovery (Devitt et al. 2015). All four sawfish species encountered in the NPF (Narrow Sawfish *Anoxypristis cuspidata*, Largetooth Sawfish *Pristis pristis*, Green Sawfish *P. zijsron* and Dwarf Sawfish *P. clavata*) are listed on the Convention on International Trade in Endangered Species (CITES) Appendix I and the Convention of Migratory Species (CMS) Appendices I & II. These species are also listed under the International Union for the Conservation or Nature (IUCN) Red List of Threatened Species as Critically Endangered (Largetooth Sawfish and Green Sawfish) and Endangered (Narrow Sawfish and Dwarf Sawfish). Within Australia, three species are listed as Vulnerable, and all four species are listed as Migratory on the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999*. Within the NPF, all four species have been classified as ‘at risk’ to trawling and the least likely to be sustainable from prawn trawl fishing (Stobutzki et al. 2002, Zhou & Griffiths 2008). Consequently, the need for improved bycatch mitigation measures has been identified by the Sawfish and River Sharks Multispecies Recovery Plan as a required action under its first Objective (Department of the Environment 2015).

The threatened status of sawfishes and their susceptibility to capture (Dulvy et al. 2016), limited refuge in protected areas (Devitt et al. 2015), ongoing catches (Fry et al. 2015), and the inefficiency of current bycatch reduction devices to reduce sawfish bycatch (Brewer et al. 2006) suggest an urgent need for the development of new approaches to minimise sawfish interactions with fishing gear. The bycatch mitigation methods currently used in the NPF typically allow unwanted species to escape after entering the nets. However, due to its anatomy (long rostrum with teeth) and escape behaviour, sawfish rostra are still prone to be entangled in the nets (Brewer et al. 2006, Wakefield et al. 2017). The development of a mechanism that prevents contact with the fishing gear, i.e. that repels sawfish before they enter the net, would therefore greatly contribute to reduce sawfish bycatch (Jordan et al. 2013). However, elasmobranchs often only react upon contact with the trawling gear (Queirolo et al. 2012), so it is important that the technology repels sawfish at a distance large enough to allow them to effectively swimming away from the trawl path.

The sensory capabilities of elasmobranchs have been used to develop repellent technologies, including electrical-based repellents (electric pulses, permanent magnets, electropositive rare earth metals) and semio-chemicals (Hart & Collin 2015). Such technologies use electrosensory or chemical stimuli to deter elasmobranchs, with aim to reduce elasmobranch bycatch (e.g. Rigg et al. 2009, Jordan et al. 2013, Siegenthaler et al. 2016, Aristi et al. 2018) or minimise shark interactions with surfers, divers, kayakers (e.g. Huveneers et al. 2013, Huveneers et al. 2018) or swimmers on beaches (e.g. O'Connell et al. 2014a, O'Connell et al. 2014c).

The use of electric pulses have been proposed as a method with the highest potential to reduce sawfish bycatch (Jordan et al. 2013). As with other elasmobranchs, sawfish have the ability to detect minute electromagnetic fields using highly sensitive electroreceptors, the ampullae of Lorenzini (Peters et al. 2007, Wueringer et al. 2012a). Their elongated toothed rostrum, or saw, has a dense array of these ampullae (Wueringer et al. 2011), allowing them to detect and capture prey both in the substrate and in the water column (Wueringer 2012, Wueringer et al. 2012a). Other methods, such as strong magnets or rare-earth metals, only affect some elasmobranchs and within very short distances (i.e. <0.5 m) at best (Kaimmer & Stoner 2008, Brill et al. 2009, Rigg et al. 2009), with several species not being affected by these types of deterrents (Tallack & Mandelman 2009). For example, while, permanent magnets reduced elasmobranch bycatch by over a third in the Snapper (*Pagrus auratus*) ocean fish trap fishery (Richards et al. 2018), SMART (Selective Magnetic and Repellent-Treated) hook technology was ineffective in reducing Greenland Shark (*Somniosus microcephalus*) bycatch in the Greenland Halibut (*Reinhardtius hippoglossoides*) longline fishery (Grant et al. 2018). In another study using baited remote underwater video (BRUV), Draughtboard Sharks (*Cephaloscyllium laticeps*) displayed both aversion and attraction behaviours in response to magnetic treatments, and that while there were more feeding attempts on bait during control trials compared to trials with magnets, there was a high variability in behavioural responses within and between treatments (Westlake et al. 2018). Necromones or semio-chemical deterrents can also be effective at repelling sharks (O'Connell et al. 2014d), but are only effective at the dispersal location and for a short period because of dilution rapidly reducing concentration. Active fishing gear such as trawling would require a constant dispersal of the chemical sufficiently ahead of the trawl to ensure that sawfish can detect and react to the chemical before the net reaches them. It is unlikely to such dispersal mechanism could be implemented, and it would also require a large amount of chemical for trawls up to 3-4 hours (e.g. when targeting tiger prawns). The effects of such deterrents on other species including targeted species are also unknown.

In contrast, several elasmobranch species have been shown to respond physiologically and behaviourally to weak, low frequency electric fields as low as <1nV.cm^{-1} (Kajiura & Holland 2002, Jordan et al. 2011). Moreover, devices that produce electric fields have been successfully incorporated in prawn trawlers, showing that such technology can be logistically used in commercial fishing vessels (van Marlen et al. 2006, Yu et al. 2007, Verschueren et al. 2019). For example, the use of electrotrawling (or pulse trawling) in the Brown Shrimp (*Crangon crangon*) fishery in the North Sea resulted in an average bycatch reduction of 35% and a significant decrease contact with the seabed, without detrimentally affecting the targeted prawn catches (Verschueren et al. 2019).

The present study tests, in a controlled laboratory environment, if strong electric fields can overwhelm the electrosensory system of sawfishes and dissuade them from approaching the source of the electric field and/or elicit a fleeing behaviour. If successful, this technology could be incorporated into a device and attached to commercial fishing nets to reduce sawfish bycatch. Since large bycatch animals can damage the fishing nets and the catch, this would also improve the quality and, therefore, the value of the catch (Salini et al. 2000). Additionally, this would also reduce sorting times and improve crew safety, as the handling and removal/release of large sawfish from the nets leads to significant risks for the sawfish and the crew (Wakefield et al. 2017).

Objectives

The overall aim of this project is to test the effect of electric fields on sawfish behaviour, to determine the potential of electric pulses to mitigate sawfish bycatch. The specific objectives are:

Objective 1. *Assess whether sawfish behaviourally respond to electric fields*

Test the effects of electrical fields of different characteristics (e.g. alternating vs. bipolar current, with different voltage, frequency, pulse duration, and pulse shape) on sawfish behaviour to identify the electric field characteristics most likely to deter sawfish.

Objective 2. *Compare sawfish behavioural response across fields of different characteristics.*

Assess the distance from which sawfish can be deterred and the fleeing behaviour induced by the electric field to determine if strong electric fields will be sufficient to avoid sawfish being caught in nets.

Methods

Animal capture and housing

Four Largetooth Sawfish (*Pristis pristis*) were caught from the Norman River, North Queensland, in April 2019 using light-weight multi-strand set nets (mesh size 50–20 mm). Nets were continually monitored to quickly remove sawfish upon capture. The four individuals caught were 1.02 m (male), 1.62 m (female), 1.65 m (male) and 1.64 m (male) total length (TL).

Captured sawfish were then transported to the Biopixel/James Cook University Aquarium facilities in Cairns (North Queensland) in 1200 L round tanks custom-built for shark and ray transport. Oxygen was pumped through carbon block air stone and dissolved oxygen (DO) content monitored. On arrival in Cairns, sawfish were acclimated to aquarium salinity (~32 ppt) and water temperature by gradually adding water from the aquarium system to the transport tank until salinity and temperature matched. Sawfish were allowed to settle in the tanks for four weeks prior to experiments starting. Water salinity, temperature and pH were monitored daily. Ammonia, nitrite, nitrate, KH, calcium, and phosphate were monitored weekly. The water volume in the system was ~9000 L.

Throughout their stay at the aquarium facilities, sawfish were fed twice a day with dead fish (mostly mullet and pilchards) and were also offered squid and prawns. Any food not eaten was collected at the end of the day. Sawfish were kept separated among three tanks, with one animal in the larger experimental tank, and three in two separate holding tanks. The experimental tank also housed teleosts including damselfish (*Pomacentrus* spp., ~30 individuals), surgeonfish (*Acanthurus* spp., ~8 individuals), one Moorish Idol (*Zanclus cornutus*) and one Orbicular Batfish (*Platax orbicularis*). Sawfish body condition, feeding behaviour, swimming behaviour, and body attitude were assessed daily to monitor their health and wellbeing.

Within two weeks of the trials commencing, Cairns experienced anomalous cold temperatures for a prolonged period, when maximum temperatures were ≤25 °C for eight consecutive days (Figure 1; Australian Bureau of Meteorology, www.bom.gov.au). This led to a decrease in water temperature of the outdoor system and to a reduction in food consumption by sawfish due to stress from cold water. As soon as animals reduced feeding, trials were stopped and as per the animal ethics protocol James Cook University Animal Ethics Committee permit number A2584, which included force-feeding and B12 injections, was implemented. Additionally, water-heaters were installed to prevent further temperature drops. Nevertheless, two individuals later died and one had to be euthanised despite a concerted effort to prevent this outcome. Only one of the three animals that died was subjected to this study's experimental procedures. The fourth sawfish participated in the experimental procedures and was released back into Norman River on the 27th September 2019. Therefore, it was only possible to conduct experiments on two individuals: sawfish 1, a 1.02 cm TL male, and sawfish 2, a 1.65 m TL male.

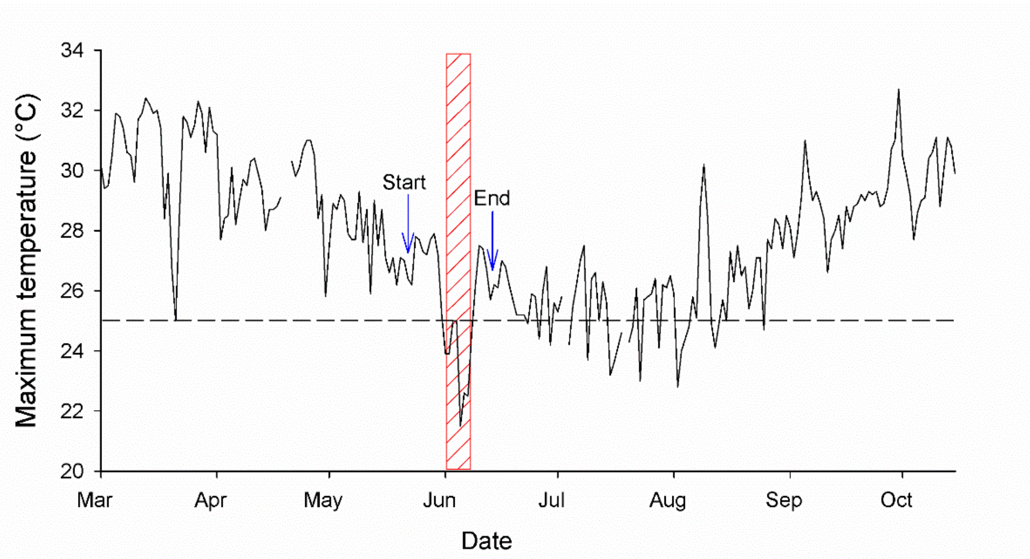

Figure 1. Maximum temperatures recorded at the City of Cairns between March 1st and October 15th 2019, showing the eight-day period of low (≤25 °C) maximum temperatures registered between the 1st and 8th June (dashed red rectangle; Bureau of Meteorology, www.bom.gov.au). Blue arrows indicate the start and end dates of the experiments, and horizontal dashed line indicates 25 °C temperature.

Experimental setup

Experiments took place in a 4.6 × 6.0 m fiberglass tank with a water depth of 64 cm and a ~2 cm layer of sand with some rocks on the tank floor. The tank's edges were fitted with skirting panels to prevent damaging the sawfish's rostra and prevent sawfish from jumping out of the tanks.

The electrode setup was based on the commercially available Ocean Guardian Freedom7™, a portable (personal) device that emits an electromagnetic field that discourages sharks from approaching divers, spear fishers, and other recreational water users. This device was selected because of its shown ability to affect shark behaviour (Huveneers et al. 2013, Kempster et al. 2016). Our experimental device therefore consisted on two galvanised steel electrodes (40 cm long, 1.5 cm diameter) hung horizontally halfway through the water column and 112 cm apart (Figure 2). The electrodes were attached with fishing line to a wooden beam that remained ~12 cm above the water surface, held in place by two 25 cm diameter round floats tied at its ends (Figure 2). The electrodes were then connected via 12–15 m long power leads to an adjustable laboratory pulse generator (LPG1, EPLG bvba, Belgium; hereafter referred to as 'LPG') borrowed from the Research Institute for Agriculture, Fisheries and Food, Belgium.

The LPG produces electrical pulse stimuli and allows the user to independently adjust the different pulse parameters (e.g. voltage, frequency, pulse duration, pulse shape). When connected to the two electrodes, it generates an electric dipole that produces an electric field in the surrounding water. The LPG can reach a maximum output of 150 V, 280 A, and 42 kW and is equipped with a feedback system to ensure that the output matched the set values. An oscilloscope (Agilent Technologies, DSO1072B) was used to measure the pulse characteristics of each pulse used, to verify the pulses generated by the LPG and ensure the desired pulse was present on the electrodes (and not only at the output of the generator).

The experimental setup used does not replicate what a setup on a commercial trawler would look like, but enabled to test different electric fields in a controlled environment to assess if they can affect sawfish behaviour and determine the potential of electric pulses to mitigate sawfish bycatch.

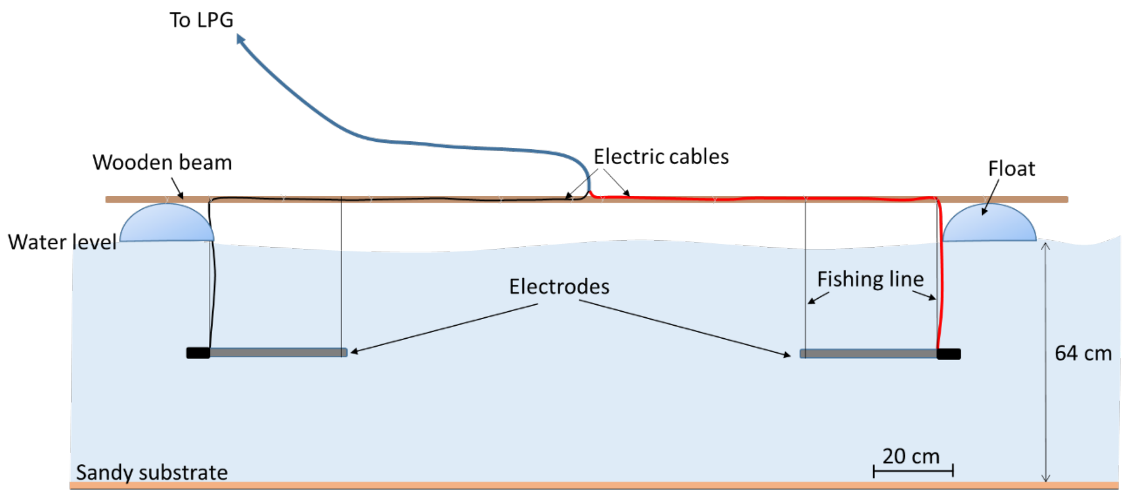

Figure 2. Diagram of the electrode setup, showing the two 40 cm long electrodes attached to a 2.4 m wooden beam by fishing line and kept above the water by two floats (25 cm diameter). Electrodes are at 112 cm distance from each other, and each is connected to a 14 gauge power lead (20–23 m long) that connects to the LPG.

For the trials, the wooden beam was placed perpendicular to and against one side of the tank, placing it across the swimming path of sawfish (Figure 3a). Although placement in the middle of the tank would minimise any potential effects of the tank boundaries on the electric field, this setup was chosen as it allowed fast removal of the electrodes from the water when needed. For example, initial observations showed that sawfish swimming between the electrodes could display signs of distress combined with an inability to move out of the electric field. In such situations, the experiments were interrupted and the electrodes were promptly removed from the water (Figure 3b).

It was originally planned to also conduct active trials, where two operators would move the electrode setup from one end of the tank, slowly approaching and “herding” the sawfish to the opposite side of the tank. This setup would be more comparable to a moving fishing net. However, preliminary tests showed that this approach would not be successful as (1) the approach was aimed at immobile sawfish lying on the seabed, but sawfish spent most of their time swimming, leading to sawfish swimming around the electronic setup field or in the opposite direction of movement, and (2) sawfish reacted to the presence of operators walking above the tank while steering the equipment. This approach was therefore not pursued.

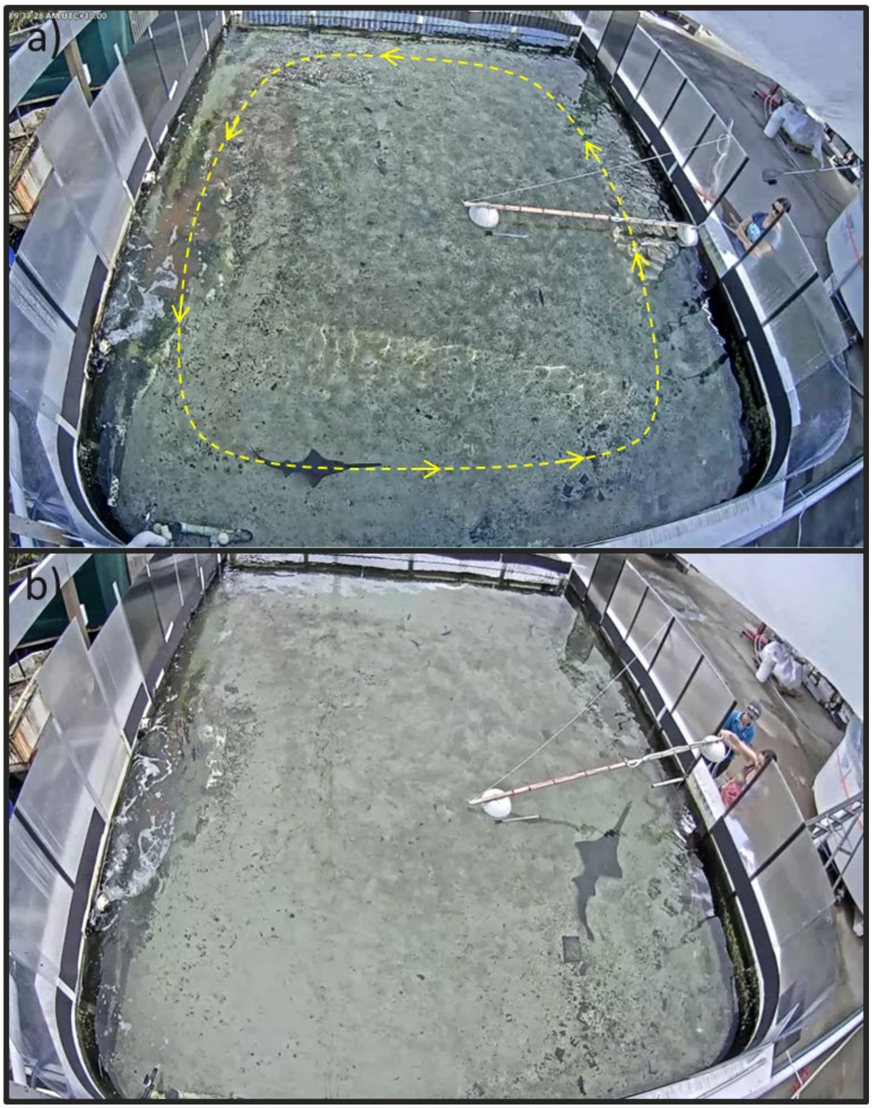

Figure 3. Overview of the overhead video camera. a) Positioning of the electrodes and the observer, and the swimming path typically taken by the sawfish just before the beginning of each experiment (yellow dashed line). b) Operator removing one of the electrodes from the water after the sawfish lost the ability to swim out of the electric field due to involuntary muscle spasms caused by the 'Exponential' treatment.

In order to prevent habituation or conditioning, with sawfish associating the experimental setup with strong electric fields, the equipment was placed in the water without electric fields activated and left for ~30 min before starting each experiment. The equipment was also left in the water for extended periods after trials, and sometimes between treatments. As with the electrified experiments (see below), an observer or other aquarium personnel also regularly positioned themselves at the observation site to limit the effect of the presence of the observer on sawfish reactions. Whenever possible, the electrodes were turned on only after sawfish established a circular swimming pattern, to increase the likelihood of sawfish approaching the electrode setup several times throughout the trial (e.g. trials were not initiated when sawfish were resting on the substrate) and to make trials more comparable (Figure 3a). We initially aimed to obtain data from at least five 'approaches', or ‘passes’, per treatment, i.e. to describe each sawfish behaviour when attempting to swim between the electrodes five times. However, sawfish did not always approach the electrode setup sufficiently during the trials, e.g. sawfish sometimes spend extended amount of time on one side of the tank during the trials. In those cases, the experiments were left to run for 10 – 12 minutes, instead of limiting the trials to five passes which typically took less than 10 minutes; see below).

Treatments

The first step of this project involved determining if a strong electric field can induce a fleeing response in sawfish. Therefore, pilot trials on two sawfish were conducted to select a waveform most likely to lead to a fleeing response. The initial selection of the waveform parameters was guided by the field characteristics of the commercially available Ocean Guardian Freedom7™ (https://ocean-guardian.com.au/collections/dive-series/products/freedom7) and Rpela (www.rpela.com), portable devices that emit electromagnetic fields, used by recreational water users to repel sharks (see Table 1 for respective pulse characteristics). These trials resulted in the selection of a waveform that seemed to best deter sawfish, from hereon named ‘Baseline’ (see Table 2). Note that frequency in the present study refers to the number of uninterrupted pulses per second, which corresponds to the standard definition of frequency (number of pulse cycles) for alternating current (AC), and to the so called apparent frequency for bipolar pulses, as defined by Soetaert et al. (2019).

Table 1. Pulse parameters of the two devices on which the electrode setup used was based: Ocean Guardian Freedom7™ and Rpela. Source: Chateauminois et al. (2019). AC = alternative current; DC = direct current.

Device	Pulse shape	Polarity	Frequency (Hz)	Duration (µs)	Voltage (V)
Ocean Guardian	Exponential	AC	1.5	1000	115
Rpela	Close to rectangular	DC	14.7	200	200

Sawfish behaviour was tested in presence of the ‘Baseline’ pulse stimulus and five variations of that pulse, where only one parameter was changed at the time to identify which change in pulse characteristics is most likely to improve the deterrent effect (Table 2; Figure 4). For most treatments, the voltage measured by the oscilloscope at the electrodes (in-water) was within 5 V of the value set at the LPG (Figure 4). Only for the AC treatment was the measured voltage 8 V lower than the set value. Sawfish behaviour was also tested in control conditions, i.e. with the electrodes in the water but LPG turned off to account for the behavioural response of sawfish to the physical presence of the device.

Experiments were run over five days for sawfish 1 (spread between 3rd and 13th June 2019), and over seven days for sawfish 2 (spread between 21st and 29th May 2019), following a 2-day acclimatisation period to the experimental tank. Up to three electrified treatment sessions were run per day.

Treatments were done in a random order and typically took less than 10 minutes. During the experiments, the electrodes were left in the water for at least 30 minutes before and after the trials, so the sawfish would get used to it and did not associate its presence to electric shocks.

Table 2. Pulse parameters used for each treatment. For each of the six electrified treatments, the parameter that differs from the 'Baseline' pulse is in bold. *N* is number of experiments run for sawfish 1 and 2. AC = alternating current; BC = bipolar current.

Treatment	Polarity	Shape	Frequency (Hz)	Duration (µs)	Voltage (V)	*N* (1/2)
Control	No current	-	-	-	-	(3/3)
'Baseline'	BC	Rectangular	5	1500	100	(2/2)
'AC'	**AC**	Rectangular	5	1500	100	(2/2)
'Exponential'	BC	**Exponential**	5	1500	100	(2/2)
'10 Hz'	BC	Rectangular	**10**	1500	100	(2/2)
'500 µs'	BC	Rectangular	5	**500**	100	(2/2)
'50 V'	BC	Rectangular	5	1500	**50**	(3/2)

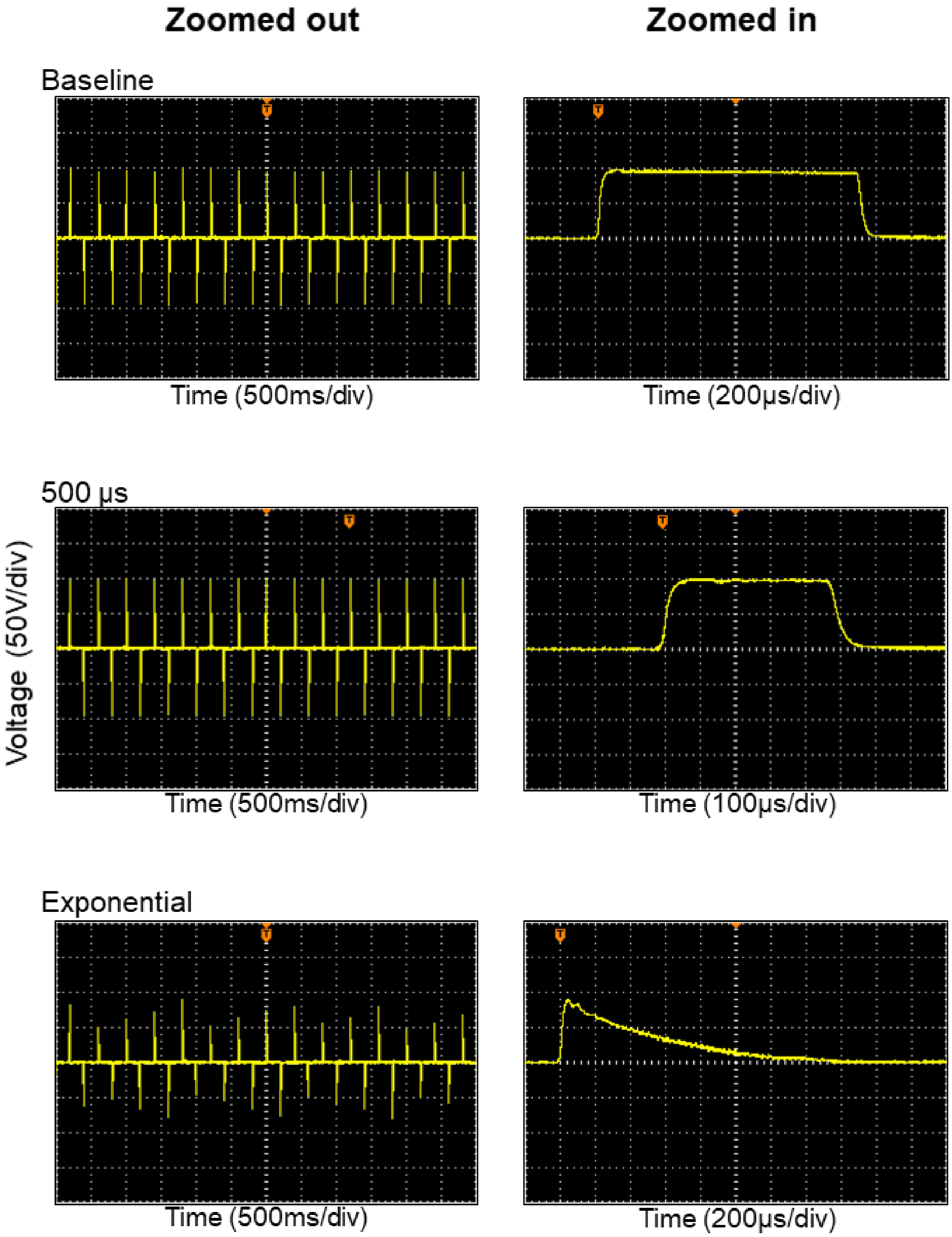

Figure 4. Overview of the electrical pulse stimuli used for the different experimental trials, measured at the electrodes in water, and plotted at longer (Zoomed out) and shorter (Zoomed in) time frames. Note the differences in both *x*- and *y*-scales. See Table 2 for detailed characteristics of each pulse. Note that, for the 'Exponential' pulse treatment, the apparently variable height of pulse amplitudes is an artefact of oscilloscope measurements and display (as it divides the chosen timeframe into 16384 measurements), due to the very narrow peak and sharp exponential decline, meaning the actual amplitude is higher than that shown in this figure.

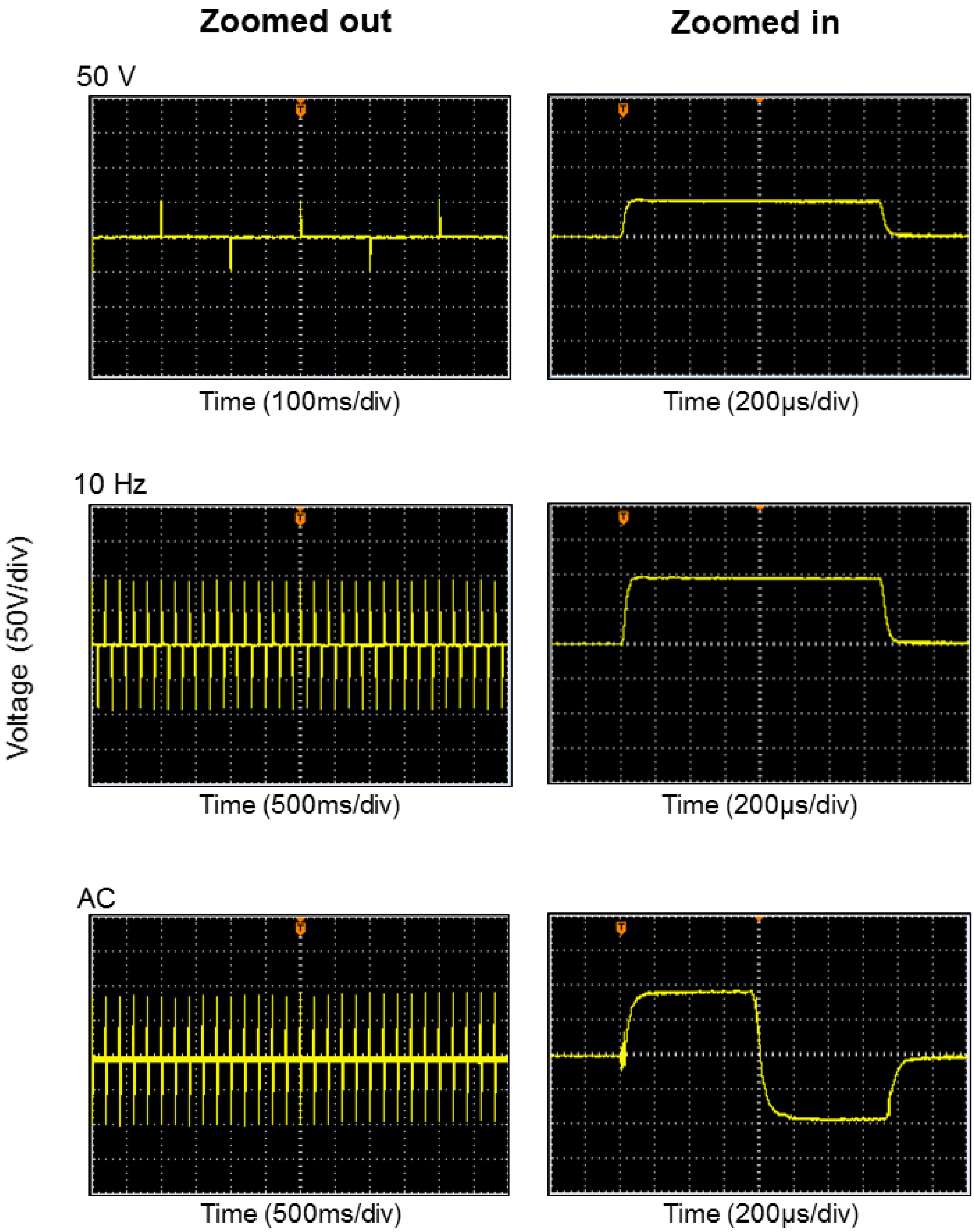

Figure 4 (cont.) Overview of the electrical pulse stimuli used for the different experimental trials, measured at the electrodes in water, and plotted at longer (Zoomed out) and shorter (Zoomed in) time frames. Note the differences in both *x*- and *y*-scales. See Table 2 for detailed characteristics of each pulse. Note that, for the 'Exponential' pulse treatment, the apparently variable height of pulse amplitudes is an artefact of oscilloscope measurements and display (as it divides the chosen timeframe into 16384 measurements), due to the very narrow peak and sharp exponential decline, meaning the actual amplitude is higher than that shown in this figure.

Data collection and analysis

During the experiments, an observer was positioned at ~0.5 m from the edge of the tank (Figure 3). One of the skirting side panels close to the electrode setup was removed to allow for direct observation of sawfish behaviour and to allow the quick removal of one electrode from the water, if needed (Figure 3b). For consistency, the same observer recorded all behaviours and measurement estimates, but these were often confirmed by a second observer. During the trials, the LPG was turned on only when the sawfish was swimming ≥3 m away from the electrode setup to avoid startling the sawfish at the beginning of the experiment. The observer wrote down the time of approach, the angle of approach, reaction distance, and type of reaction. Reaction distance was estimated as the distance at which sawfish showed a reaction to the electronic setup, e.g. by rapidly moving its head side-to-side, twitching its whole body, changing speed or direction. Distance was estimated using the number of wall panels between the sawfish and the electrodes, as the 60 cm wide skirting panels around the tank's edge provided an easy guide to visually estimate distances. Due to the non-central positioning of the overhead camera (see Figure 3) and the variability in swimming depths, reaction distances were more accurate when directly estimated by an observer rather than through video footage.

The different experiments were recorded with a video camera placed above the tank (see Figure 2 for an example of the view from this camera) and video footage was used to code sawfish behavioural responses using the open source event-logging software *Behavioural Observation Research Interactive Software (BORIS* v.7.7.3*)* (Friard & Gamba 2016). For these analyses, a range of behaviours were defined and encoded as point events (for short behaviours) or state events (for longer behaviours for which the time is recorded) (Table 3). The time, type, and duration (when applicable) of the different behaviours was then quantified and tabulated into ethogram tables, which were used to produce timelines of the observed behaviours to quantitatively analyse the data to describe the responses of sawfish to the different electric fields. Video cameras were also placed underwater to estimate the sawfish distance from the bottom as they swim into and away from the electrode device, and to describe the sawfish behaviour when subjected to the different electric fields.

Upon swimming towards the electrode setup, four different reactions to the electric field were observed: (1) Turned back - the sawfish turned back after sensing the electric pulses (see Videos 1 and 2), (2) Swam parallel - the sawfish changed swimming direction and continued on a path parallel to the electrodes, along the wooden pole (see Video 3), (3) Swam between - the sawfish continued its path and swam between the electrodes (i.e. under the wooden pole) (see Videos 4 and 5), and (4) Freezing - during which the sawfish moved its head side-to-side in a stationary position, while seemingly losing the ability to swim away from the electric field (see Video 6) (Table 3; Figure 5). The first behaviour (turning back) would be the most desirable for the development of a sawfish repelling device, as it would mean that the animal would actively turn back and swim away from a net, displaying an effective escape behaviour. The second behaviour (swimming parallel) can also be considered a positive outcome, as it means the sawfish can sense the electric field, actively respond to it, and swims away from the direction of the trawl. The two last behaviours (swimming between and freezing) are less desirable, as both would lead to the sawfish entering the nets.

Table 3. Ethogram showing the behaviours recorded for the quantitative analysis of sawfish reaction to the various electric fields.

Category	Behaviour	Behav. type	Description
Activity	Swimming	State event	Sawfish is swimming throughout the tank.
	Resting	State event	Sawfish is resting on the substrate.
Approach	Approach	Point event	Sawfish swims towards the experimental setup.
Direction of approach	Direction of approach	Point event	Direction of the swim in relation to the electrode setup. Classified as 'towards the area between the electrodes', or 'towards the electrode placed in the middle of the tank'. See Figure 5.
Reaction distance	Reaction distance	Point event	Distance from the electrodes at which the individual showed reaction, estimated in number of panels (1 panel = 60 cm). Reaction could be e.g. head twitching or changing swimming speed and/or direction.
Reaction type (see Figure 5)	Turning back	Point event	Sawfish turned around ~180° after sensing the electric field, and typically swam away at higher speed. See Videos 1 and 2.
	Swim parallel to electrodes	Point event	Sawfish changed direction to swimming parallel to the electrode setup, towards the middle of the tank, after sensing the electric field. See Video 3.
	Swim between electrodes	Point event	Sawfish swam between the electrodes, through the middle of the electric field. See Videos 4 and 5.
	Freeze	Point event	Sawfish tensed the muscles including fins and body, quickly moving the head side-to-side in a stationary position, while seemingly losing the ability to swim away from the electric field. See Video 6.
Twitching	Twitching	Point event	Presence/absence of twitching (Yes/No).
	Twitching duration	State event	Duration of twitching behaviour, in seconds.

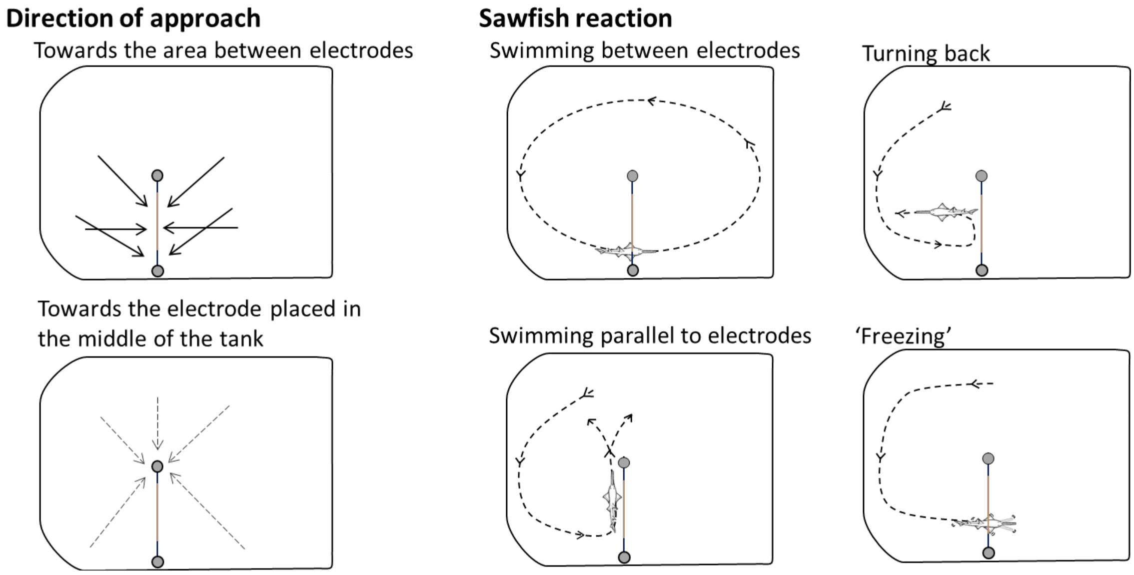

Figure 5. Diagrams showing (left) the direction of the swimming in relation to the electrode setup, and (right) movement paths of the four reaction types of the sawfish as they approached the electrode setup (blue line with two circles at the ends, represent the wooden beam and floats). See Table 3 for a description of each reaction.

For data analysis, conditional inference trees (Hothorn et al. 2006) were used to identify the effects of individual, treatment, treatment day, session number (within the day), trial number, approach number (within the trial) and time of the day (morning, midday, or afternoon) on 1) reaction distance, 2) inter-approach times (i.e. time between two consecutive approaches), 3) reaction type, 4) twitching presence, and 5) twitching duration (Table 4). Trees were constructed using the function '*ctree()*' from the R package '*party*' (Hothorn et al. 2010, Hothorn et al. 2015). Conditional inference trees use significance test procedures to recursively split the dataset into two relatively homogeneous and mutually exclusive groups based on one only explanatory variable (Hothorn et al. 2006), therefore identifying the predictor variable(s) that best explain the variability in the dependent variable. This non-parametric method can be applied to a range of data (e.g. nominal, ordinal, categorical, unbalanced) and leads to easy to interpret graphical results in the form of a tree, with the root node at top, representing the overall dataset, from which branches and leaves merge, representing the final groups and the explanatory variables responsible for group formation.

The use of conditional inference trees allowed accounting for the limitation of using each individual repeatedly (pseudo-replication) by including independent variables related to time as continuous predictors (see Table 4). Note also that although repeatedly testing on the same individual leads to some shortcomings, it has the advantage of allowing for the testing of conditioning, learning or habituation, where it will be possible to determine if the sawfish get used to the electric fields and change their behavioural response through time.

Following the identification of the waveform that best repels sawfish, we intended to measure the field strength (in $V.m^{-1}$) at the distance at which animals reacted. However, equipment failure did not allow these measurements to take place, so information from the literature was used instead to help interpret results.

Table 4. Parameters used in the quantitative analyses of sawfish behaviour in response to the different electric fields.

Variables	Description
Independent variables	
Individual	One individual sawfish. Tests were done on two individuals: sawfish 1 (1.02 m TL) and sawfish 2 (1.65 m TL). Categorical predictor.
Treatment	One of the seven treatments (including a control treatment) used to investigate sawfish reaction to the electric fields. See Table 2 for pulse characteristics of each treatment. Categorical predictor.
Treatment day	Treatment days ranged from day 1, when the sawfish was first subjected to a treatment, to the last day trials were conducted (day 5 for the sawfish 1 and 7 for sawfish 2). Only days that involved experimental trials were included in this count. Discrete predictor.
Trial number	Trial number, for each sawfish. Sixteen trials (experiments) were run for sawfish 1, and 15 for sawfish 2 (including control treatments). Discrete predictor.
Session number	If the experiment was the first, second or third electrified session of the day (Sessions 1 – 3). Discrete predictor.
Approach number	Approach number, within an experiment. During each experiment, sawfish approached the experimental setup a number of times. Discrete predictor.
Time of day	Time of the day when experiment was run: morning (9:00 – 11:30), mid-day (11:30 – 3:00), afternoon (13:00 – 15:00). Categorical predictor.
Response variables	
Reaction distance	Distance from the electrodes at which sawfish showed some reaction to the experimental setup (e.g. twitching, rapid change in speed and/or direction, etc.). Note that this variable was also considered as an explanatory variable for the analysis of twitching presence and twitching time. Continuous variable.
Reaction type	Reaction of the sawfish to the experimental setup. Reaction was separated into four categories: turn back, swim parallel, swim between, and freezing. Categorical predictor.
Twitching	Presence of twitching behaviour (yes/no). Categorical predictor.
Twitching duration	Duration of twitching behaviour, in seconds. Continuous variable.
Inter-approach time (IAT)	Period of time between two consecutive approaches to the electrode setup, in seconds. Continuous variable.

Results

For both experimental sawfish, the typical behaviour (with electrodes out of the water) was to swim along the edge of the tank, sometimes stopping by the water outlet with the rostrum up above water. Resting on the substrate was also common, but it was not frequently observed during the experiments.

For the sawfish 1 experiments, water temperatures (measured between 8 and 9 am) ranged between 24.5°C and 26.0 °C (mean ± SD = 25.0 ± 0.6 °C), and salinities between 31.2 and 32.5 ppt (31.9 ± 0.6 ppt). For sawfish 2, temperatures varied from 24.7°C to 26.0 °C (25.0 ± 0.3 °C), and salinity from 31.2 to 31.6 ppt (31.5 ± 0.2 ppt). Based on the measured salinity and temperature values, the estimated seawater conductivity was 47.6 – 49.4 $mS.cm^{-1}$ (average 48.3 $mS.cm^{-1}$) (Lide 2002).

A total of 201 approaches to the electrode setup were recorded, including 166 (82.5%) towards the area between the electrodes (see Video 7), and 35 towards the inside electrode, i.e. towards the electrode placed in the middle of the tank (see Video 8) (Figure 5). All electric pulses used affected sawfish' behaviour, but only when sawfish were close to the electrode setup (typically within 1.2 m). A clear visible effect of the electric pulses on sawfish was 'twitching', where the sawfish moved the head and saw side-to-side simultaneously to the frequency of the electric pulse. Occasionally, more intensive twitching, that included muscle spasms over the body and fins, would make the sawfish unable to swim out of the electric field, in a behaviour classified as 'freezing'. Reactions also included a rapid change in swimming direction and speed. Electric pulses also seemed to affect teleost fish present in the tank, leading to agitated swimming and twitching, and fishes generally avoiding the electric field. Sawfish did not seem harmed by the experiments, and continued to behave and feed normally after the trials.

Reaction distance

The sawfish did not display aversive behaviour to the electrodes being turned on (note that the LPG was turned on only when sawfish were >~3 m from the electrodes). However, for one of the two 'AC' treatments (electrified Trial 13, second session of the day), sawfish 1 avoided the electrode area during the whole 11 min experiment, remaining >2 m away.

In general, reaction distances were small, typically <2 panels (<120 cm) (Figure 6). Reaction distances were larger for the 'Baseline', '500 µs', '10 Hz' and 'AC' treatments than for the 'Exponential' and '50 C' treatments (Figure 6). Note that for these analyses, only reaction distances from approaches made towards the area between the electrodes (see Figure 5) were considered (n = 126), as it was often difficult to estimate reaction distance when sawfish approached from the side of the tank opposite to the observer.

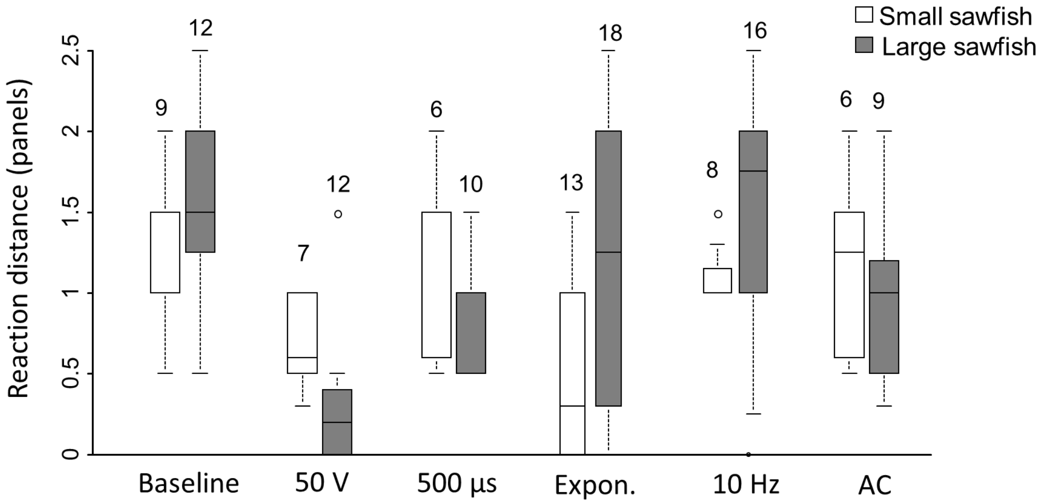

Figure 6. Reaction distances (in number of 'panels', with each panel being 60 cm in width), for each treatment and each sawfish. Box and whiskers plots represent the upper and lower quantiles (boxes), medians (lines within boxes), minimums and maximums (whiskers) and outliers (circles). Numbers above plots are number of replicates (i.e. number of approaches to the electrode setup). Only distances from approaches towards the area between the electrodes were considered in this analysis. Reaction distances for the Control treatment are not included because no clear reaction was observed when sawfish swam between the electrodes or parallel to the electrode setup during Control trials (e.g. no increase in swimming direction, speed or twitching).

The conditional inference tree on reaction distance resulted in four terminal nodes, and shows that *treatment* had the most significant effect on reaction distance (Figure 7), with distance being larger for the 'Baseline' and '10 Hz' treatments (mean ± SD for both treatments and both sawfish: 1.4 ± 0.6 panels) than for the remaining treatments (0.8 ± 0.7 panels; Figure 7b). Further splits indicate that time also had a significant effect on reaction distance, demonstrating a significant effect of learning. For the 'Baseline'/'10 Hz' treatments, a secondary split indicates that reaction distance was significantly smaller for the first experiments of the day (1.0 ± 0.5 panels) than for experiments run on the second or third sessions of the day (1.7 ± 0.5 panels) (Figure 7). Regression analysis shows that this split represented a positive relationship between session number and reaction distance (Figure 8). This suggests that animals learn what to expect and react from further away following the first session (i.e. first experiment) of the day. For the remaining electrified treatments ('50 V', '500 µs', 'AC' and 'Exponential' pulse treatments), the effect of time was related to trial number, with reaction distance smaller for the first 10 trials (0.6 ± 0.5 panels) than for the last few trials (1.2 ± 0.7 panels) (Figures 7 and 8).

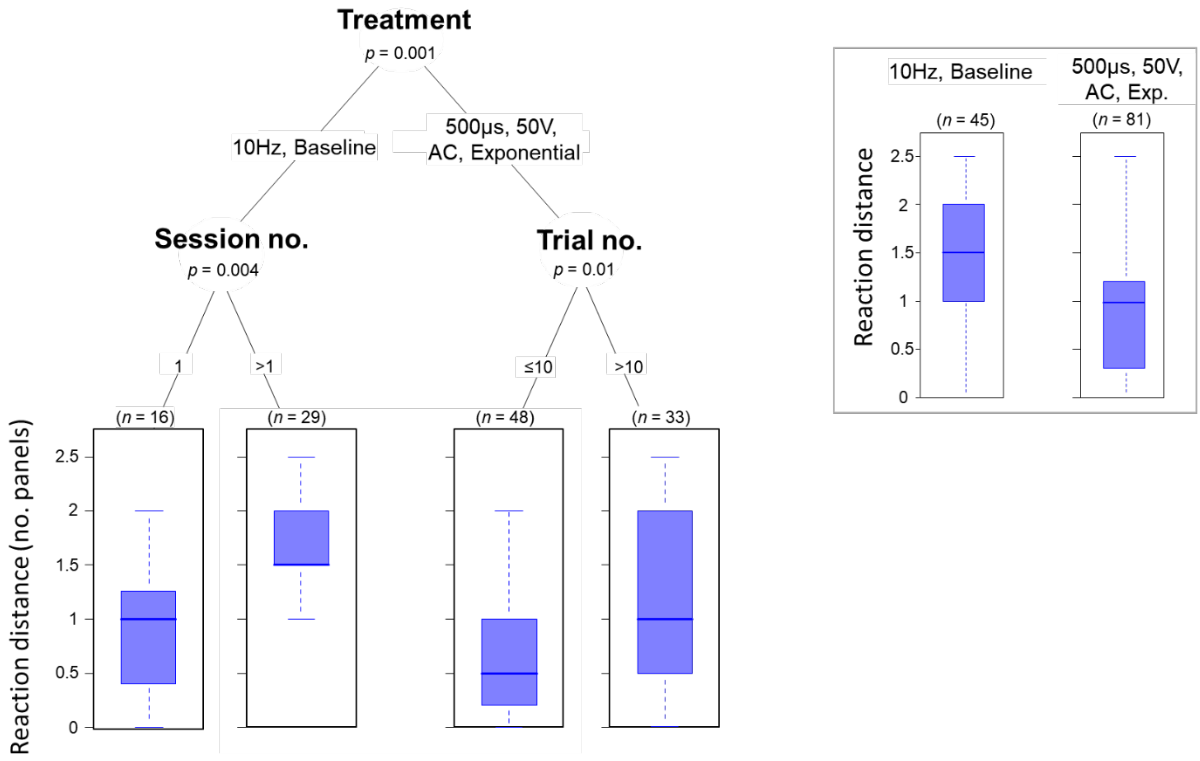

Figure 7. Conditional inference tree model for the contribution of various factors on sawfish reaction distance. Inset plot on the right is the distribution of reaction distances for the first split of the tree. Distance is presented as number of panels, with each panel being 60 cm in width. Box and whisker plots show the distribution of reaction distance values for all samples included in each terminal node, where boxes show the upper and lower quantiles, lines within boxes are the medians, and whiskers are the minimums and maximums. Only data from approaches towards the area between the electrode setup were included in the model.

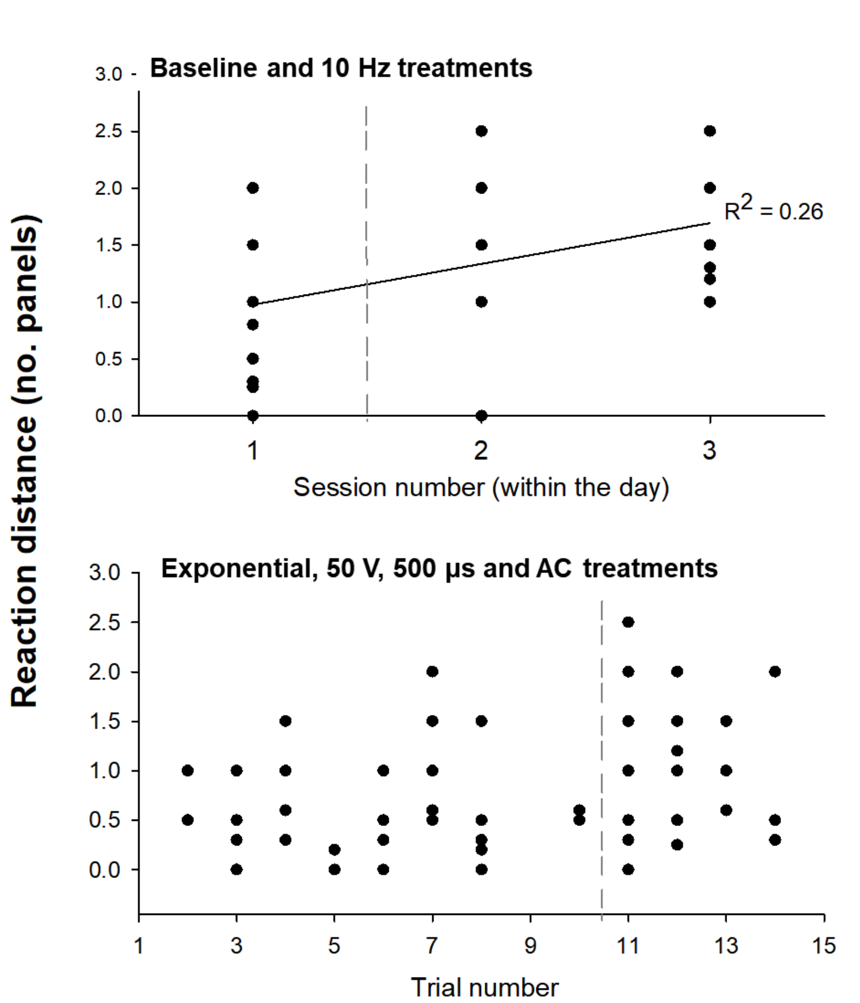

Figure 8. Relationships between sawfish session number (above)/trial number (below) and sawfish's reaction distance. For the 'Baseline' and '10 Hz' treatments (top), a significant positive relationship between session number on number of passes was found (p = 0.0009). For the 'Exponential', '50 V', '500µs', and 'AC' treatments (bottom), vertical dashed line delimitates the value at which the tree split the dataset (see Figure 7).

Inter-approach times

In general, inter-approach times (IATs), i.e. the time between two consecutive approaches to the electrode setup, did not differ between the Control and electrified treatments (Figures 9 to 11), but IAT tended to be longer for the '500 µs' treatment of sawfish 1.

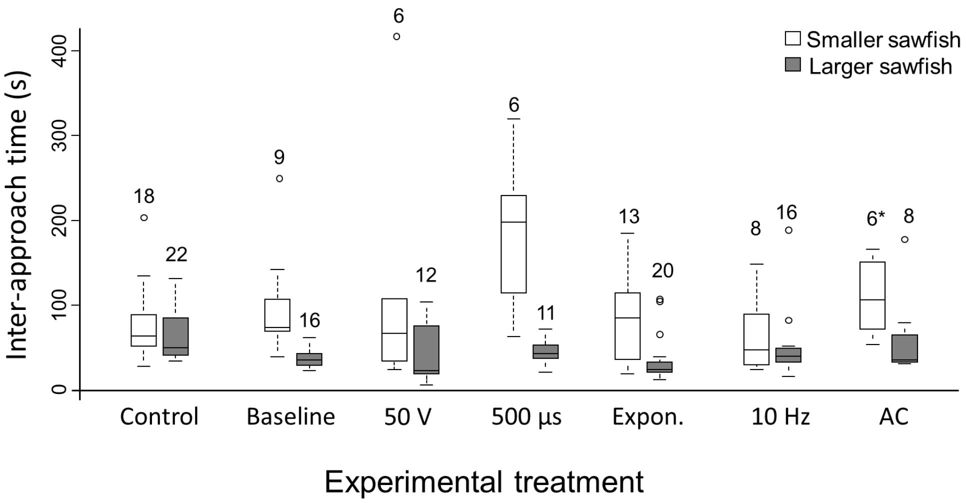

Figure 9. Inter-approach times (i.e. time between two consecutive approaches to the electrode setup) for each treatment and for each sawfish. Box and whiskers plots show the upper and lower quantiles (boxes), medians (lines within boxes), minimums and maximums (whiskers) and outliers (circles). Numbers above plots are number of replicates, i.e. number of inter-approach intervals. Intervals that included any resting periods were removed before analysis. * for one of the two 'AC' treatments, sawfish 1 did not go close to the electrodes during the whole experiment.

The conditional inference tree identified *individual* as the most important factor explaining the time between consecutive approaches to the electric setup, as sawfish 1 had longer time periods between approaches than sawfish 2 (Figures 9 and 10). This was however expected as sawfish 2, due to its larger size, can cover a larger distance in the same time, therefore approaching the electrode setup more often. Moreover, the smaller individual (sawfish 1) had higher manoeuvrability and could swim around the tank without coming close to the electrode setup, whereas the larger animal (sawfish 2) has less space to move so it approached the electrode setup more often. However, there were no differences in IAT between the two individuals for the Control treatment (Figure 9), which could indicate that the differences between individuals could be related to individual reactions to the electric fields. Indeed, for each individual, the tree identified an effect of time (i.e. experience) on IAT, although this effect was not the same for the two individuals: while for sawfish 1 IATs were shorter in the first session of the day (i.e. first experiment of the day), IATs of sawfish 2 were longer in the first five electrified trials (Figure 10). Accordingly, there was a significant negative relationship between session number and number of passes per minute for sawfish 1, and a significant positive relationship between trial number and number of passes per minute for sawfish 2 (Figure 11).

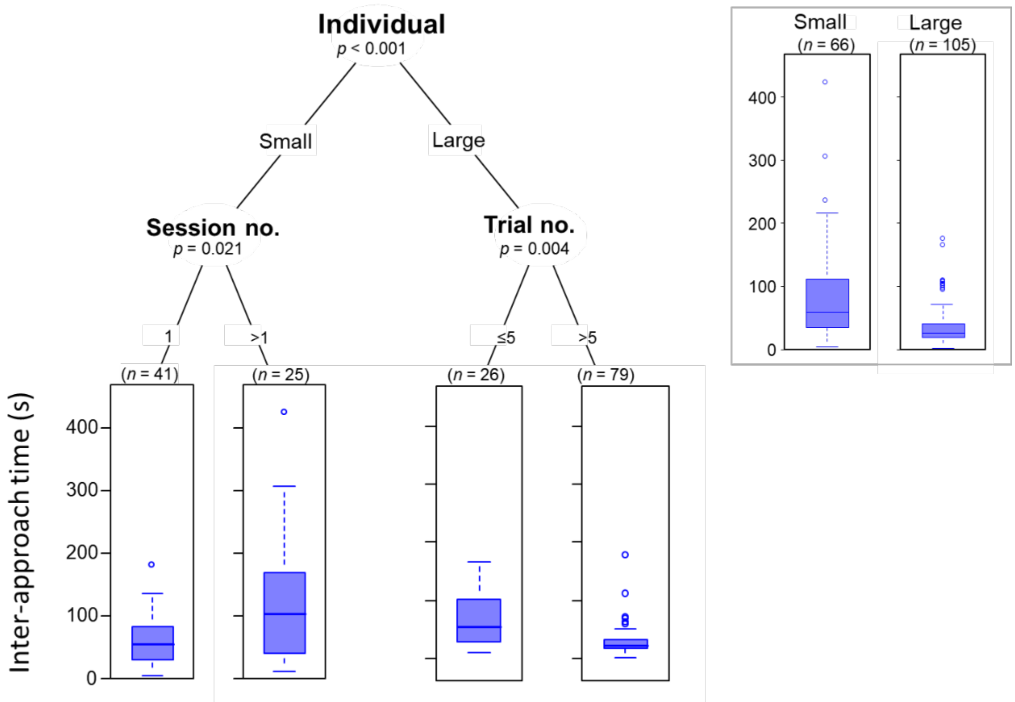

Figure 10. Conditional inference tree on the effect of the different explanatory variables (see Table 4) on inter-approach time, i.e. the time between consecutive approaches to the electric setup. Inset plot on the right is the distribution of inter-approach time for the first split of the tree. Box and whiskers plots represent the distribution of inter-approach times, showing the upper and lower quantiles (boxes), medians (lines within the boxes), minimums and maximums (whiskers), and outliers (dots). Intervals that included resting periods were removed before analysis.

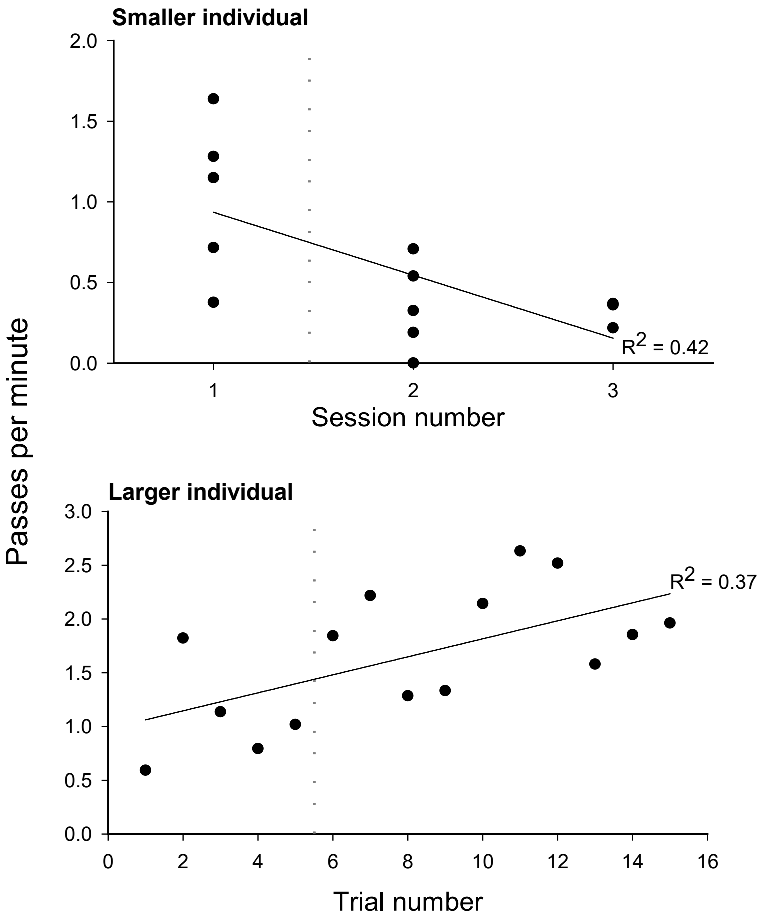

Figure 11. Relationships between sawfish session number (above)/trial number (below) and number of passes per minute, i.e. number of approaches to the electrode setup, per minute. For sawfish 1 (top), a significant negative relationship between session number and number of passes was found (p = 0.0164), while for sawfish 2 (bottom) the significant relationship was with trial number (p = 0.0153). Grey dashed lines delimitate the value at which the tree split the dataset (see Figure 10). Intervals that included resting periods were not included in this analysis.

Reaction type

The timelines of behaviours for each treatment can be found in Figure 12 (sawfish 1) and Figure 13 (sawfish 2). In the Control treatments, the behaviour most commonly recorded was swimming between the electrodes, although sawfish 1 turned back 20% of the time, and the sawfish 2 swam parallel to the electrodes 42% of the time (Table 5). This difference in behaviour between the two sawfish is likely related to size as, due to its smaller size, sawfish 1 had a smaller turning circle, making it easier to turn ~180° within the available area, whereas sawfish 2 had a much larger turning circle.

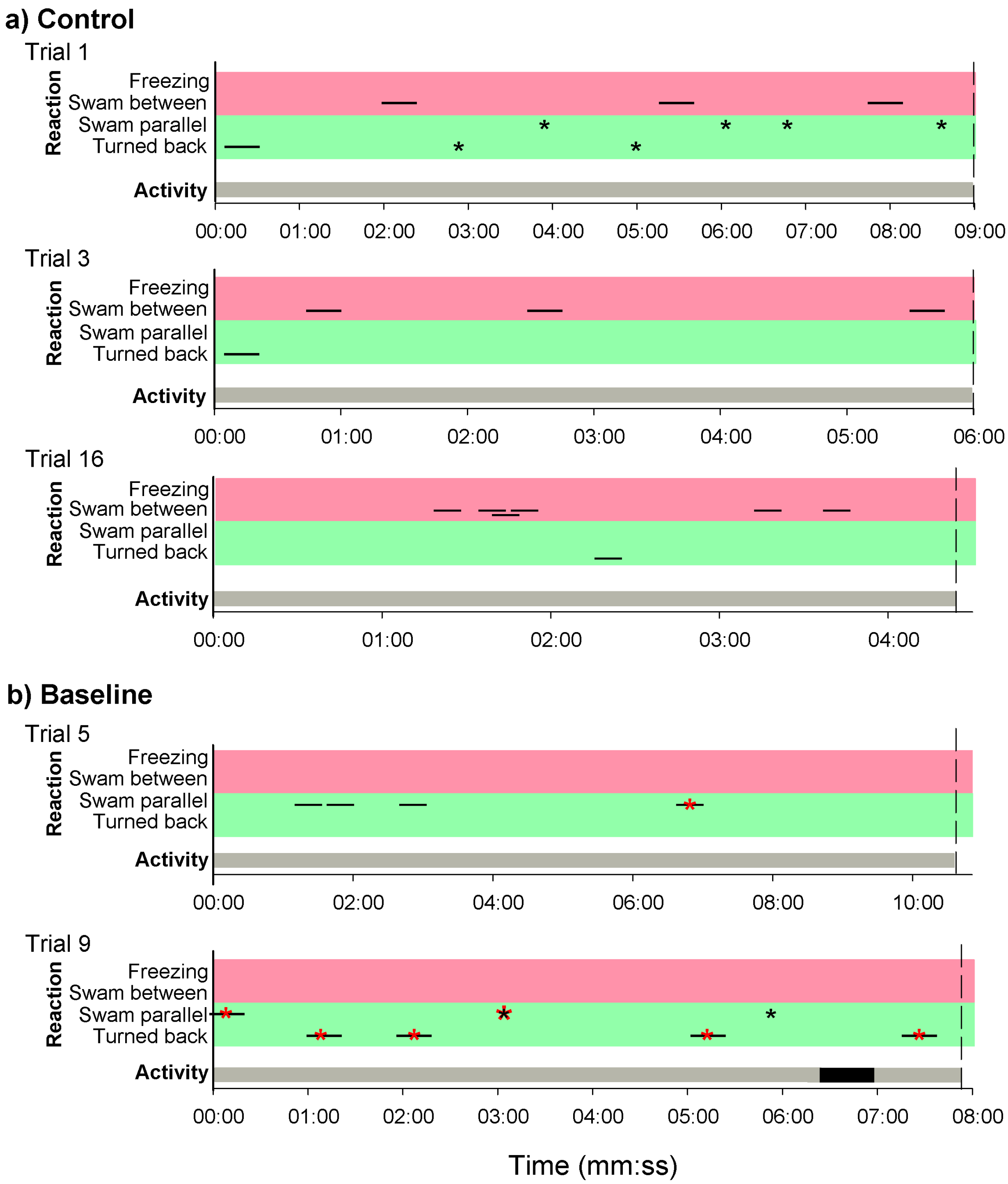

Figure 12. Timeline showing the reactions of sawfish 1 to the different electric fields from the beginnig (time 00:00) to the end (vertical dashed line) of each experiment (note the difference in time-scales of the x-axes). For electrified treatments, this corresponds to the period of time from when the electrodes were turned on until they were turned off. – = Sawfish approaches the electrode setup, swimming towards the area between the electrodes; * = sawfish approaches the electrode setup, but swimming towards the electrode located in the middle of the tank. * = sawfish displayed 'twitching' behaviour. X = Sawfish freezing to the extent that electrodes had to be removed from the water. The region of the most desirable reactions is highlighed in green, and the region of least desirable reactions in red. See Figure 5 for details of the approach and reaction types. Activity: grey - swimming; black - resting.

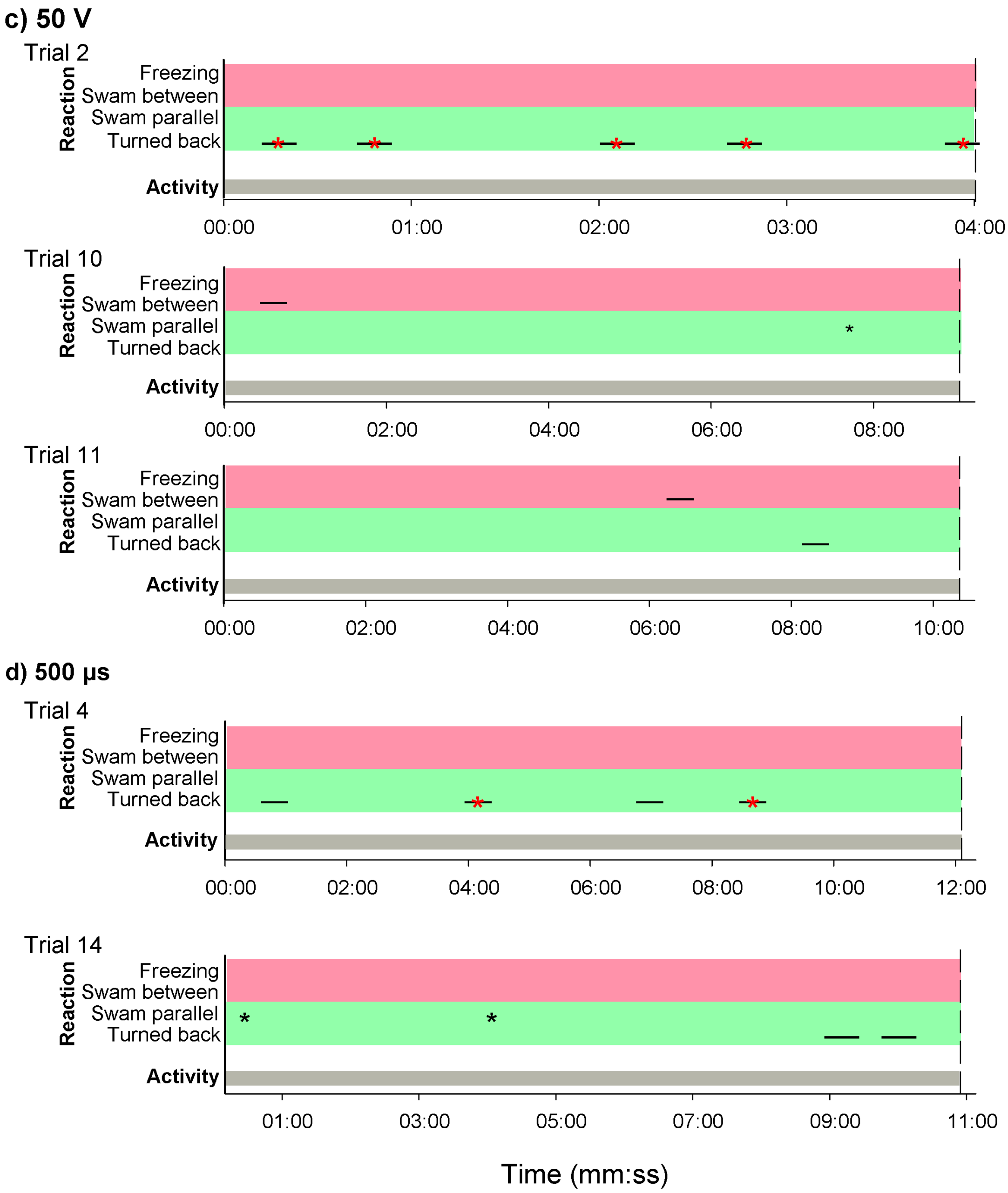

Figure 12 (cont.) Timeline showing the reactions of sawfish 1 to the different electric fields from the beginnig (time 00:00) to the end (vertical dashed line) of each experiment (note the difference in time-scales of the x-axes). For electrified treatments, this corresponds to the period of time from when the electrodes were turned on until they were turned off. – = Sawfish approaches the electrode setup, swimming towards the area between the electrodes; * = sawfish approaches the electrode setup, but swimming towards the electrode located in the middle of the tank. * = sawfish displayed 'twitching' behaviour. X = Sawfish freezing to the extent that electrodes had to be removed from the water. The region of the most desirable reactions is highlighed in green, and the region of least desirable reactions in red. See Figure 5 for details of the approach and reaction types. Activity: grey - swimming; black - resting.

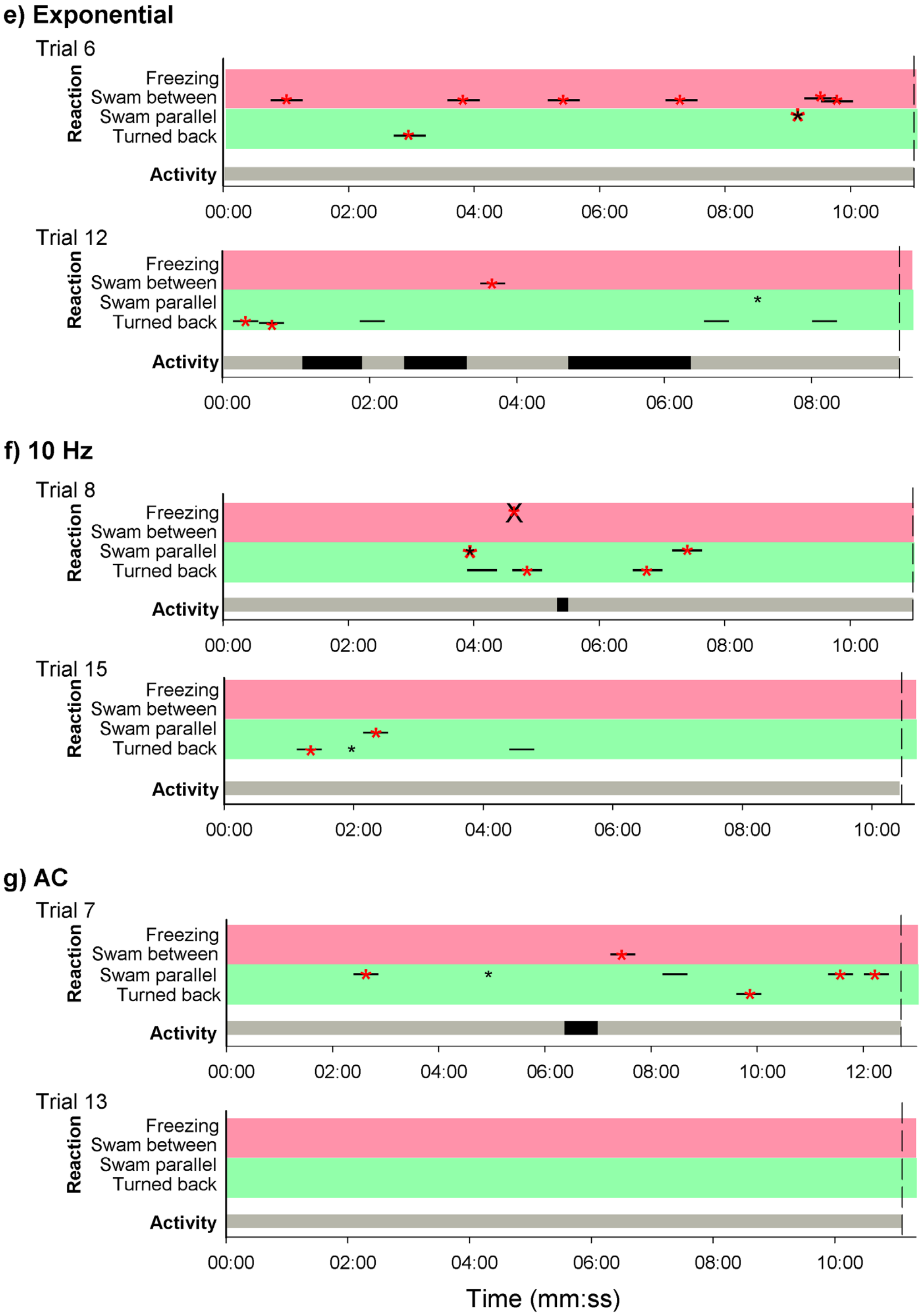

Figure 12 (cont.) Timeline showing the reactions of sawfish 1 to the different electric fields from the beginnig (time 00:00) to the end (vertical dashed line) of each experiment (note the difference in time-scales of the x-axes). For electrified treatments, this corresponds to the period of time from when the electrodes were turned on until they were turned off. – = Sawfish approaches the electrode setup, swimming towards the area between the electrodes; * = sawfish approaches the electrode setup, but swimming towards the electrode located in the middle of the tank. * = sawfish displayed 'twitching' behaviour. X = Sawfish freezing to the extent that electrodes had to be removed from the water. The region of the most desirable reactions is highlighed in green, and the region of least desirable reactions in red. See Figure 5 for details of the approach and reaction types. Activity: grey - swimming; black - resting.

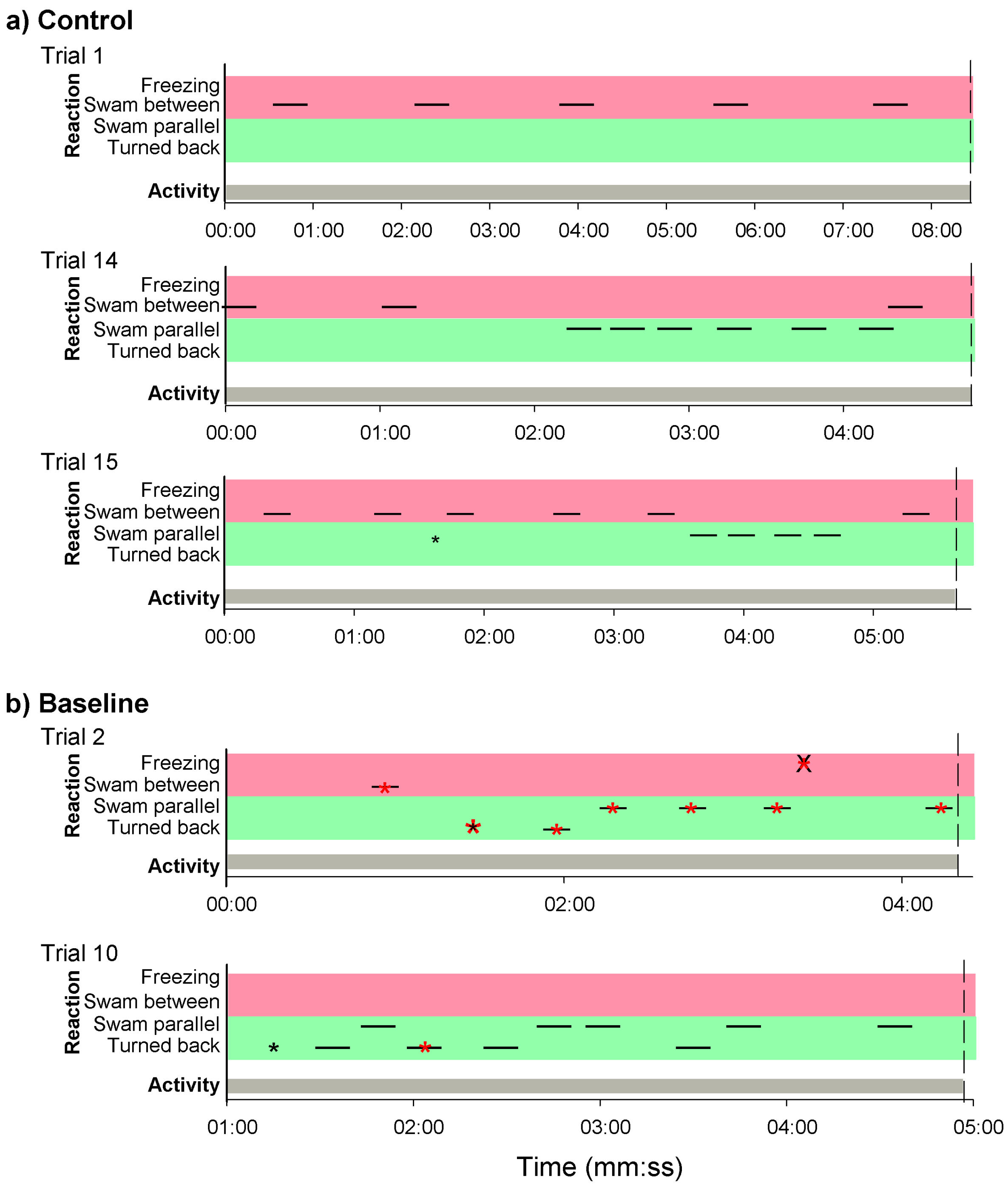

Figure 13. Timeline showing the reactions of sawfish 2 to the different electric fields from the beginnig (time 00:00) to the end (vertical dashed line) of each experiment (note the difference in time-scales of the x-axes). For electrified treatments, this corresponds to the period of time from when the electrodes were turned on until they were turned off. – = Sawfish approaches the electrode setup, swimming towards the area between the electrodes; * = sawfish approaches the electrode setup, but swimming towards the electrode located in the middle of the tank. * = sawfish displayed 'twitching' behaviour. X = Sawfish freezing to the extent that electrodes had to be removed from the water. FL = electrode was removed fromthe water because the sawfish's rostrum was caught in the fishing line that spports the electrode to the wooden beam. The region of the most desirable reactions is highlighed in green, and the region of least desirable reactions in red. See Figure 5 for details of the approach and reaction types. Activity: grey - swimming; black - resting.

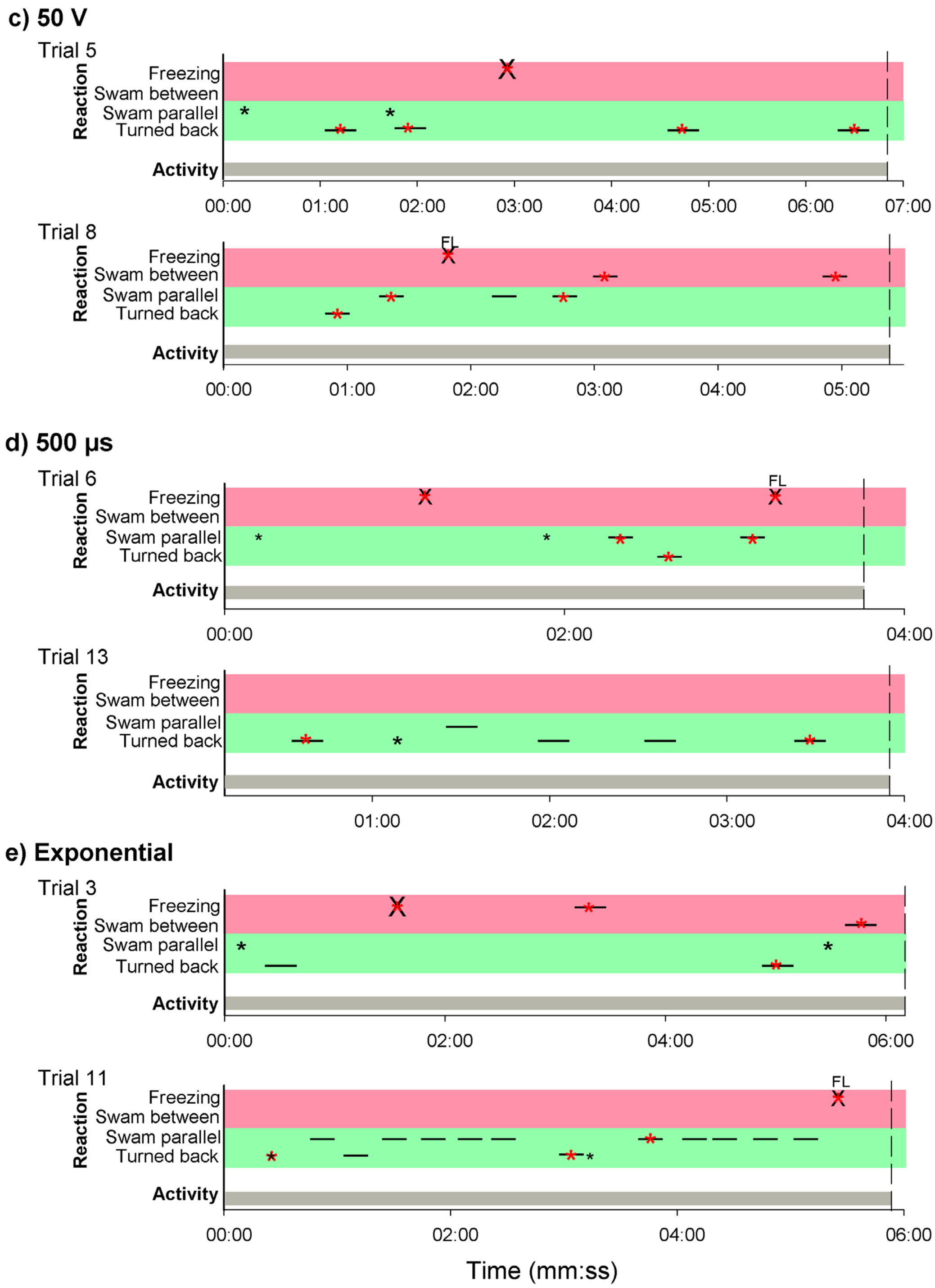

Figure 13 (cont.). Timeline showing the reactions of sawfish 2 to the different electric fields from the beginnig (time 00:00) to the end (vertical dashed line) of each experiment (note the difference in time-scales of the x-axes). For electrified treatments, this corresponds to the period of time from when the electrodes were turned on until they were turned off. – = Sawfish approaches the electrode setup, swimming towards the area between the electrodes; * = sawfish approaches the electrode setup, but swimming towards the electrode located in the middle of the tank. * = sawfish displayed 'twitching' behaviour. X = Sawfish freezing to the extent that electrodes had to be removed from the water. FL = electrode was removed fromthe water because the sawfish's rostrum was caught in the fishing line that spports the electrode to the wooden beam. The region of the most desirable reactions is highlighed in green, and the region of least desirable reactions in red. See Figure 5 for details of the approach and reaction types. Activity: grey - swimming; black - resting.

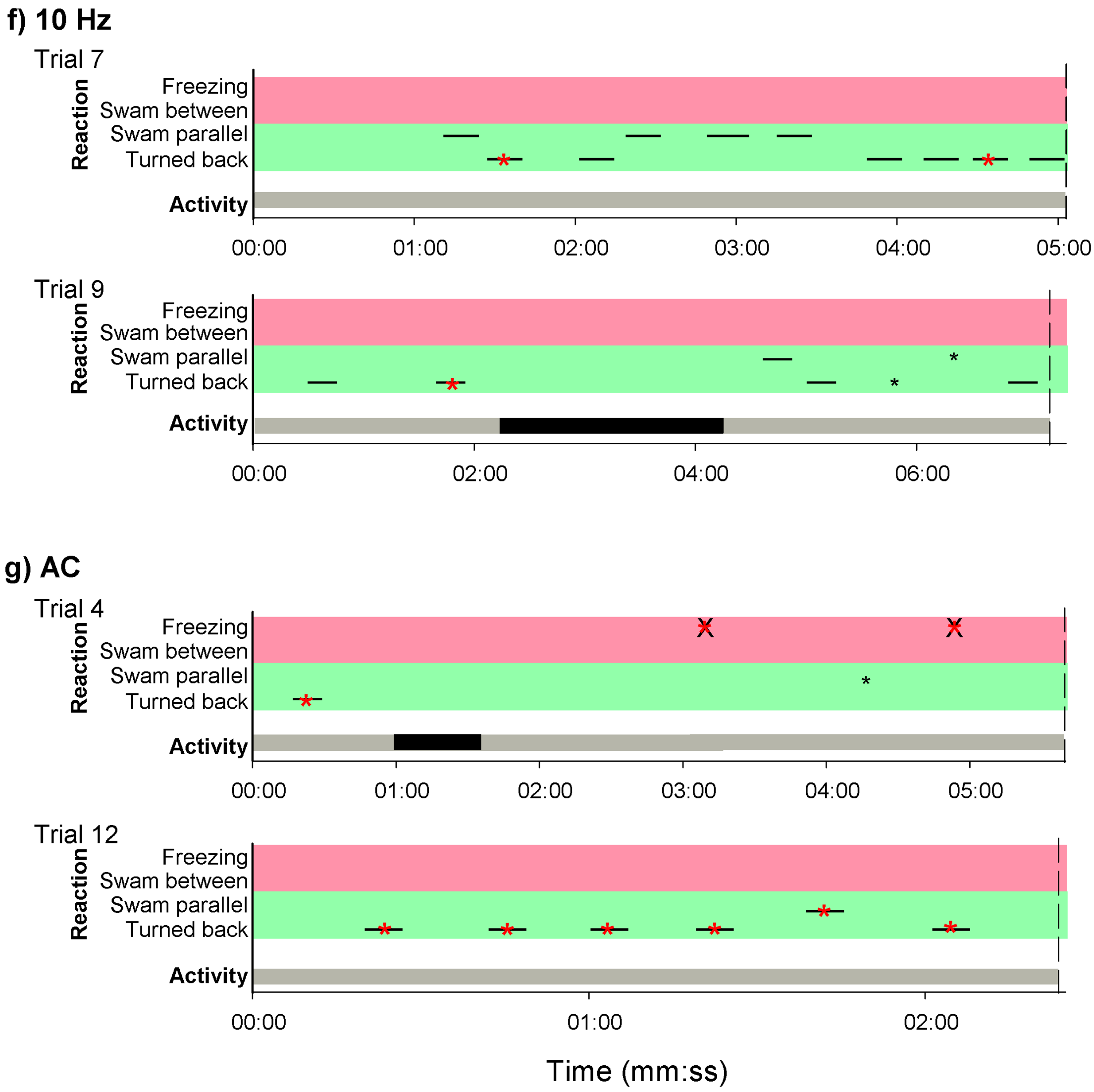

Figure 13 (cont.). Timeline showing the reactions of sawfish 2 to the different electric fields from the beginnig (time 00:00) to the end (vertical dashed line) of each experiment (note the difference in time-scales of the x-axes). For electrified treatments, this corresponds to the period of time from when the electrodes were turned on until they were turned off. – = Sawfish approaches the electrode setup, swimming towards the area between the electrodes; * = sawfish approaches the electrode setup, but swimming towards the electrode located in the middle of the tank. * = sawfish displayed 'twitching' behaviour. X = Sawfish freezing to the extent that electrodes had to be removed from the water. FL = electrode was removed fromthe water because the sawfish's rostrum was caught in the fishing line that spports the electrode to the wooden beam. The region of the most desirable reactions is highlighed in green, and the region of least desirable reactions in red. See Figure 5 for details of the approach and reaction types. Activity: grey - swimming; black - resting.

The effect of the different treatments also varied between the two individuals tested. Table 5 shows that, for sawfish 1, the pulse most likely to be effective in repelling sawfish from trawl fishing gear was the '500 µs', as the sawfish turned back 100% of the time. The 'Baseline' treatment can also be considered as potentially efficient, as only the two favourable behaviours were observed (turning back and swimming parallel to the electrodes) (Table 5). The '10 Hz', 'Exponential', 'AC', and '50 V' treatments led to the most unfavourable behaviours of freezing and/or swimming between the electrodes (i.e. behaviours that would lead to sawfish being caught in the nets). For sawfish 2, however, results differed greatly. This larger individual showed the freezing behaviour more often (seven times) than the smaller individual (sawfish 1, which froze only once), and data suggests that the '10 Hz' pulse would be the most efficient at repelling this individual, as only for this treatment no freezing or swimming between electrodes behaviours was observed (Table 5). Therefore, the treatments that best worked for the smaller individual were not as favourable for the larger individual, and vice-versa.

Table 5. Proportion of times each behaviour was observed in response to each treatment. Colours are in a green-yellow-red scale of this proportion, calculated for each individual sawfish separately, and indicate where each treatment *vs*. behaviour falls within the observed range of proportions, so that red is the maximum value, dark green the lowest, and yellow is the cell with the median value. Other cells are colored proportionally, in a gradient. *n* = total number of approaches for each treatment; only approaches made perpendicularly to the electrode setup are included as not all reactions (e.g. swim between electrodes) could be observed from approaches towards the electrode placed in the midde of the tank (see Figure 5). The pulses most likely to not lead to capture (for each individual) are in bold.

	Behavioural response to electrodes (%)				
	Turned back	**Swam parallel**	**Swam between**	**Freezing**	***n***
Sawfish 1					
Control	20	0	80	0	15
Baseline	**44**	**56**	**0**	**0**	**9**
AC	67	17	17	0	6
Exponential	46	0	54	0	13
10 Hz	63	25	0	13	8
500 µs	**100**	**0**	**0**	**0**	**6**
50 V	75	0	25	0	8
Sawfish 2					
Control	0	42	58	0	24
Baseline	34	50	8	8	12
AC	67	11	0	22	9
Exponential	24	59	6	12	17
10 Hz	**63**	**38**	**0**	**0**	**16**
500 µs	56	33	0	11	9
50 V	45	27	18	9	11

The conditional inference tree identified *treatment* as the variable that better explains the reaction data, separating the Control treatment from the electrified treatments (Figure 14). This split was due to sawfish most often swimming between the electrodes in the control treatment (67% of the time) than in the electrified treatments (11% of the time), and sawfish turning back more often in the electrified treatments than in the control (52% vs. 8% of the time). For the electrified treatments, a secondary split separated the two individuals, as sawfish 1 turned back more often and swam parallel to the electrodes less often than sawfish 2 (62 vs. 46% and 16 vs. 39%, respectively) (Figure 14).

For sawfish 2, there was also a significant effect of *trial number* on reaction type: freezing behaviour was only recorded in the first six trials, and the sawfish also swam between the electrodes more often and swam parallel to the electrodes less often in the first six trials than after the sixth trial (Figure 14). This is likely because the animal learned to avoid swimming too close to the electrode setup following initial exposure, and to turn back rather than swim between the electrodes. Indeed, in the first electrified treatment for sawfish 2 ('Baseline'), the animal swam between the electrodes on the first pass, but in subsequent passes it turned back or swam parallel to the electrode setup (Figure 13b). This individual also typically took a long time to approach the experimental setup after freezing to the extent that the electrodes had to be taken out of the water (e.g. Figure 13e, g), suggesting that the animal learned from experience. This change in reaction type is in agreement with the reaction distance, which was smaller in the first few trials (see Figure 7).

For sawfish 1, a further split separated the 'Baseline' treatment from all others, as freezing and swimming between electrodes behaviour was not registered for this treatment. The factor *individual* also significantly affected sawfish behaviour for the Control treatment because, as mentioned above, when not swimming between the electrodes, sawfish 1 turned back, whereas sawfish 2 swam parallel the electrode setup (Figure 14).

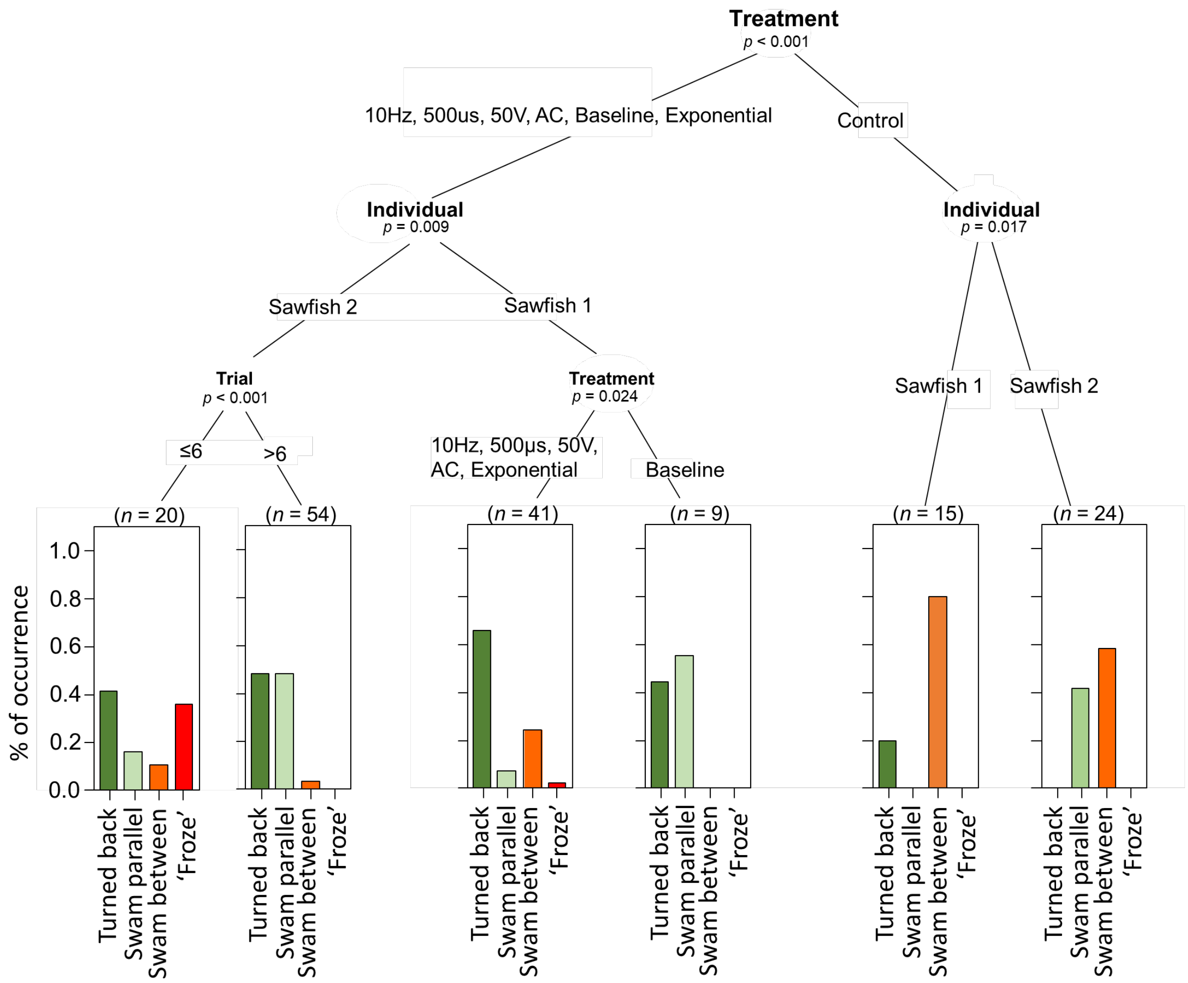

Figure 14. Conditional inference tree model for the contribution of various factors on sawfish reaction to the electrode setup. Bars are the proportion of times each behaviour was recorded for that group. Only data from approaches made perpendicularly to the electrode setup were included.

Twitching

All treatments with the exception of the Control treatment led to twitching behaviour, where the sawfish quickly moved its head and sometimes its whole body side-to-side. Accordingly, the conditional inference tree identified *treatment* as the most important factor explaining the presence of twitching, separating the Control treatment from all others (Figure 15). For the electrified treatments, a secondary split separated the data according to *reaction distance*, where twitching was observed more frequently at distances of ≤1.3 panels (~80 cm) (84% of the time) than at distances >1.3 panels (19% of the time). Twitching was also more vigorous when sawfish came closer to the electrodes. When further away, sawfish could still react to the electric pulse by a sudden change in direction and/or speed, but without twitching behaviour (see Figure 12c,d and Figure 13b,f). For cases when sawfish reacted at ≤1.3 panels distance, a third split on the tree shows that sawfish twitched more frequently in approaches towards the area between the electrodes than when approaches were towards the electrode placed in the middle of the tank (see Figure 5). Finally, for the approaches towards the area between the electrodes, trial number also had a significant effect on twitching, as up to Trial 8, sawfish showed twitching behaviour 98% of the time, whereas from Trial 9 onwards, sawfish only twitched 59% of the time.

Twitching behaviour lasted from one twitch up to prolonging twitching over a 6.4 s period. However, in 8 occasions, the electric field overwhelmed the sawfish's sensory system to the extent that the animal was immobilised by the twitching behaviour (i.e. freezing) and the electrodes had to be removed from the water (Figure 16). This freezing behaviour was observed only once for sawfish 1 (for the '10 Hz' treatment), but was observed seven times for sawfish 2 (once for 'Baseline', '50 V', and '500 µs' treatments, and twice each for the 'Exponential' and 'AC' treatments). Conditional inference tree analysis found that none of the explanatory variables considered (see Table 4) could significantly explain twitching duration.

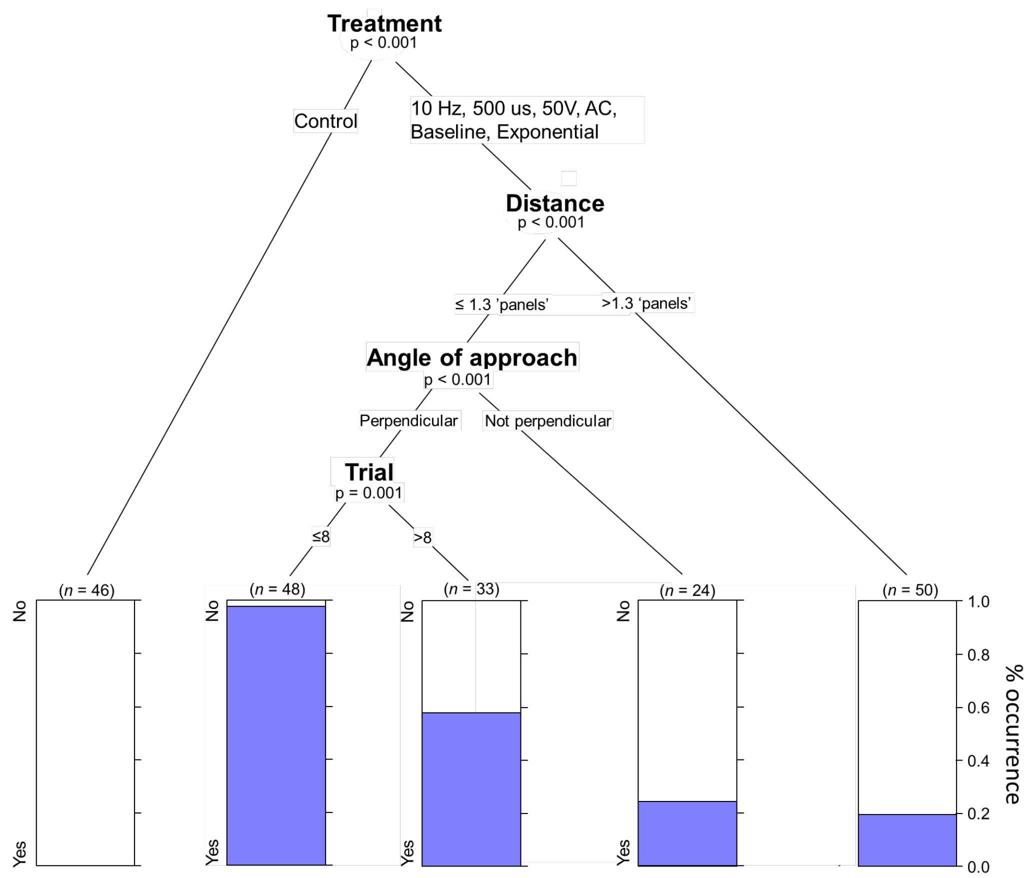

Figure 15. Conditional inference tree on the effect of the different explanatory variables (see Table 4) on the presence/absence (Yes/No) of twitching behaviour (proportion).

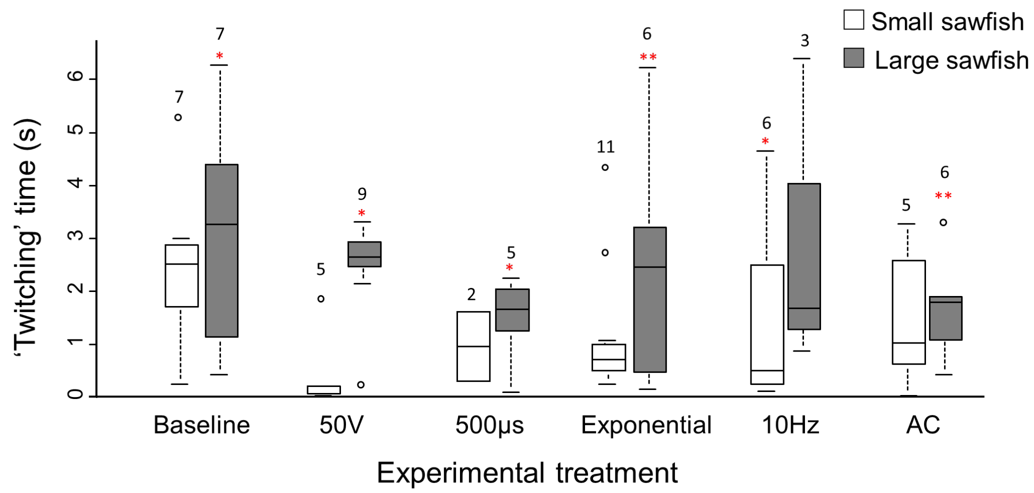

Figure 16. Box and whisker plots showing the distribution of twitching times for each treatment and each sawfish. Boxes delimitate the upper and lower quantiles, lines within the boxes represent the medians, whiskers represent the minimums and maximums, and circles are the outliers. Numbers above each box represent the number of samples (number of times twitching behaviour was observed). * - number of times the animal froze under the influence of the electric field, and the electrodes had to be taken out of the water.

Underwater video observations

Underwater video observations show that sawfish typically swim between 10 and 30 cm from the substrate, and typically reacted to the electric fields by elevating the rostra, moving higher in the water column (i.e. at increasing distances from the substrate) and moving the head side-to-side, in a behaviour described as twitching. See Figure 17 for examples of the images captured with the underwater camera.

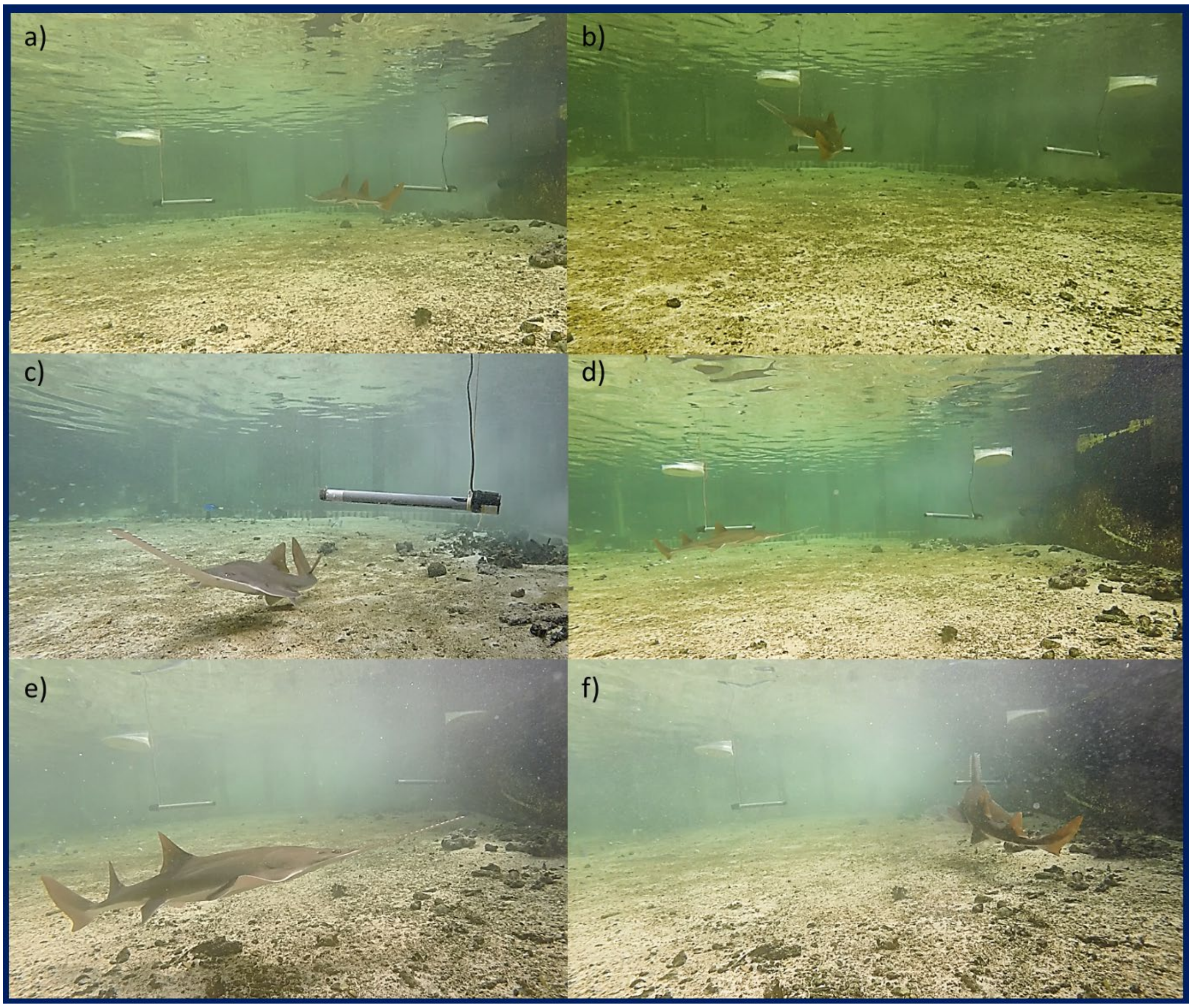

Figure 17. Examples of images of sawfish 1 registered by the underwater video camera, showing (a) the sawfish swimming at ~25 cm from the substrate between the electrodes in the Control Trial 3; (b) the sawfish turning around (turning back) after entering the 'Baseline' electric field (Trial 9; note the elevated rostrum); (c) the sawfish starting to react to the 'Exponential' pulse field by twitching, elevating the rostrum, and swimming upwards through the electric field (Trial 6); (d) the sawfish swimming through the tank before turning to approach the electric field; and the sawfish (e) swimming before approaching the '10 Hz' electric field and (f) starting to turn back after entering the '10 Hz' electric field (Trial 8).

Discussion

Both sawfish clearly sensed and reacted to the electric fields tested. However, none of the waveforms used could repel from a distance likely to be sufficient to deter sawfish from entering trawl nets (3–4 m). Indeed, reaction distances were small, typically <1.2 m, likely too small to avoid sawfish being captured by moving nets, e.g. the NPF trawl at speeds of ~3.2–3.5 knots (1.6–1.8 $m.s^{-1}$) (Bishop & Sterling 2007).

One of the most noticeable reactions to the electric field was twitching. Although twitching was more frequently observed when sawfish moved closer to the electrode setup, twitching incidence and intensity did not seem to be related to pulse frequency, voltage, or duration (pers. obs; Figures 15 and 16). Interestingly, twitching was not always observed, sawfish sometimes reacted to the electric field by rapidly changing swimming speed and/or direction without twitching (see Figures 12 and 13), and twitching occurred more often in trials run on the first experimental days than on the last experimental days (see Figure 15). This was most likely related to the smaller reaction distances in the first experiments compared to the last experiments (see Figure 7), i.e. to sawfish learning to react earlier (by changing swimming direction/speed) following initial exposures, therefore not swimming into the strongest parts of the electric field and decreasing the likelihood of twitching. Although the reduced amount of twitching could also be due to sawfish becoming habituated to the electric field and decreasing behavioural reaction after repeated exposures. Such habituation to electric (Kimber et al. 2014, Kempster et al. 2016, Egeberg et al. 2019) and magnetic fields (O'Connell et al. 2011, Robbins et al. 2011) has been shown for other elasmobranch species, where individuals showed decreasing reaction after repeated exposures.

The twitching observed in the present study is a different behaviour from what has been described for juvenile Largetooth Sawfish before, in the context of feeding and as a reaction to (weak, 18–80 mA) prey-simulating electric fields (Wueringer et al. 2012b). Wueringer et al. (2012b) named that behaviour *wiggle* and describe it as follows: *"When the sawfish's saw almost touches the prey or dipole centre it is engaged in short lateral movements, during which neither the saw nor its teeth are aimed at the prey."* Twitching in the present study is a response to a strong electric field, and is not related to a feeding response elicited by the detection of prey or a weak electric field, as in Wueringer et al. (2012b). The distance from the electric field source at which twitching was displayed was also much larger in the present study than the distance at which *wiggle* was reported to occur (<5 cm from the dipoles; Wueringer et al. (2012b)).

Twitching behaviour similar to that of the present study has been previously reported for other elasmobranch species such as Scalloped Hammerhead (*Sphyrna lewini*) and Leopard Sharks (*Triakis semifasciata*) upon entering electric fields (Marcotte & Lowe 2008). In the Leopard Sharks, it was observed that twitches can occur in any part of the body, but generally occur in the head because the animals swim into the field head first, suggesting that the electric field directly affects the muscles, in a neuromuscular response (Marcotte & Lowe 2008). In our pilot study, while low frequencies of 1–2 Hz led to almost no response, at 5–10 Hz sawfish were still able to escape the electric field (despite twitching), and at a higher frequency of 20 Hz strong involuntary muscle contractions of the fins and body were observed, which led to sawfish immobilisation. This agrees with previous studies that show that the higher the frequency, the less power is needed to immobilise fish (Dolan & Miranda 2003) and suggests that the twitching and freezing behaviours were physiological responses to the electric fields.

It was also clear that the effect of the electric field was much stronger on the sawfish's head than on the relatively thin rostrum. For example, sawfish were observed to swim into the field until the rostrum was between the electrodes, when they would start moving the head side-to-side, but would only react by changing direction when the head was between the electrodes. On another example, in the '500 µs' treatment, sawfish 2 could have the rostrum between the two electrodes and still be able to turn back and swim away but, if it swam into the field until the head was between the two electrodes, it was often unable to exit the electric field and froze to the extent that one electrode had to be removed from the water (Trial 6, Figure 14d). This could be related to the difference in width between the heads and the rostra, as at the same voltage gradient, the potential difference will be greater for the wider head than for the thinner rostra. This difference could also be related to ampullary canal length, which is directly correlated with electric field sensitivity (for a review see Wueringer (2012)), as in the Largetooth Sawfish, the longest ampullary canals are located posterior of the eyes and mouth (Wueringer et al. 2011).

The sawfish not only reacted to the electric fields, but reaction distance and reaction type also changed with time, suggesting that the animals are capable of learning to avoid an unpleasant stimulus. Learning abilities have been reported for several elasmobranch species, e.g. Ocellate River Stingrays (*Potamotrygon motoro*) (Schluessel & Bleckmann 2005) and Grey Bamboo Sharks (*Chiloscyllium griseum*) (Schluessel & Bleckmann 2012) can learn to perform spatial tasks, and Blacktip Reef Sharks (*Carcharhinus melanopterus*) can learn to avoid recapture following previous catch-and-released experiences (Mourier et al. 2017). Although a repeated number of exposures was necessary for sawfish to avoid the electric fields, this learnt behaviour could be useful for stationary fisheries such as gill net fisheries, as nets are often set in the same location for several days. Note however that the teleost fish present in the experimental tank also seemed affected by the electric fields and avoided the area, staying >~1.5 m away from the electrode setup. This is in agreement with results from Verschueren et al. (2019), where it was found that teleost bycatch in the Brown Shrimp (*Crangon crangon*) fishery (North Sea) was reduced when pulse trawling was used. However, previous studies suggested that the electric fields used in shark repellents had no impact on teleosts (Broad et al. 2010). Further studies on the effects of electric fields on teleosts are required to better understand the potential impacts on target species.

Individual differences. The two sawfish tested reacted differently to the different treatments, and the treatments that best worked for sawfish 1 were not favourable for sawfish 2, and vice-versa. For example, for sawfish 1, the '500 µs' treatment lead to the most desirable reaction (turning back) 100% of the time, and inter-approach times were also amongst the longest, suggesting that that individual generally avoided the electric field area, and when it approached it, it displayed effective escaping behaviour. However, for sawfish 2, this '500 µs' treatment led to freezing 11% of the time, a behaviour that would lead to capture by moving fishing nets. The 'Baseline' treatment could also be considered as potentially effective for sawfish 1, as it led to reaction at largest distances (although still too small to be effective) and only resulted in 'turning back' or 'swimming parallel to the electrodes' reactions. For sawfish 2, this 'Baseline' pulse also led to a repelling behaviour, but only in 84% of the passes, suggesting that this treatment is likely to be less effective in repelling this larger sawfish.

This difference between the two individuals could be related to animal size. Larger teleost fish react more strongly to strong electric fields than smaller fish (Dolan & Miranda 2003) as their larger dimensions lead to a larger potential difference over their body. Although this size effect becomes minor once fish reach 14–18 cm in size (Dolan & Miranda 2003), i.e. at much smaller sizes than our smaller sawfish, it can still be relevant to our experiments, as sawfish rostra and heads (which are the parts that first enter the electric field) were narrower than this size threshold. In addition, with growth, the ampullary canals of elasmobranchs lengthen and the number of receptor cells increases, meaning large individuals will have higher sensitivity and larger sensory fields than smaller individuals (Sisneros et al. 1998, Kajiura 2001, Rivera-Vicente et al. 2011). This could explain the differences between the two individuals, including for example why the larger sawfish displayed freezing behaviour more often (seven times) than the smaller sawfish (once).

Stobutzki et al. (2002) found that sawfish caught in the NPF were 193 ± 19 cm (range: 124–255 cm) TL, i.e. closer to the size of the larger individual tested here. So, results for sawfish 2 could be considered the most appropriate to be used to develop an effective deterrent. If that is the case, a device that produces an electric pulse similar to the '10 Hz' treatment would be most appropriate, as this was the only treatment that led to behaviours conducive to escaping, and to a reaction from a larger distance. However, reaction distance was still too small to allow escaping moving fishing nets, so if such electric field setup was to be incorporated into fishing nets, it would have to be placed ahead of the net to be effective.

Since only two individuals, and of different sizes, were tested in the present study, it is not possible to determine if this treatment would consistently work on other large sawfish. Note however that the differences in reaction between the two sawfish tested could be related to individual behavioural differences, regardless of animal size, e.g. Huveneers et al. (2013, 2018) found that behavioural responses to electric fields to be highly variable accross White Shark (*Carcharodon carcharias*) individuals. Additionally, the relative large size of the animals in relation to the experimental tank somewehat limits their manoeuvrability in response to and in avoiding the electrodes, particularly for the larger individual. This could also have contributed to the differences in reaction between individuals.

Voltage gradient. Due to equipment failure, it was not possible to describe the voltage field gradients around the electrodes or to measure the field strength (in $V.m^{-1}$) for the treatment and distance at which sawfish most reacted. However, the voltage gradient around the Ocean Guardian Freedom7™ (pulse characteristics: bipolar pulse of exponential shape, 115 V peak voltage, 1.5 Hz frequency, 1000 µs duration) has been described by Kempster et al. (2016). Since the experimental setup used in the present study was based on the Ocean Guardian™ setup, resulting in similar electrode size, positioning and distance between electrodes, we can assume that our setup had a voltage gradient similar to that described in that study. Kempster et al. (2016) found the greatest voltage gradient of ≥100 $V.m^{-1}$ within 5 cm of each electrode, and that the gradient decreased sharply with distance from the electrodes (Figure 19), i.e. that the electric field quickly dissipated.

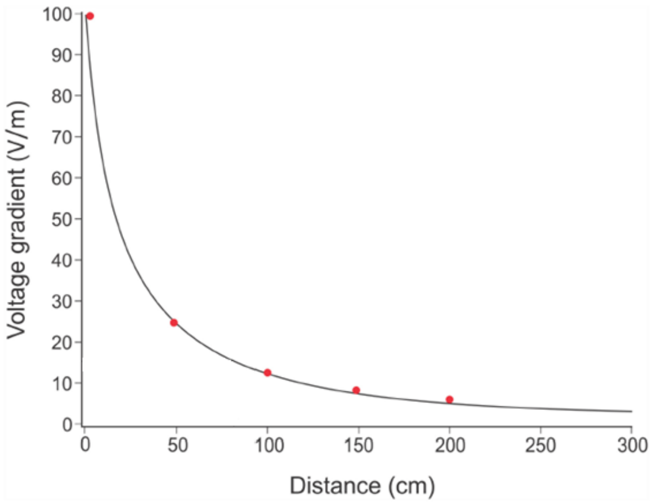

Figure 18. Ocean Guardian™ voltage gradient decline with increasing distance from the electrodes, measured in a 4 m deep bay, at seawater temperature and salinity conditions of 15 °C and 37 ppt, respectively. Red dots are the measurements taken using the voltage gradient probe. Figure from Kempster et al. (2016).

Although our voltage output was lower than that of the Ocean Guardian™ (100 vs. 115 V), our other waveform parameters, namely rectangular vs. exponential pulse shape, higher frequency (5 vs. 1.5 Hz) and longer pulse duration (1500 vs. 1000 µs), would make our pulse stronger and more easily detectable by fish (Bird & Cowx 1993, Dolan & Miranda 2003, Weber et al. 2016). Moreover, seawater temperature (15 °C) and salinity (37 ppt) in Kempster's study mean that conductivity was lower than that estimated based on the average temperature (25 °C) and salinity (32 ppt) conditions of the present study (45.1 vs. 49.5 $mS.cm^{-1}$ (Lide 2002)), and the higher the seawater conductivity, the less voltage is needed to produce the same effect on fish (Lines & Kestin 2004). Additionally, electric field propagation in the field (and in Kempster's study, which was done in a 4 m deep bay) would be different to that in our study due to the effect the confined boundaries and relatively shallow depth of our experimental tank. Since the produced electricity will dissipate in the available volume of water, under similar conditions the electrical field would be stronger and more easily detectable by sawfish in our experimental tank than at sea. However, despite this more concentrated, stronger field, the pulse stimuli tested did not consistently lead to fleeing reaction, and reaction distances were small. If our experimental setup was used in the field, sawfish might react at even smaller distances.

It has been estimated that a voltage gradient of 15.7 $V.m^{-1}$ is needed to repel White Sharks, which on the Ocean Guardian™ is attained at ~82 cm from the electrodes (Kempster et al. 2016) (corresponding to 1.3 'panels' in this study). Similar voltage gradient thresholds elicited retreat behaviour in scalloped hammerhead (18.5 $V.m^{-1}$) and leopard sharks (~9.6 $V.m^{-1}$) (Marcotte & Lowe 2008), which, based on the relationship from Kempster et al. (2016), would correspond to a distance of ~65 and ~120 cm (i.e. 1 and 2 'panels'), respectively, from the Ocean Guardian™ electrodes. These distances are not far from the average reaction distances of our 'Baseline' and '10 Hz' treatments (1.4 ± 0.6 panels), the treatments that led to the largest reaction distances. However, while the aim of the Ocean Guardian™ and other shark deterrents is to startle/repel approaching sharks to reduce the likelihood of shark bites, the aim of a sawfish BRD would be to avoid the capture of sawfish by moving nets. In the case of the shark deterrents, the objective can be met by startling and making the animal stop its intended behaviour and swim away from the user in any direction, while in a BRD the sawfish can only avoid capture by 1) sensing and being repelled at a distance large enough that allows turning around without being caught by the moving fishing net and 2) actively swimming outside the path of the net, in the opposite direction that the net is travelling. These outcomes are more difficult to obtain.

Future directions and possible solutions. Increasing voltage, frequency or pulse duration could potentially improve the usefulness of an electric field to repel sawfish. Adverse side effects from strong electric fields have, however, been reported in teleosts, including haemorrhages and spinal injuries (e.g. Snyder 2003, van Marlen et al. 2014, de Haan et al. 2016, Soetaert et al. 2016, ICES 2017). Although such injuries have not been observed in elasmobranchs, i.e. the two studies on elasmobranchs available to date did not report negative effects (de Haan et al. 2009, Desender et al. 2017, both conducted on the Small-Spotted Catshark, *Scyliorhinus canicula)*, we did not subject the sawfish to stronger electric fields due to ethical concerns. In addition, higher energy waveforms (i) be logistically more challenging to implement and (ii) potentially increase stress.

Note also that the 'Baseline' treatment was selected following a two-day pilot tests on two sawfish, where the different waveform parameters (pulse polarity, shape, voltage, frequency, and duration) were independently adjusted to identify the waveform most likely to lead to fleeing reaction, without being too stressful for the fish. Those tests showed that a higher frequency of 20 Hz led to very fast muscle stimulation, cramping and immobility, visibly stressing the animals. Given the conservation concern of sawfish species, this is not a positive outcome, particularly if subjecting animals to an electric field would not necessarily stop them from entering fishing nets.

Magnetic fields could also be used to reduce sawfish bycatch, as these have been found to repel elasmobranchs (e.g. Rigg et al. 2009, O'Connell et al. 2015, Siegenthaler et al. 2016). For example, a recent study showed magnets reduced elasmobranch bycatch in fish traps (Richards et al. 2018). However, the distance from which sharks reacted to magnets in those studies was small, typically <0.5 m (e.g. Rigg et al. 2009, O'Connell et al. 2010). Barium-ferrite permanent magnets generate a flux that rapidly decreases in intensity, from ~1,000 G near the magnet to an amount comparable to the Earth's magnetic field (0.25–0.65 G) at distances of 0.30–0.50 m (O'Connell et al. 2014a, 2014b), showing how rapidly the magnetic field decreases. Sharks would therefore need to be <0.30 m for such magnets to act as real deterrents. As such, a magnet can reduce elasmobranch bycatch when placed next to a trap entrance, but is unlikely to reduce bycatch in longline or nets (e.g. Grant et al. 2018). Moreover, magnetic fields often affect some species but not others (O'Connell et al. 2011, O'Connell et al. 2014b), and the effectiveness of magnetic field deterrents can vary depending on magnet-type (Hart & Collin 2015), and on context such as level of satiation (O'Connell et al. 2014b) and presence of conspecifics (Robbins et al. 2011). Magnetic deterrents can also lead to highly variable behaviour among individuals (O'Connell & He 2014, Westlake et al. 2018), and some studies even reported increased elasmobranch catches in hooks equipped with magnets (Porsmoguer et al. 2015). Rigg et al. (2009) tested the effect of ferrite magnets on the reaction and spatial use of five shark species, and found that the Speartooh Shark (*Glyphis glyphis*) showed low magnetic sensitivity. They proposed that this was because of their use of both fresh and saltwater habitats, which that species has in common with sawfishes. In the present study, we placed the same magnets used by Rigg et al. (2009) in our experimental tank and noted no effect on sawfish swimming behaviour, suggesting that at least Rigg's ferrite magnets are not likely to effectively reduces sawfish bycatch.

We suggest that the use of electric fields as sawfish deterrents should be revisited if/when technological advances allow for electric field propagation to be increased and elicit fleeing behaviour from greater distances. Until then, other mitigation measures that can reduce sawfish interactions should be investigated. If bycatch cannot be reduced, an assessment of post-release survival and means to increase post-release survival could be an alternative approach to reduce the effects of bycatch on population resilience, without needing to change the spatio-temporal distribution of the fishery.

Conclusion

Overall, results from this study show that sawfish did not display a fleeing behaviour from a distance large enough to avoid entering trawl nets and that currently available devices that produce electric fields are unlikely to significantly reduce sawfish bycatch in prawn trawlers. Indeed, 1) reaction distances were too small to allow for effective escaping moving nets; and 2) exposure to the electric fields tested did not consistently lead to reactions conducive to escaping.

Implications

Although sawfish reacted to the tested electric fields with two behaviours that can be considered as desirable for the development of a sawfish repelling device, the small reaction distances mean that the currently available pulse generators are unlikely to reduce sawfish bycatch in trawl nets. It is however possible that future technological advances can lead to the improvement of those devices, allowing for the production of electric fields with greater effective range, that elicit effective fleeing behaviours from greater distances. When such technological advances are achieved, there will be subsequent challenges related to successfully incorporating such devices into fishing vessels.

Recommendations

The use of electric fields as sawfish deterrents should be revisited if/when technological advances allow for electric field propagation to be increased to elicit fleeing behaviour from larger distances. Until then, methods that improve post-release survival should be used (see "A guide to releasing sawfish - Gulf of Carpentaria inshore and offshore set net fishery", Department of Employment Economic Development and Innovation 2010) and developed, other mitigation measures should be investigated, and a better understanding of the spatio-temporal overlap between sawfish distribution and the various fisheries catching them should be developed, to reduce sawfish interactions and increase post-release survival.

Further development

The development of a bycatch reduction device that effectively deters sawfish requires further research and development to identify the electric fields or other methods that increase sawfish's reaction distance. New/improved pulse generator devices need to be developed before this method can be considered to be used as a sawfish deterrent in net fisheries.

Extension and Adoption

The Northern Prawn Fishery (NPF) committees have been updated on the progress of this study at each meeting (the Northern Prawn Fishery Resource Assessment Group in May and November 2019, the Northern Prawn Fishery Management Advisory Committee in February 2019 and the Northern Prawn Fishery Industry in July 2018, February and August 2019). The broader NPF industry has been updated at pre-season briefings in March and July in 2018 and 2019 in Darwin, Cairns, and Karumba since the project began. Results from this project will also be presented and discussed with industry by lead researchers and/or co-investigators at pre-season skipper briefings in March 2020 in Darwin, Cairns, and Karumba.

We will also engage in a variety of outreach activities to reach a broad cross-section of the chondrichthyan (shark, ray, and chimaera) research, management, and policymaker community. Articles will be submitted to the Oceania Chondrichthyan Society and the International Union for the Conservation or Nature (IUCN) Species Survival Commission Shark Specialist Group newsletters, enabling exposure to national, regional, and international scientists and managers.

We will present results in Canberra at a visit to the Department of the Environment and Energy and the Australian Fisheries Management Agency in April 2020 to engage directly with the Commonwealth Government (beyond FRDC). This visit is being facilitated by the National Environmental Science Program (NESP) Marine Biodiversity Hub's Threatened Species Theme to engage directly with managers on issues surrounding Australia's threatened marine species.

Appendices

References

Aristi DF, Boesono H, Prihantoko K, Gautama D (2018) Electro shield system applications on set gill net as efforts to preserve shark resources. Journal of Physics: Conference Series 1025:012022

Bird D, Cowx I (1993) The selection of suitable pulsed currents for electric fishing in waters. Fisheries Research 18:363-376

Bishop J, Sterling DJ (2007) Technology Utilisation in Australia's Northern Prawn Fishery. Report on the Gear Sheet supplementary questionnaire 2006 and Revised assessment of swept area performance and relative fishing power in Australia's Northern Prawn Fishery, 2001-2006. 48 pp. AFMA (Australian Fisheries Management Authority), Canberra.

Brewer D, Heales D, Milton D, Dell Q, Fry G, Venables B, Jones P (2006) The impact of turtle excluder devices and bycatch reduction devices on diverse tropical marine communities in Australia's northern prawn trawl fishery. Fisheries Research 81:176-188

Brill R, Bushnell P, Smith L, Speaks C, Sundaram R, Wang J (2009) The repulsive and feeding-deterrent effects of electropositive metals on juvenile sandbar sharks *(Carcharhinus plumbeus*). Fishery Bulletin 107:298

Broad A, Knott N, Turon X, Davis AR (2010) Effects of a shark repulsion device on rocky reef fishes: no shocking outcomes. Marine Ecology Progress Series 408:295-298

Brodziak J, Link J (2002) Ecosystem-based fishery management: what is it and how can we do it? Bulletin of Marine Science 70:589-611

Campbell MJ, Tonks ML, Miller M, Brewer DT, Simpfendorfer CA, Courtney AJ (2020) Factors affecting elasmobranch escape from turtle excluder devices (TEDs) in a tropical penaeid-trawl fishery. Fisheries Research 224

Chateauminois E, Hoarau M, Maillard F (2019) Innovative projects of the shark risk reduction resource and support center (CRA) - Results of experimental tests on individual electrical impulse repulsion equipment - Final Report. CRA-V 2.1.

Davies R, Cripps S, Nickson A, Porter G (2009) Defining and estimating global marine fisheries bycatch. Marine Policy 33:661-672

de Haan D, Fosseidengen J, Fjelldal P, Burggraaf D, Rijnsdorp A (2016) Pulse trawl fishing: characteristics of the electrical stimulation and the effect on behaviour and injuries of Atlantic cod (*Gadus morhua*). ICES Journal of Marine Science 73:1557-1569

de Haan D, Van Marlen B, Velzeboer I, van der Heul J, van de Vis J (2009) The effects of pulse stimulation on biota-Research in relation to ICES advice-Effects on dogfish. No. C105/09. IMARES

Department of Employment Economic Development and Innovation (2010) A guide to releasing sawfish - Gulf of Carpentaria inshore and offshore set net fishery. Queensland Government.

Department of the Environment (2015) Sawfish and River Sharks Multispecies Recovery Plan, Commonwealth of Australia.

Desender M, Kajiura S, Ampe B, Dumolein L, Polet H, Chiers K, Decostere A (2017) Pulse trawling: Evaluating its impact on prey detection by small-spotted catshark (*Scyliorhinus canicula*). Journal of Experimental Marine Biology and Ecology 486:336-343

Devitt KR, Adams VM, Kyne PM (2015) Australia's protected area network fails to adequately protect the world's most threatened marine fishes. Global Ecology and Conservation 3:401-411

Dolan C, Miranda L (2003) Immobilization thresholds of electrofishing relative to fish size. Transactions of the American Fisheries Society 132:969-976

Dulvy NK, Davidson LN, Kyne PM, Simpfendorfer CA, Harrison LR, Carlson JK, Fordham SV (2016) Ghosts of the coast: global extinction risk and conservation of sawfishes. Aquatic Conservation: Marine and Freshwater Ecosystems 26:134-153

Egeberg CA, Kempster RM, Hart NS, Ryan L, Chapuis L, Kerr CC, Schmidt C, Gennari E, Yopak KE, Collin SP (2019) Not all electric shark deterrents are made equal: Effects of a commercial electric anklet deterrent on white shark behaviour. PLoS one 14:e0212851

Friard O, Gamba M (2016) BORIS: a free, versatile open-source event-logging software for video/audio coding and live observations. Methods in Ecology and Evolution 7:1325-1330

Fry G, Barwick M, Lawrence E, Tonks M (2015) Monitoring interactions with bycatch species using crew-member observer data collected in the Northern Prawn Fishery: 2013 – 2014. Final Report to AFMA; R2013/0806. CSIRO, Australia. Pp. 218.

Grant SM, Sullivan R, Hedges KJ (2018) Greenland shark (*Somniosus microcephalus*) feeding behavior on static fishing gear, effect of SMART (Selective Magnetic and Repellent-Treated) hook deterrent technology, and factors influencing entanglement in bottom longlines. PeerJ 6:e4751

Griffiths SP, Brewer DT, Heales DS, Milton DA, Stobutzki IC (2006) Validating ecological risk assessments for fisheries: assessing the impacts of turtle excluder devices on elasmobranch bycatch populations in an Australian trawl fishery. Marine and Freshwater Research 57:395-401

Hall MA, Alverson DL, Metuzals KI (2000) By-catch: problems and solutions. Marine Pollution Bulletin 41:204-219

Hall SJ, Mainprize BM (2005) Managing by-catch and discards: how much progress are we making and how can we do better? Fish and Fisheries 6:134-155

Hart NS, Collin SP (2015) Sharks senses and shark repellents. Integrative zoology 10:38-64

Hothorn T, Hornik K, Strobl C, Zeileis A (2010) Party: A laboratory for recursive partytioning.

Hothorn T, Hornik K, Zeileis A (2006) Unbiased recursive partitioning: A conditional inference framework. Journal of Computational and Graphical statistics 15:651-674

Hothorn T, Hornik K, Zeileis A (2015) ctree: Conditional inference trees. The Comprehensive R Archive Network:1-34

Huveneers C, Rogers PJ, Semmens JM, Beckmann C, Kock AA, Page B, Goldsworthy SD (2013) Effects of an electric field on white sharks: in situ testing of an electric deterrent. PLOS ONE 8:e62730

Huveneers C, Whitmarsh S, Thiele M, Meyer L, Fox A, Bradshaw CJ (2018) Effectiveness of five personal shark-bite deterrents for surfers. PeerJ 6:e5554

ICES (2017) Final Report of the Working Group on Electrical Trawling. ICES CM 2017/SSGIEOM:11

IJmuiden, the Netherlands

Jaiteh VF, Allen SJ, Meeuwig JJ, Loneragan NR (2014) Combining in-trawl video with observer coverage improves understanding of protected and vulnerable species by-catch in trawl fisheries. Marine and Freshwater Research 65:830-837

Jordan LK, Mandelman JW, Kajiura SM (2011) Behavioral responses to weak electric fields and a lanthanide metal in two shark species. Journal of Experimental Marine Biology and Ecology 409:345-350

Jordan LK, Mandelman JW, McComb DM, Fordham SV, Carlson JK, Werner TB (2013) Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: a review with new directions for research. Conservation Physiology 1:cot002

Kaimmer S, Stoner AW (2008) Field investigation of rare-earth metal as a deterrent to spiny dogfish in the Pacific halibut fishery. Fisheries Research 94:43-47

Kajiura SM (2001) Head morphology and electrosensory pore distribution of carcharhinid and sphyrnid sharks. Environmental Biology of Fishes 61:125-133

Kajiura SM, Holland KN (2002) Electroreception in juvenile scalloped hammerhead and sandbar sharks. Journal of Experimental Biology 205:3609-3621

Kempster RM, Egeberg CA, Hart NS, Ryan L, Chapuis L, Kerr CC, Schmidt C, Huveneers C, Gennari E, Yopak KE (2016) How close is too close? The effect of a non-lethal electric shark deterrent on white shark behaviour. PLOS ONE 11:e0157717

Kimber JA, Sims DW, Bellamy PH, Gill AB (2014) Elasmobranch cognitive ability: using electroreceptive foraging behaviour to demonstrate learning, habituation and memory in a benthic shark. Animal cognition 17:55-65

Lide DR (2002) Handbook of Chemistry and Physics, 2002-2003, 83rd Edition. CRC Press, Boca Raton, FL

Lines J, Kestin S (2004) Electrical stunning of fish: the relationship between the electric field strength and water conductivity. Aquaculture 241:219-234

Marcotte MM, Lowe CG (2008) Behavioral responses of two species of sharks to pulsed, direct current electrical fields: testing a potential shark deterrent. Marine Technology Society Journal 42:53-61

Milton DA (2001) Assessing the susceptibility to fishing of populations of rare trawl bycatch: sea snakes caught by Australia's Northern Prawn Fishery. Biological Conservation 101:281-290

Mobsby D, Curtotti R, Bath A (2019) Australian fisheries economic indicators report 2017: Financial and economic performance of the Northern Prawn Fishery, ABARES, Canberra, February. CC BY 4.0. https://doi.org/10.25814/5c60cb388f85f

Mourier J, Brown C, Planes S (2017) Learning and robustness to catch-and-release fishing in a shark social network. Biology Letters 13:20160824

O'Connell C, He P (2014) A large scale field analysis examining the effect of magnetically-treated baits and barriers on teleost and elasmobranch behavior. Ocean & Coastal Management 96:130-137

O'Connell CP, Abel DC, Stroud EM, Rice PH (2011) Analysis of permanent magnets as elasmobranch bycatch reduction devices in hook-and-line and longline trials. Fishery Bulletin 109:394-401

O'Connell CP, Andreotti S, Rutzen M, Meÿer M, He P (2014a) The use of permanent magnets to reduce elasmobranch encounter with a simulated beach net. 2. The great white shark (Carcharodon carcharias). Ocean & Coastal Management 97:20-28

O'Connell CP, He P, Joyce J, Stroud EM, Rice PH (2014b) Effects of the SMART™(Selective Magnetic and Repellent-Treated) hook on spiny dogfish catch in a longline experiment in the Gulf of Maine. Ocean & Coastal Management 97:38-43

O'Connell CP, Hyun S-Y, Gruber SH, He P (2015) Effects of barium-ferrite permanent magnets on great hammerhead shark *Sphyrna mokarran* behavior and implications for future conservation technologies. Endangered Species Research 26:243-256

O'Connell CP, Hyun S-Y, Gruber SH, O'Connell TJ, Johnson G, Grudecki K, He P (2014c) The use of permanent magnets to reduce elasmobranch encounter with a simulated beach net. 1. The bull shark (*Carcharhinus leucas*). Ocean & Coastal Management 97:12-19

O'Connell CP, Stroud EM, He P (2014d) The emerging field of electrosensory and semiochemical shark repellents: Mechanisms of detection, overview of past studies, and future directions. Ocean & Coastal Management 97:2-11

O'Connell CP, Abel DC, Gruber SH, Stroud EM, Rice PH (2011) Response of juvenile lemon sharks, Negaprion brevirostris, to a magnetic barrier simulating a beach net. Ocean & Coastal Management 54:225-230

O'Connell CP, Abel DC, Rice PH, Stroud EM, Simuro NC (2010) Responses of the southern stingray (*Dasyatis americana*) and the nurse shark (*Ginglymostoma cirratum*) to permanent magnets. Marine and Freshwater Behaviour and Physiology 43:63-73

Oliver S, Braccini M, Newman SJ, Harvey ES (2015) Global patterns in the bycatch of sharks and rays. Marine Policy 54:86-97

Peters RC, Eeuwes LB, Bretschneider F (2007) On the electrodetection threshold of aquatic vertebrates with ampullary or mucous gland electroreceptor organs. Biological Reviews 82:361-373

Peverell SC (2005) Distribution of sawfishes (Pristidae) in the Queensland Gulf of Carpentaria, Australia, with notes on sawfish ecology. Environmental Biology of Fishes 73:391-402

Pikitch EK, Santora C, Babcock EA, Bakun A, Bonfil R, Conover DO, Dayton P, Doukakis P, Fluharty D, Heneman B (2004) Ecosystem-based fishery management. Book 305. Science

Porsmoguer SB, Bănaru D, Boudouresque CF, Dekeyser I, Almarcha C (2015) Hooks equipped with magnets can increase catches of blue shark *(Prionace glauca*) by longline fishery. Fisheries Research 172:345-351

Queirolo D, Gaete E, Montenegro I, Soriguer M, Erzini K (2012) Behaviour of fish by-catch in the mouth of a crustacean trawl. Journal of Fish Biology 80:2517-2527

Richards R, Raoult V, Powter D, Gaston T (2018) Permanent magnets reduce bycatch of benthic sharks in an ocean trap fishery. Fisheries Research 208:16-21

Rigg DP, Peverell SC, Hearndon M, Seymour JE (2009) Do elasmobranch reactions to magnetic fields in water show promise for bycatch mitigation? Marine and Freshwater Research 60:942-948

Riskas KA, Fuentes MM, Hamann M (2016) Justifying the need for collaborative management of fisheries bycatch: a lesson from marine turtles in Australia. Biological Conservation 196:40-47

Rivera-Vicente AC, Sewell J, Tricas TC (2011) Electrosensitive spatial vectors in elasmobranch fishes: implications for source localization. PLoS One 6:e16008

Robbins W, Peddemors V, Kennelly S (2011) Assessment of permanent magnets and electropositive metals to reduce the line-based capture of Galapagos sharks, *Carcharhinus galapagensis*. Fisheries Research 109:100-106

Roda MAP, Gilman E, Huntington T, Kennelly SJ, Suuronen P, Chaloupka M, Medley PAH (2019) A third assessment of global marine fisheries discards. FAO Fisheries and Aquaculture Technical Paper No. 633. Rome, FAO. 78 pp.

Salini J, Brewer D, Farmer M, Rawlinson N (2000) Assessment and benefits of damage reduction in prawns due to use of different bycatch reduction devices in the Gulf of Carpentaria, Australia. Fisheries Research 45:1-8

Salini J, McAuley R, Blaber S, Buckworth R, Chidlow J, Gribble N, Ovenden J, Peverell S, Pillans R, Stevens J (2007) Northern Australian sharks and rays: the sustainability of target and bycatch species. Phase II. CSIRO

Schluessel V, Bleckmann H (2005) Spatial memory and orientation strategies in the elasmobranch *Potamotrygon motoro*. Journal of Comparative Physiology A 191:695-706

Schluessel V, Bleckmann H (2012) Spatial learning and memory retention in the grey bamboo shark (*Chiloscyllium griseum*). Zoology 115:346-353

Siegenthaler A, Niemantsverdriet P, Laterveer M, Heitkönig I (2016) Aversive responses of captive sandbar sharks *Carcharhinus plumbeus* to strong magnetic fields. Journal of Fish Biology 89:1603-1611

Simpfendorfer CA (2000) Predicting population recovery rates for endangered western Atlantic sawfishes using demographic analysis. Environmental Biology of Fishes 58:371-377

Sisneros J, Tricas T, Luer C (1998) Response properties and biological function of the skate electrosensory system during ontogeny. Journal of Comparative Physiology A 183:87-99

Snyder DE (2003) Invited overview: Conclusions from a review of electrofishing and its harmful effects on fish. Reviews in Fish Biology and Fisheries 13:445-453

Soetaert M, Boute PG, Beaumont WR (2019) Guidelines for defining the use of electricity in marine electrotrawling. ICES Journal of Marine Science doi:10.1093/icesjms/fsz122

Soetaert M, Decostere A, Verschueren B, Saunders J, Van Caelenberge A, Puvanendran V, Mortensen A, Duchateau L, Polet H, Chiers K (2016) Side-effects of electrotrawling: Exploring the safe operating space for Dover sole (*Solea solea* L.) and Atlantic cod (*Gadus morhua* L.). Fisheries Research 177:95-103

Stevens J, McAuley R, Simpfendorfer C, Pillans R (2008) Spatial distribution and habitat utilisation of sawfish (*Pristis* spp.) in relation to fishing in northern Australia. A report to Department of the Environment, Water, Heritage and the Arts 31

Stobutzki IC, Miller MJ, Heales DS, Brewer DT (2002) Sustainability of elasmobranchs caught as bycatch in a tropical prawn (shrimp) trawl fishery. Fishery Bulletin 100:800-821

Tallack SM, Mandelman JW (2009) Do rare-earth metals deter spiny dogfish? A feasibility study on the use of electropositive “mischmetal” to reduce the bycatch of *Squalus acanthias* by hook gear in the Gulf of Maine. ICES Journal of Marine Science 66:315-322

Trochta JT, Pons M, Rudd MB, Krigbaum M, Tanz A, Hilborn R (2018) Ecosystem-based fisheries management: Perception on definitions, implementations, and aspirations. PLOS ONE 13:e0190467

van Marlen B, Grift R, van Keeken O, Ybema M, Van Hal R (2006) Performance of pulse trawling compared to conventional beam trawling. IMARES

van Marlen B, Wiegerinck J, van Os-Koomen E, Van Barneveld E (2014) Catch comparison of flatfish pulse trawls and a tickler chain beam trawl. Fisheries Research 151:57-69

Verschueren B, Lenoir H, Soetaert M, Polet H (2019) Revealing the by-catch reducing potential of pulse trawls in the brown shrimp (*Crangon crangon*) fishery. Fisheries Research 211:191-203

Wakefield CB, Santana-Garcon J, Dorman SR, Blight S, Denham A, Wakeford J, Molony BW, Newman SJ (2017) Performance of bycatch reduction devices varies for chondrichthyan, reptile, and cetacean mitigation in demersal fish trawls: assimilating subsurface interactions and unaccounted mortality. ICES Journal of Marine Science 74:343-358

Weber MJ, Thul MD, Flammang M (2016) Effectiveness of pulsed direct current at reducing Walleye escapement from a simulated reservoir. Fisheries Research 176:15-21

Westlake EL, Williams M, Rawlinson N (2018) Behavioural responses of draughtboard sharks (*Cephaloscyllium laticeps*) to rare earth magnets: Implications for shark bycatch management within the Tasmanian southern rock lobster fishery. Fisheries Research 200:84-92

Wueringer BE (2012) Electroreception in elasmobranchs: sawfish as a case study. Brain, Behavior and Evolution 80:97-107

Wueringer BE, Jnr LS, Kajiura SM, Tibbetts IR, Hart NS, Collin SP (2012a) Electric field detection in sawfish and shovelnose rays. PLOS ONE 7:e41605

Wueringer BE, Peverell S, Seymour J, Squire Jr L, Kajiura S, Collin S (2011) Sensory systems in sawfishes. 1. The ampullae of Lorenzini. Brain, Behavior and Evolution 78:139-149

Wueringer BE, Squire Jr L, Kajiura SM, Hart NS, Collin SP (2012b) The function of the sawfish's saw. Current Biology 22:150-151

Yu C, Chen Z, Chen L, He P (2007) The rise and fall of electrical beam trawling for shrimp in the East China Sea: technology, fishery, and conservation implications. ICES Journal of Marine Science 64:1592-1597

Zeller D, Cashion T, Palomares M, Pauly D (2018) Global marine fisheries discards: A synthesis of reconstructed data. Fish and Fisheries 19:30-39

Zhou S, Griffiths SP (2008) Sustainability Assessment for Fishing Effects (SAFE): A new quantitative ecological risk assessment method and its application to elasmobranch bycatch in an Australian trawl fishery. Fisheries Research 91:56-68

Videos illustrating sawfish response to electric fields

Video 1. Sawfish 2 turning back upon encountering the electric field produced by the '500 µs' treatment (top view).

Video 2. Sawfish 1 turning back upon approaching the electric field produced by the '10 Hz' treatment (underwater view).

Video 3. Sawfish 2 swimming parallel to the electrode setup upon encountering the electric field produced during the 'Exponential' treatment (top view).

Video 4. Sawfish 2 swimming between the electrodes during the 'Baseline' treatment (top view).

Video 5. Sawfish 1 swimming between the electrodes during the 'Exponential' treatment (underwater view).

Video 6. Sawfish 2 showing freezing behaviour upon entering the electric field during the 'Exponential' treatment.

Video 7. Sawfish 1 swimming between the electrodes during the Control treatment.

Video 8. Sawfish 2 approaching the electric field towards the electrode placed in the middle of the tank.