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HOW SHARKS ARE VULNERABLE PREY: KINEMATICS OF ESCAPE RESPONSES IN PACIFIC SPINY DOGFISH *(SQUALUS SUCKLEYI)* DURING MECHANICAL AND ELECTRICAL STIMULI.

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ABSTRACT

The kinematics and characteristics of escape responses have been heavily studied in teleost species. With some elasmobranchs being seen as mesopredators, escape responses do occur within this category of animals, thereby making the kinematics of the particular escape responses important parameters to understand in terms of predator-prey interactions; an area that is missing empirical data.

This study have been divided in to two parts, with Part A concentrating on the latency of escape responses of the Pacific spiny dogfish, *Squalus suckleyi*, during mechanical stimuli, and Part B containing the an analysis of how the pacific spiny dogfish react when exposed to electrical and electrochemical stimuli in the form of a by-catch reduction device (BRD) and mischmetal, respectively.

Latency was found to be slower than that found for teleost species, during mechanical stimuli. As several studies has found Mauthner cells in all teleost species and connected their function to their fast latency when reacting to a potential predator threat, our results suggest that the lack of Mauthner cells in elasmobranchs is resulting in a higher latency time.

The kinematics of escape responses during electrical and electrochemical stimuli showed that these types of stimuli provoked slow escape responses compared to more sudden stimuli like mechanical stimuli and attack from a predator. Additionally, the

turning angles of these escape responses was found to be quite large and the response to both the BRD and the mischmetal might be categorized more as an avoidance than escape. This supports the incentive that these devices can be used in the fishery industry to reduce their bycatch of elasmobranches and increase their capture efficiency.

PART A

LATENCY IN ESCAPE RESPONSES OF PACIFIC SPINY DOGFISH, *SQAULUS SUCKLEYI,* DURING MECHANICAL STIMULI

INTRODUCTION

The ability of teleosts to perform escape responses plays a vital role in avoiding mortality events by predation and has been investigated to a great extent (Dadda *et al.*, 2010, Domenici, 2010, Domenici *et al.*, 2004, Eaton *et al.*, 1977, Eaton and Emberley, 1991, Hale, 2000, Lefrançois and Domenici, 2006, Marras *et al.*, 2011). Aspects that have been investigated tend to focus on predator-prey interactions and include parameters such as turning speeds and turning angles, acceleration and speed, trajectory of escape and latency (Domenici, 2001, 2010, Domenici and Blake, 1997, Eaton and Emberley, 1991, Webb and Skadsen, 1980).

Escape responses in teleost fish are typically controlled by a special type of neurons called Mauthner cells (Eaton *et al.*, 2001), which is a pair of big interneurons located in the hind-brain that receives sensory inputs from visual, auditory and mechanosensory cells (Eaton *et al.*, 1977, Marras *et al.*, 2011). The Mauthner cells have been directly correlated with startle reflexes, with neuron-firings from Mauthner cells being observed together with contralateral muscle contractions (Yasargil and Diamond, 1968, Zottoli, 1977). This unilateral activation and contraction of the side muscles on the fish results in a bending of the body, usually away from the predator, into what is called a C-start (stage 1) (Webb, 1978, Weihs, 1973). The C-start is typically accompanied by a following return flip of the tail, accelerating the fish forward and away from the predator. The C-start can be succeeded by stage 2 of the escape response, though it is found to be present in some species and absent in others (Domenici and Blake 1997). Startle responses are often provoked by predator-prey interaction. The time from when a prey has detected a predator (i.e. stimulation of sensory cells) to visible movement away from the danger is called the latency time.

Latency times vary amongst fish species, and are effected by parameters such as temperature, distance to predator, the strength of the stimuli and whether or not the prey is schooling or not (Batty and Blaxter, 1992, Domenici and Batty, 1997, Eaton and Hackett, 1984, Webb, 1978). The time it takes for a detectable movement is controlled by the time of stimuli onset to firing from Mauthner cells, time from Mauthner cell firings to spinal motorneurons, and time to muscle activation with following visible movement (Eaton *et al.*, 2001, Turesson and Domenici, 2007). A decrease in latency time during an escape response have been correlated with Mauthner cell mediated activation of the side muscles of fish, due to the action potential of Mauthner neurons being as low as 1 ms (Eaton et al. 2001; Hale, 2000). In a study by Hale (2000) larval zebrafish was found be twice as fast in regard to latency time than that of larval lumpfish, 3.9 and 9 ms, respectively, with the difference being the larval zebrafish possessing Mauthner cells, and larval lumpfish lacking these neuron cells. Furthermore, it has been shown that the removal of both Mauthner cells in goldfish resulted in longer latency times compared to escape responses initiated by Mauthner cells (DiDomenico *et al.*, 1988).

Though general consensus is that Mauthner cells are related to fast latency times, it is important to note that short-latency escapes have been found during the removal of the Mauthner cells, but with the preservation of the two startle neurons MiD2cm and MiD3cm (Domenici and Hale, 2019, Liu and Fetcho, 1999). These escape responses, provoked in the absence of Mauthner cells, was only affected when stimuli was introduced tail-on and not head-on (Liu and Fetcho, 1999). The lack of short latency responses during tail-on stimuli, without Mauthner cells, is due to Mauthner-cell-escape responses being activated by vibration and auditory stimulus, whereas MiD3cm firing is triggered by head-tactile stimulus (Kohashi and Oda, 2008). Additionally, Mauthner cell firings have been suggested to be necessary for short latency times to occur during fast escapes, whereas MiD3cm is associated with non-Mauthner-escapes with longer latency times, though this depend on the stimuli placement (Domenici and Hale, 2019, Kohashi and Oda, 2008).

While Mauthner cells have been described in many teleost species (Eaton et al., 1977; Zottoli et al., 1977; Eaton et al., 1991; Domenici et al., 1997, Eaton et al., 2001; Medan and Preuss, 2014) they are rarely found in elasmobranchs, although they have been described in embryos and pups of sharks in the Squalus order (Bone, 1977). Escape kinematics, and thereby also latency times related to escape maneuvers are particularly understudied in adult elasmobranchs, which is most likely due to sharks being part of higher trophic levels and are usually seen as the predator and not the prey (Seamone *et al.*, 2014). However, mesopredators such as Spiny dogfish, *Squalus acanthias,* are exposed to predation from larger elasmobranchs and marine mammals (Ford *et al.*, 2011, Vaughn *et al.*, 2007).

Compared to teleost, *S. acanthias,* exhibit relatively low swimming speeds and acceleration after stimulation, with low turning radius’ and comparable turning rates to teleost species (Domenici *et al.*, 2004). Two types of escape responses have been found for this species: slow and fast escape responses during manual thrusting of a pole towards the dogfish (Domenici *et al.*, 2004). It has been suggested that the presence of the two response intensities could be contributed to a potential “two-gear” system, which would mean different energetic costs probably regulated by the perception of the level of the threat (Domenici *et al.*, 2004). However, while some studies have observed escape responses in spiny dogfish, when startled by either thrusting of a pole or approaching realistic shark models, no studies have investigated the latency times of this species and elasmobranches in general (Domenici *et al.*, 2004, Seamone *et al.*, 2014).

To address this knowledge gap our study aimed to investigate the latency time in Pacific spiny dogfish, *S. suckleyi*, when performing escape responses provoked by mechanical stimulus, compared to the latency times of two teleost species, Great sculpin, *Myoxocephalus polyacanthocephalus*, and Pile perch, *Rhacochilus vacca*, which in contrast to Pacific spiny dogfish both possess Mauthner cells. We, therefore, hypothesise that the latency times of the Pacific spiny dogfish are considerably longer then the two teleost species.

METHODS & MATERIAL

ANIMALS

The Pacific spiny dogfish, S. suckleyi (Girard, 1855), (n = 12; total length = 76.25 ± 6.05 cm; means ± SD) were caught off Pier H in Friday Harbor, San Juan Island, WA, USA, with hook and line and kept in three separate circular flow-through seawater tanks (12.0-14.4 °C, 12:12 light-dark photoperiod) at Friday Harbor Laboratories of the University of Washington. Test animals where fed, when interested, with locally caught fish from beach seining.

To have teleost species, which could be used for comparison in terms of latency times mediated by Mauthner cell firing, great sculpin, Myoxocephalus polyacanthocephalus (Pallas, 1814), (n = 7; total length = 16.30 ± 1.30; mass = 44.90 ± 8.90 g; means ± SD) and pile perch, Rhacochilus vacca (Girard, 1855), (n = 10; total length = 15.85 ± 1.76 cm; mass = 54.17 ± 20.30 g; means ± SD) were caught by beach seining at Jackson beach, San Juan Island, WA, USA. All fish were kept in flow-through seawater tanks (12.0-14.4 °C, 12:12 light-dark photoperiod) at Friday Harbor Laboratories of University of Washington, separated by species.

EXPERIMENTAL SETUP

Experimental trials inducing escape responses in dogfish were performed in a 3870 L circular flow-through experimental tank with a diameter of 3.60 m. Fish were allowed to acclimate to the experimental tank for at least one hour before their escape responses were induced by a sudden stimulation. A cylindrical grey plastic tube with a diameter of 0.17 m and a height of 1.30 m was hung 3 cm above the water surface and placed 0.10 m from the wall of the tank. The mechanical stimuli consisted of a 75 cl bottle filled with sand, which was hung from a string in the middle of the tube and dropped from a height of 1.33 m. A GoPro (GoPro Hero5 Black) was placed 3.45 m above the water surface and 0.35 m, perpendicular in front of the tube, from the tank wall, recording the escape response at a framerate of 240 fps. A mirror was attached to the side of the tank 0.15 m from the tube and placed right over the water surface at a 45-degree angle. This enabled detection of the stimuli at the moment of it breaking the water surface.

Experimental trials with great sculpin and pile perch were performed based on the same principles, however, the experimental setup was scaled down. Here, a 300 L, square flow-through tank (1.30 m x 1.10 m x 0.74 m) was used, with a water depth of 0.21 m. However, the test area for pile perches was confined to 0.60 m x 0.40 m due to fish rarely staying within the camera's field of view. A cylindrical tube with a diameter of 0.10 m and a height of 0.54 m was placed 0.06 m out from the middle of the 1.30 m long side, 0.02 m above the water. A dummy object filled with sand was hung on a string in the middle of the tube on an electromagnet and dropped at the appropriate time, using a switch, from a height of 0.56 m. An Olympus Tough TG-870 camera was mounted on a plank of wood with a hole in it 0.77 m above the water, recording with a framerate of 240 fps. A mirror was mounted on the side of the tank in a 45-degree angle so the camera could detect the object breaking the surface of the water.

PROTOCOL

Experimental protocols for Pacific spiny dogfish and teleost species were similar with a few differences. For both the sharks and the teleost, each individual was allowed to acclimate to the experimental tank for at least one hour before fast escape trials commenced. The goal was to do five trials and thereby get five escape responses for each individual. For the sharks, a waiting period of 30 minutes between each trial were applied to allow the sharks to calm down and regain naiveté before being exposed to the stimuli again. If an escape response under the mechanical stimuli was not observed at first attempt of a trial, it was attempted once more right away. If the shark performed an escape response, the trial was deemed a success and if there was no reaction again the trial failed. Trials were continuously run until five escape responses had been collected for each individual, though if three consecutive trials had failed, the test with that particular shark was over. For the teleost, great sculpin and pile perch, a waiting period of five minutes between each trial was implemented and trials were run until five escape responses per individual were induced or three consecutive trials had failed. However, for the teleost one trial never consisted of more than one exposure to stimulus, even if no reaction was observed.

MEASUREMENTS OF LATENCY

Response latencies of all three species was measured as the time interval between the object breaking the surface of the water (t0) and the first detectable movement of the fish initiating an escape response (t1). Latencies was measured and tracked in Kinovea (version 0.8.15) and graphic illustrations was done using Graphpad Prism 8 (version 8.2.1. 2019).

RESULTS

The latency time from the mechanical stimulus to initiation of escape response of the spiny dogfish varied between individuals and trials, though clear groupings can be seen from the frequency distribution (Fig. 1). The peak in frequency was found to be between 70-80 ms, with the shortest latency time recorded at 66.67 ms and the mean latency time for the sharks was 98.15 ± 20.04 ms (n=37). No faster latency times was found for Pacific spiny dogfish during the trials, regardless of placement and distance to the stimuli.

Considerably lower latency times were found for both experiments performed on the great sculpin and the pile perch, when compared to the results for the spiny dogfish. Both the sculpin and pile perch exhibited a clear peak in frequency at 30-40 ms (Fig. 1) and had a minimum latency of 20.8 and 16.7 ms, respectively. The mean latency time was 44.62 ± 16.71 ms (n=31) for the sculpin and 60.76 ± 39.36 ms (n=43) for the pile perch.

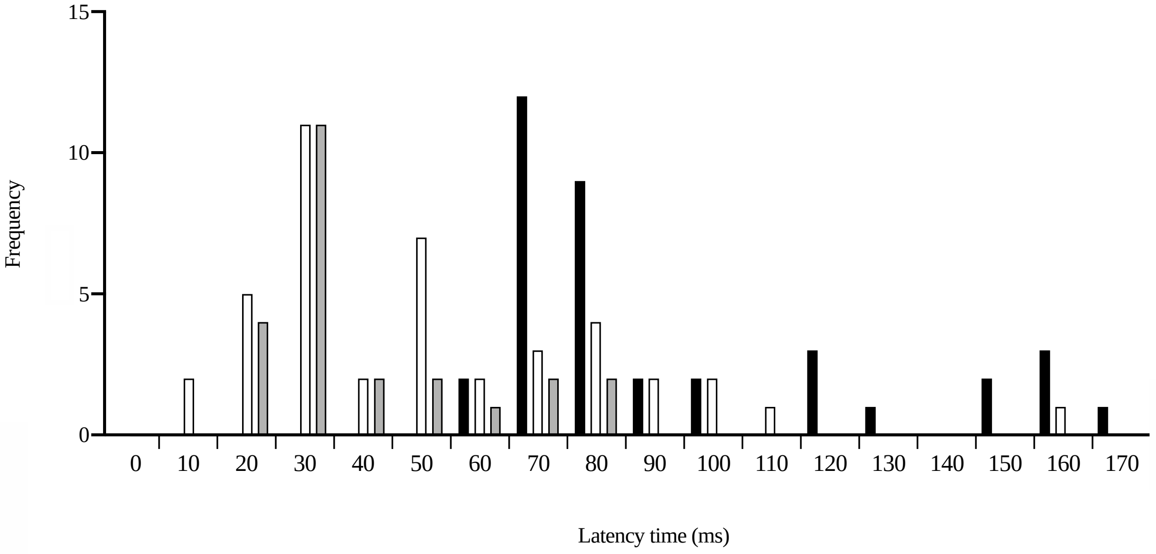

Figure 1: Frequency distribution of latency (ms) to mechanical stimuli for two species of teleost and one species of elasmobranch. The two teleost species are the great sculpin (grey) and the pile perch (white) and the one elasmobranch species is the Pacific spiny dogfish (black). Each bin contains the value in the interval greater than that of the bin.

DISCUSSION

The peak frequency of latencies observed for the teleost species in our studies, falls within the range found by other studies (Domenici and Batty, 1997, Turesson and Domenici, 2007). However, while no other studies have investigated latency times in the Pacific spiny dogfish, or elasmobranches in general, it is apparent from our study that Pacific spiny dogfish have considerably longer latency times. A possible explanation might be the lack of Mauthner cells in the adult life stages of elasmobranchs (Bone, 1977). As previously mentioned, the Mauthner cells have shown to be associated with low latency times, due to their action potential only lasting for 1 ms (Eaton et al., 2001). This enables the signal from the Mauthner cells to the brain to travel quicker than what would be possible without Mauthner cells

(Eaton *et al.*, 2001). Results from Domenici et al. (2004) indicate that Mauthner cells might not be implicated in the control of whether or not an escape is fast or slow, but actually is associated with other neural commands. This suggestion, according to the present study, seems not be the case when considering the latency of the response (Domenici and Batty, 1997, Domenici *et al.*, 2004). It has furthermore been shown that the removal of the Mauthner cells in adult goldfish significantly extended the latency time when exposed to stimulus, thereby indicating that these neurons are required for processing the sensory signal and reacting fast to a threat (Nissanov *et al.*, 1990). While the case is compelling that the presences of Mauthner cells are responsible for short latencies in teleost, it is not possible to test whether the absence of the neurons are the reason behind slow latencies in Pacific spiny dogfish.

The difference in body lengths of fish have been connected to various performance parameters in unsteady swimming, such as manoeuvrability i.e. increased turning radii and decreased turning rates with longer body lengths (Domenici, 2001). It could therefore also be expected that size would have an impact on the sensory performance, meaning a possible slower latency time with increased body size. This could be explained by the increased length of axons between contracting muscles and Mauthner cells with increased body size and the possible lack of compensation by larger fish (Funch *et al.*, 1981). Furthermore, an increase in body volume does not mean a proportional increase in muscle power, and would therefore lead to less muscle power per mass, and it is to be expected that fish of larger sizes could have higher activation time of muscle to visible movement (Webb, 1978), thereby possibly explaining the longer latency time by the bigger dogfish in this study. However, results from Turrenson & Domenici (2007) suggests that no relationship could be found between total body length and latency of grey mullets ranging from 6.1 cm to

28.5 cm, i.e. latency time being independent of body length. The fact the latency time was found to be size independent, has to be taken into consideration, when evaluating why the latency time of dogfish was higher than that of the two teleost species. Although, the difference in body length in the present study is higher than that for the grey mullets, ranging from 76.25 ± 6.05 cm of the biggest specie i.e. Pacific spiny dogfish, to 15.85 ± 1.76 cm for the smallest specie i.e. pile perch.

No effect on latency time was found when looking at the placement and distance of the stimuli to the dogfish. This is in contradiction with findings for solitary herring by Domenici and Batty (1997), where a correlation between the distance to stimuli and the fraction of latencies, below 50 ms was found. It was observed that when stimuli were moved from 25-35 cm away from target fish to 35-45 cm away, an approximate 20 % decrease in latencies below 50 ms occurred. Additionally it has been shown in teleost that the direction at which the stimuli is introduced have an effect on the latency time (Liu and Fetcho, 1999). For larvae zebrafish this difference was found to be 4.3 ms and 7 ms, when stimuli was head- or tail-directed, respectively (Liu and Fetcho, 1999). In addition to the latency being directionally dependent in teleost, it was also shown that the elimination of Mauthner cells, not including the MiD2cm and MiD3cm startle neurons, only effected latency times tail-directed responses (Liu and Fetcho, 1999). This suggests that Mauthner cells might not be the only neuron pathway that is involved in the latency time, and therefore that the slower latencies in dogfish, when exposed to mechanical stimuli, can not only be explained by the lack of Mauthner cells in elasmobranchs.

The Pacific spiny dogfish, *S. suckleyi*, showed slow latency times, but this could potentially be counteracted by other parameters in a predator-prey situation. Domenici et al. (2004) found that the spiny dogfish, *S. achantias*, had a low turning radius compared to other teleost, which most likely is due to the morphology of the spiny dogfish, which exhibits high maneuverability and flexibility (Domenici *et al.*, 2004, Webb, 1978, Webb 1984). With similar turning rates as other teleosts as well as small turning radius, the dogfish species might be able to make up for the lower distance-performance time and the slower latency in predator-prey interactions (Domenici *et al.*, 2004).

In a study from 2005 it was found that the survival rate of prey, in this case Guppies (*Poecilia reticulata*), increased with increasing fast start performance i.e. the accelerative behavior in an escape context (Walker *et al.*, 2005). Though the study states that latencies were not investigated, it could be speculated if lower latency times would have a positive effect on survival rate, and thereby giving teleost an advantage compared to small elasmobranchs.

CONCLUSION

The latency time in escape responses for the Pacific spiny dogfish, was found to be considerably slower than that of two teleost species. Our study, in conjunction with the existing literature, supports the hypothesis that the presence of Mauthner cells play an essential role in fast escape responses and decrease an individual’s latency time when escaping from a potential predator.

PART B

ESCAPE AND AVOIDANCE BEHAVIOR OF PACIFIC SPINY DOGFISH, *SQUALUS SUCKLEYI*, IN RESPONSE TO ELECTROCHEMICAL AND ELECTRIC STIMULI

INTRODUCTION

Bycatch of sharks constitutes a major problem in longline fisheries worldwide (Rago et al., 1998; Beerkircher et al., 2002; Oliver et al., 2015). Sharks compete with the target species for bait, thereby decreasing the capture efficiency by occupying a large number of the hooks (Stoner & Kaimmer, 2008). In addition to having an effect on the fishing industry, the bycatch of sharks can lead to severe effects on the stability of certain ecosystems and could potentially increase the rate at which important resources collapse (Worm et al., 2006). Methods to reduce shark bycatch would, therefore, not only increase the yield and economic gain of fishermen but also mitigate the reduction of the shark population.

One potential method could be to utilize the special sensory system of sharks called Ampullae of Lorenzini (Murray, 1960), which enables them to detect electric fields down to 1nV (Jordan et al., 2011; McCutcheon & Kajiura, 2013; Howard et al., 2018). Since teleosts do not have these specialized sensory cells it could be a way to target and dissuade only sharks and other elasmobranchs from hooks on longlines, without affecting any teleosts.

A shark-specific deterrent that has been investigated to some extent is lanthanide metals (Kaimmer & Stoner, 2008; Stoner & Kaimmer, 2008; Brill et al., 2009; Jordan et al., 2011 McCutcheon & Kajiura, 2013). These metals have an electropositive charge and a mixture of them, called mischmetal, have been shown to deter sharks of the species spiny dogfish (*Squalus acanthias*) (Kaimmer & Stoner, 2008). Another study tested the effect of the lanthanide metal neodymium on Pacific spiny dogfish (*Squalus suckleyi*) and the dusky smooth-hound (*Mustelus canis*), which found that avoidance behavior did occur, with less sharks attacking the bait (Jordan et al., 2011).

In 2018, a prototype of an electronic Bycatch Reduction Device (BRD) was tested on both sandbar sharks (*Carcharhinus plumbeus*) and *S. acanthias*. The study showed that the median bait consumption of *S. acanthias* was halved when BRD was located 10 cm from the bait (Howard et al., 2018).

The aim of this study was to investigate the kinematics of escape responses during electrical and electrochemical stimulation, and whether or not a mischmetal, containing primarily neodymium, (Nd) and the BRD could be used as a potential shark repellent. We hypothesize that both the Nd and the BRD deter sharks from feeding when compared to control trials, and that both the electrical stimuli would result in escape responses and avoidance behavior.

METHOD & MATERIAL

ANIMALS

The Pacific spiny dogfish, Squalus suckleyi (Girard, 1855), (n = 12; total length = 76.25 ± 6.05 cm; means ± SD) were caught off Pier H in Friday Harbor with hook and line and kept in three separate circular flow-through seawater tanks (12.0-14.4 °C, 12:12 light-dark photoperiod) at Friday Harbor Laboratories of the University of Washington and fed, when interested, with locally caught fish from beach seining.

EXPERIMENTAL SETUP

Feeding trials were performed in a large circular flow-through tank (3.6 m diameter X 0.95 m height, filled with 0.38 m of water depth). A cylindrical box (10 cm diameter

X 5 cm height) was used to house the electropositive mischmetal blocks (Nd) and the bycatch reduction device (BRD). The Nd was comprised of neodymium (74.95%) and praseodymium (24.7%) and minor amounts (<0.042%) of lanthanum, cerium, samarium, and gadolinium (Hefa Rare Earth, Vancouver, Canada). The box was connected to two PVC pipes (2.0 cm in diameter) put together in a 90-degree angle, that housed an electric cord for the BRD and allowed the box to be consistently placed 70 cm out from the edge of the tank. Directly above the box was placed a GoPro (GoPro Hero5 Black) 345 cm above the water and 35 cm out from the tank wall, recording the shark's interaction with the treatments (see below) at 240 fps.

PROTOCOL

Spiny dogfish takes up to 4.7 days at 13 °C to empty their digestive tract (Bangley and Rulifson, 2014), so sharks were fasted for five days before the feeding trials. Sharks were transferred individually to the experimental tank and allowed to acclimate for at least 5 hours. The cylindrical treatment box was in the tank during the whole acclimation period to allow sharks to become familiar with its presence. Furthermore, during the acclimation period, a piece of herring was placed in the tank ~10 cm from the box to induce hunger and feeding behavior. Each shark was subject to three trials consisting of three treatments. Each treatment lasted 20 minutes, with one hour resting period between each trial. The three treatments consisted of a control where the BRD was turned-off and with no mischmetal in the box, a treatment where the BRD was on and lastly a treatment where the BRD was turned-off and three small blocks of Nd was placed in the box. To start each treatment the box was removed from the water and placed in the same position, whether or not changes were made regarding the treatments, and a new piece of herring was placed ~10 cm in front of the box. The order of all treatments within a trial was chosen pseudo randomly.

MEASUREMENTS OF RESPONSES AND EFFECTS OF BRD AND ND

The shark's response and behavior to the treatments were quantified in two parts. The time it took for the sharks to forage on the herring placed in front of the treatment box was noted for each trial. This allowed us to compare the effectiveness of deterring the sharks from feeding with a given treatment. However, this proved to be mostly unsuccessful, as the majority of the sharks were not interested in the food, even without any treatments present i.e. the control scenario. However, we did observe a general interest in the food, in which the sharks would repeatedly swim close to or over the food, even though it meant they had to deviate from their general swim pattern (swimming around the tank close to the edge). We, therefore, quantified their response and behavior to the treatment as the number of times they swam within a 20 cm radius of the box and kinematically quantified any escape responses, with turning rates and distance from the tip of the head to the centre of the box, if such behavior was exhibited.

RESULTS

Electrochemical stimuli (Nd) mostly provoked a response corresponding to either slow escape responses or spontaneous turns and only a few fast escape responses (Figure 2). Furthermore, while the turns for the electrochemical stimuli were generally much slower than those found for mechanical stimuli, they were also done with much higher turning angles. This translates into higher turning rates at mechanical stimuli compared to electrical stimuli (352.4 ± 136.6 deg/s and 201 ± 149.5 deg/s, mean ± SD respectively). More data have to be analyzed in terms of times and encounters where the shark entered within a 20 cm distance to the bait as well as more analyzation of escape response kinematics.

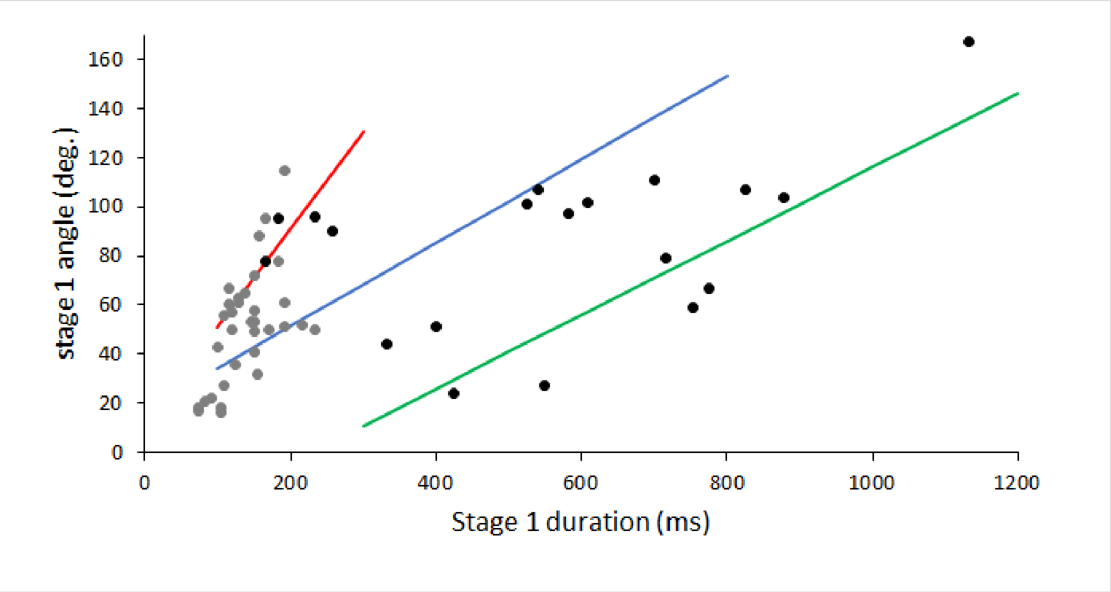

Figure 2: The relationship between stage 1 angle (deg.) and stage 1 duration (ms) for the Pacific spiny dogfish, S. Suckleyi, during different stimuli. The lines are redrawn from Domenici et al. (2004), that chased the dogfish with a stick to induce escape responses. The red line represents fast escape responses, the blue slow escape responses, and the green spontaneous turns. The grey dots are the escape responses induced by sudden mechanical stimuli and the black dots are the avoidance/escape responses to approaching the treatment box containing the mischmetal.

DISCUSSION

The difference in characteristics of escape responses when comparing mechanical and electrical stimuli could be explained by responsiveness and sensitivity of these two different sensory systems, the relative magnitude of the stimuli as well as the sharks intended outcome of the escape behavior. Although the electroreception in sharks is highly specialized and sensitive, the force created by the object dropping into the water might have been more powerful than the electric field of the BRD and annoyance created by the electropositive charged metal.

The goal of escape from a sudden mechanical stimulus in the water is to escape from a potential predator, and the intent is, therefore, to turn and get away fast and not necessarily to make a large turn angle. In contrast, the escape from the stationary electric stimuli could be seen more like avoidance, and here a large change in direction would be a quicker and more energy efficient way to stop the approach to the object and get away. Visual detection of predators has been shown to be an influential factor in the escape response by dogfish (Seamone et al. 2014). In a study by Seamone et al. (2014), it was observed that reactions to predators by the dogfish could be divided into head-on avoidance, and tail-on startles, which is similar to observations found in this study with electrical and mechanical stimuli, respectively. Furthermore, the electrical stimuli were stationary and therefore the sharks were always approaching the stimuli head-on, while the mechanical stimuli were dropped from above at various positions relative to the position of the shark. Higher turning angles might have been observed if the mechanical stimuli were consistently dropped in front of the shark.

CONCLUSION

Our study suggests that the escape responses, of the pacific spiny dogfish when exposed to electrical and electrochemical stimuli was shown to be categorized as slow escape responses. Furthermore, the escape responses showed to have a larger turning angle, and these two combined could be a sign of avoidance of the stimuli, more so than a startle and escape response. To be able to determine whether the BRD or the mischmetal can be used as a deterrent, more data have to be analyzed, especially control treatments compared to treatments where stimuli was present.

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