A Field and Laboratory Investigation of the Influence of Light on the Behaviour of Atlantic Cod (*Gadus morhua*)

by

© Robert Blackmore (B.Sc. Hons.)

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Abstract

Enhancements to fishing gears that could increase their efficacy are becoming globally popular both in use and in research. Effective enhancements could facilitate fishing, encourage sustainability through economic incentives, and mitigate bycatch. Visually mediated behaviours can be exploited by fishers to influence the capture of target species through modifications to the light environment, such as LED lures. Atlantic cod (*Gadus morhua*) are a commercially harvested species adapted to a low-light environment with a narrow range of available wavelengths in the blue-green range, and devices using green light are commonly available to fishers. To test the behaviour of cod in relation to LEDs, I assessed the catch efficacy of handline gear with green LED attachments and performed experiments in an artificial setting with multiple colours of LEDs to study phototactic responses to various wavelengths of light. Catch rates of handlines did not improve with the use of LED lures. As well, no behavioural responses were observed in choice test experiments, indicating that light may not be effective for exploiting the behaviour of Atlantic cod. These findings can be applied directly to fishery and aquaculture practices and encourage further research into the role of visual ecology in the conservation of Atlantic cod.

General Summary

Fishing practices are constantly evolving to provide efficient means of catch to fishers while improving sustainability. Attaching lights to gear is a popular modification that has had varying results. To test the practicality of using LEDs in the cod fishery in Newfoundland and Labrador, I designed a field and lab study to test the behaviour of cod toward lights. I found that fishers' catch rates did not improve when using the LEDs, but the research suggested that the lights may reduce the catch of species at risk (SAR). I also found that, in a lab setting, cod did not react to lights across a range of wavelengths. These findings contribute to our basic understanding of the behavioural ecology of cod, and to both industry and fisheries research and suggest that the catch of Atlantic cod is not improved through the use of light devices.

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Chapter 1: Introduction and Background

1.1 Common Fishing Methods in the Newfoundland Inshore Cod Fishery

In 1992, a moratorium on commercial groundfishing in the Northwest Atlantic Ocean was imposed by the Government of Canada, owing to a collapse of Atlantic cod (*Gadus morhua*) stocks through over-fishing, coupled with environmental changes and socioeconomic factors (Hutchings and Myers 1994, Myers et al. 1996, Milich 1999, DFO 2011, Buren et al. 2014, Sierra-Flores 2014). Since the moratorium was imposed, cod stocks have shown some recovery but have remained susceptible to depletion through over-fishing and mismanagement (Hutchings and Myers 1994, Shelton et al. 2006, DFO 2011, Morgan et al. 2017, Rowe and Rose 2017). As well, climate-induced effects on demersal ecological conditions such as prey availability have also been ongoing (Buren et al. 2014).

Atlantic cod populations within the Newfoundland and Labrador Designatable Unit, including the cod stocks of NAFO Division 2J3KL known as “Northern Cod” (Rowe and Rose 2017), have declined by between 97-99 % over the past 40 years. As of 2010, the Newfoundland and Labrador population of Atlantic cod has remained classified as Endangered by the Committee on the Status of Endangered Wildlife in Canada (herein: COSSEWIC; COSEWIC 2010, DFO 2011). A major contributing influence on the decline of these stocks was increasing technological advancement, such as rapid improvements in vessel design, fish-finding capability, and fishing gear technology, including the widespread use of monofilament nylon gillnets that replaced biodegradable twine nets (Myers et al. 1996, Montgomerie 2015).

Different fishing gears have different catch rates and selectivity, with advantages and disadvantages specific to each. Gillnets, owing to their high catch rates, passive fishing, and selectivity for larger fish, are the preferred gear of inshore commercial fishers in the Northwest Atlantic. There are some exceptions to gillnet use in the Newfoundland inshore cod fishery, such as the Fogo Island and Petty Harbour Fisherman's Cooperatives where gillnet fishing is prohibited in specific areas. Otherwise, gillnets are the ubiquitous gear choice. Though gillnets are the most efficient fishing method, netted cod are often moribund or dead, lowering the quality and value of the catch (Rouxel and Montevecchi 2018).

Many fishing gears, including gillnets, also often capture non-target marine organisms (referred to as incidental catch or herein: bycatch), including fish (Shester and Micheli 2011), corals (Žydelis et al. 2013, Rouxel and Montevecchi 2018, Dias et al. 2020), sea turtles (Ortiz et al. 2016, Alfaro-Shigueto et al. 2018, Darquea et al. 2020), marine birds (Tasker et al. 2000, Regular et al. 2013, Žydelis et al. 2013, Hedd et al. 2015), and mammals (Davoren 2007, Reeves et al. 2013, Bryhn et al. 2014). Bycatch reduction is a major focus of fisheries research and industry technology development. These concerns are essential components of fishing sustainability for gillnet and other fisheries (Montevecchi 2023).

Bycatch mitigation methods often include gear attachments and modifications to decrease the possibility of incidental catch and deter non-target species from the nets and other gear (e.g., long-lines). Deterrence modifications often aim to increase the detectability of the nets via visual and acoustic modalities, and less often, olfactory, electro-magnetic and mechanosensory mitigation measures. Visual deterrents include increasing the visibility of the gear by changing the colour of the net (nylon filament colour [Hanamseth et al. 2018] or LED attachments [Ortiz et al. 2016, Sigurdsson 2023]), adding visual cues like high-contrast banners (Field et al. 2019, Montevecchi et al. 2023), above-water predator-shaped kites (Almeida et al. 2023), and looming eyespot buoys (Rouxel et al. 2021). “Pingers” (Barlow and Cameron 2003) or acrylic “pearls” embedded into nets with high acoustic reflectivity (Kratzer et al. 2021) are well-studied acoustic deterrents.

Each of these methods has had varying success both within and between fisheries, with similar gear modifications working well in some fisheries and not others (see Carretta and Barlow 2011, Field et al. 2019, Montevecchi et al. 2023, Sigurdsson 2023). The removal of thousands of gillnets after the closure of the cod fisheries in the early 1990s positively influenced populations of diving seabirds in Newfoundland (Regular et al. 2013), and to date, gillnet removal and gear-switching appears to be the best and most effective strategy for reducing bycatch across fisheries (Northridge 1991, Slooten 2013, O’Keefe et al. 2021). A transition from the widespread use of gillnets toward a less impactful gear in the Newfoundland inshore cod fishery could benefit non-target marine vertebrate populations (Regular et al. 2013, Rouxel and Montevecchi 2018). Baited cod pots have proven to be effective in both Canada (Meintzer et al. 2017, 2018) and western

Europe (Bryhn et al. 2014, Anders et al. 2017). Uptake however has been slow due to higher capital investments and work requirements. Newfoundland cod pots, though less efficient than gillnets, catch live fish, are size-selective, and capture minimal bycatch (Meintzer et al. 2018, Rouxel and Montevecchi 2018). This inefficiency may be due to the tendency for many groundfish, including *G. morhua*, to avoid confined spaces (Winger, Løkkeborg, and Pol 2016). Fixed gears like gillnets and pots are prone to detachment and displacement, allowing for ghost-fishing and self-baiting which can negatively impact marine ecosystems, especially targeting sensitive species such as demersal benthic juvenile cod on the seabed (Large et al. 2009, DFO 2011). Cod pots are the least common fishing gear employed in Newfoundland's inshore fishery (Guy 1994, Meintzer et al. 2018).

1.2 Rationale for Handline Enhancement

Handlines are the oldest, most basic, and traditional fishing gear (Everhart et al. 1975, Guy 1994). Compared to the passive setting of gillnets and cod pots, handlining is an active fishing method. Handlining precludes ghost-fishing and produces high-quality, live catch with minimal bycatch (Rouxel and Montevecchi 2018, Blackmore and Montevecchi 2019). Handlined catch can fetch a good market price because of the minimal tissue damage that the fish sustains when caught live. Handlining also carries the potential for relatively low catch rates and the capture of undersized fish (Rouxel and Montevecchi 2018), as well as (in the Northwest Atlantic) the infrequent bycatch of endangered wolffish (*Anarhichas* spp.), of which all three species that occur in the region are Species of Concern (COSEWIC 2012). Handlines have been shown to be the most sustainable gear compared to gillnets and cod pots (Rouxel and Montevecchi 2018). In a comprehensive comparative fishing gear assessment, handlines scored better than both cod pots and gillnets in terms of safety, quality of catch, bycatch, price, ease of use, need for crew members, maintenance, weather dependence, and need for additional equipment. While handlines have many benefits, they have been surpassed by gillnets for the simple reason that catch rates are much higher with passive gillnetting than handlining. Any improvement to catch rate that would allow handlines to contend as a viable gear alternative may persuade inshore fishers to move away from or reduce gillnet use and return to hook-and-line fishing.

1.3 Influence of Light on Fish

Visually-oriented fishes, including many benthic and demersal species, depend on light to forage and interact with their environment (Woodhead 1966, Brynh et al. 2014, Winger, Løkkeborg, and Pol 2016, Humborstad et al. 2018). Predator avoidance, migration patterns (Woodhead 1966), and foraging (McMahon and Holanov 1995) are strongly influenced by fishes' visual systems and ambient light environment. Fishers are aware of this and have used light to attract fish for centuries (Bryhn et al. 2014, McEneaney 2017, Nguyen and Winger 2018). Many modern fishing practices such as those targeted at squid, shrimp, snow crab, and fishes like tuna, swordfish, and salmon use various lighting techniques including metal-halide lights, incandescent lights, and light-emitting diodes (herein LED) (Migaud et al. 2007, Bryhn et al. 2014, Ortiz et al. 2016, Humborstad et al. 2018, Larsen et al. 2018, Nguyen and Winger 2018, Utne-Palm et al. 2018). Light attraction has been evaluated and used in other contexts, such as in cod and salmon farming, to alter behaviour by exploiting fishes' positive phototaxis, aggregating the fish in a specific area of the tank or altering the depth at which they swim (Bryhn et al. 2014, Stien 2014, Tabor et al. 2015, Sullivan et al. 2016), without imposing excessive stress (Migaud et al. 2007).

The specific wavelengths of light present in a species' habitat influence both its behavioural and physiological characteristics. Light radiation is absorbed exponentially as it passes through water, and the absorption rate differs across the light spectrum (Woodhead 1966, Levine and MacNichol 1982, Douglas and Djamgoz 1990, Mann and Lazier 1991). In clear water columns, long wavelengths (red and orange) of light rapidly attenuate close to the surface (Mann and Lazier 1991; Figure 1.1). At approximately 50 metres depth on a clear, sunny day with little turbulence, 460 - 530 nm (indigo-blue to yellow) is the maximum range of light available, and it is likely that the range of colour perception for visually oriented animals who inhabit this environment lies within the blue-green part of the spectrum (Levine and MacNichol 1982; Figure 1.1).

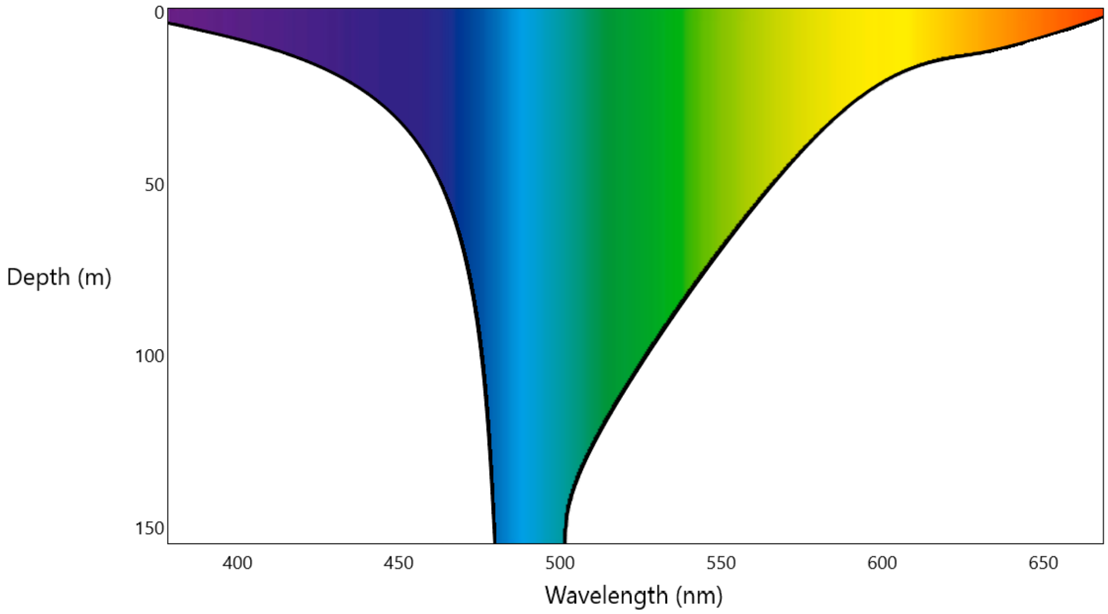

Figure 1.1. An approximation of the attenuation of the visible light spectrum through a clear water column.

Influenced by the cold Labrador Current, the waters in coastal areas of the Northwest Atlantic are classified as low arctic ecosystems (Brown 1985), the habitat in which Atlantic cod and their main prey, capelin (*Mallotus villosus*), thrive (Graham 2017). The spring bloom of phytoplankton production, beginning anywhere from February-May along Newfoundland and Labrador's coast (Henson, Dunne and Sarmiento 2009) causes surface water in the euphotic zone along the coasts to become murky and green, due to the absorption of short-wavelength light by their photosynthetic pigment - chlorophyll a (Mobley 1994, Valen et al. 2014). Chlorophyll a reflects green wavelengths of light and, along with animal and plant debris, causes the blue light that would normally reach depths of 200 m to be absorbed more readily near the surface (Douglas and Djamgoz

1990, Mobley 1994). Therefore, the light environment of the inshore Northwest Atlantic at 40-50 meters depth is mostly green light for much of the spring.

A species' spectral sensitivity is the quality of light it is most sensitive to detecting, relating to its visual pigments and the dominant wavelength of light in its environment (Krag et al. 2012). Many deep-water fish, including Atlantic cod, are dichromatic, incorporating only two short-wavelength (blue-green) sensitive photopigments in their photoreceptors to distinguish contrast and colour (Woodhead 1966, Anthony and Hawkins 1983, Figure 1.2). Their restricted light environment may not have provided a wide enough colour-spectrum range to select for more visual pigments.

Gadus morhua is a benthopelagic demersal species that possesses two opsin subfamilies in its cones, SWS2 and RH2A, which are blue-sensitive (446 nm) and green-sensitive (517 nm) photopigment types, respectively (Douglas and Djamgoz 1990, Valen et al. 2014, Figure 1.2). These retinal photopigments maximize cod's sensitivity to blue/green light, allowing them to best discriminate colour differences in the light environment of deep waters. The photosensitivity of the cod's retina also changes as it matures, through changes in genotypic expression and subsequent opsin pigment presence (Valen et al. 2014). This plasticity allows the fish to adapt to the changing behavioural needs of a juvenile such as predator avoidance and foraging on zooplankton in the upper water column (Grant and Brown 1998, DFO 2011, Sierra-Flores 2014, Valen et al. 2014) to more advanced and complex needs of an adult (the identification of larger prey items, mating, communication, migration, swimming depth, etc.; Nguyen and Winger 2018). Adult Atlantic cod are the target of major commercial fisheries across the Atlantic Ocean, and an understanding of the physiological mechanisms underlying their perception of colour could be exploited for improving the efficacy of current fishing methods.

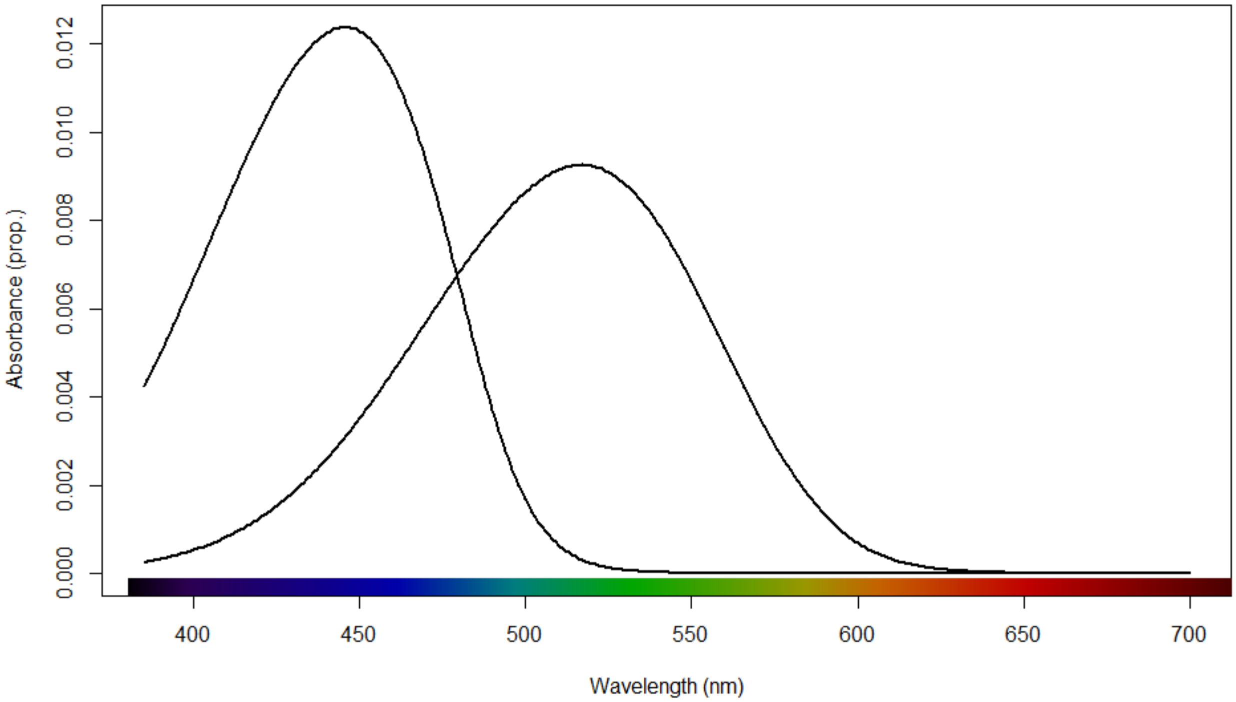

Figure 1.2. Spectral sensitivities of cones from *Gadus morhua* as measured by microspectrophotometry; λmax SWS = 446 nm, λmax RH2A = 517 nm (Douglas and Djamgoz 1990). These probability curves were produced using a vertebrate template (Govardovskii et al. 2000) and represents the maximum sensitivity range of the species because the range in the short wavelength may be cut off by ocular media in the eye (e.g., lens).

1.4 Knowledge Gap

I performed a pilot study in 2018 that suggested an increase in catch rates when using green LEDs (Blackmore 2019). There have been no further studies on the effects of light modifications on handlines for Atlantic cod, nor has the effects that such devices could have on the efficacy of the gear been determined. Furthermore, few behavioural tests have been performed in a controlled setting to assess the effect that light stimuli have on the behaviour of adult Atlantic cod, and none have simultaneously presented light stimuli to indicate preferential choice behaviour to one light condition of another.

1.5 Thesis Objectives

In this thesis, I investigated the behaviour of Atlantic cod towards LED lights both in a field experiment and lab experiment. Field experiments were designed and conducted to assess the efficacy of short-wavelength modifications on handlining catch. I worked with commercial Newfoundland fishers who use handline gear exclusively. My aim was to better understand the behavioural ecology of cod relative to their interactions with handline fishing gear. I aimed to encourage handline use and reduce the need for less favourable methods such as gillnetting. Working with commercial Newfoundland inshore fishers and independent behavioural trials, I aimed to close the gap in my knowledge of cod's behavioural interactions with fishing gears and LED gear modifications. Such understanding could mitigate gillnet bycatch by enhancing the alternative, more sustainable handlining method and facilitate best-practice fishing for commercial and recreational groundfishers. In Chapter 2, I determined the effect of green LED handline attachments on the catch rate, bycatch rate, catch length and catch weight of handlines.

The profitability and feasibility of handline gear as an alternative to gillnets in a commercial setting needs to be enhanced through the enhanced catchability of handlines.

In Chapter 3, behavioural tests were performed with wild-caught adult Atlantic cod to help determine if there is a preference and/or phototactic response to various wavelengths of LED light presented in pairwise combination. My goal was that my findings would provide a better understanding of the visual ecology of Atlantic cod and inform the use of light in fisheries' applications, while filling in a knowledge gap in the cognitive and behavioural ecology of Atlantic cod.

1.6 References

Alfaro-Shigueto, J., Mangel, J. C., Darquea, J., Donoso, M., Baquero, A., Doherty, P. D. and Godley, B. J. (2018). Untangling the impacts of nets in the southeastern Pacific: Rapid assessment of marine turtle bycatch to set conservation priorities in small-scale fisheries. *Fisheries Research*, 206, 185-192. doi:10.1016/j.fishres.2018.04.013

Almeida, A., Alonso, H., Oliveira, N., Silva, E., and Andrade, J. (2023). Using a visual deterrent to reduce seabird interactions with gillnets. *Biological Conservation*, 285. ISSN 0006-3207. doi:10.1016/j.biocon.2023.110236.

Anders, N., Fernö, A., Humborstad, O-B., Løkkeberg, S., and Utne-Palm, A. C. (2017). Species specific behaviour and catchability of gadoid fish to floated and bottom set pots. *ICES Journal of Marine Science*, 74, 769-779. doi:10.1093/icesjms/fsw200

Anthony, P. D. and Hawkins, A. D. (1983). Spectral sensitivity of the cod, *Gadus morhua* L. *Marine Behaviour and Physiology,* 10(2), 145-166. doi:10.1080/10236248309378614

Barlow, J. and Cameron, G. A. (2003). Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. *Marine Mammal Science*, 1 9(2), 265-283. https://doi.org/10.1111/j.1748-7692.2003.tb01108.x

Blackmore, R. (2019). Testing Handline Catch Efficacy for Atlantic Cod (*Gadus morhua*) in the Inshore Newfoundland Fishery: Two Studies of Short-Wavelength Modifications. [Unpublished Bachelor of Science Honours thesis]. Memorial University of Newfoundland and Labrador.

Blackmore, R. J. and Montevecchi, W. A. (2019). Green-lighting Cod Jigs: A New Handline Fishing Enhancement. *The Navigator*, 22:10. doi:10.13140/RG.2.2.11261.31209

Brown R. B. G. (1985). *Atlas of Canadian Seabirds*. Canadian Wildlife Service, Ottawa.

Bryhn, A. C., Konigson, S. J., Lunneryd, S. G. and Bergenius, M. A. J. (2014). Green lamps as visual stimuli affect the catch efficiency of floating cod (*Gadus morhua*) pots in the Baltic Sea. *Fisheries Research*, 157, 187-192. doi:10.1016/j.fishres.2014.04.012

Buren, A. D., Koen-Alonso, M., Pepin, P., Mowbray, F., Nakashima, B., Stenson, G., Ollerhead, N., and Montevecchi, W. A. (2014). Bottom-up regulation of capelin, a keystone forage species. *PLoS ONE*, 9(2): e87589. doi:10.1371/journal.pone.0087589

Carretta, J. V. and Barlow, J. (2011). Long-term effectiveness, failure rates, and "dinner bell" properties of acoustic pingers in a gillnet fishery. *Marine Technology Society Journal*, 45(5), 7-19. https://doi.org/10.4031/MTSJ.45.5.3

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). (2012). COSEWIC assessment and status report on the Atlantic wolffish *Anarhichas lupus* in Canada. Retrieved from: https://species-registry.canada.ca/index-en.html#/consultations/1133

Darquea, J. J., Ortiz-Alvarez, C., Córdova-Zavaleta, F., Medina, R., Bielli, A., Alfaro-Shigueto, J. and Mangel, J. C. (2020). Trialing net illumination as a bycatch mitigation measure for sea turtles in a small-scale gillnet fishery in Ecuador. *Latin American Journal of Aquatic Research*, 48(3), 446-455. doi:10.3856/vol48-issue3-fulltext-2428

Department of Fisheries and Oceans Canada. (2011). Recovery potential assessment for the Newfoundland and Labrador Designatable Unit (NAFO Division 2GHJ, 3KLNO) of Atlantic Cod (*Gadus morhua*). Department of Fisheries and Oceans

Canada, Canadian Science Advisory Secretariat, Scientific Advisory Representatives. 2011/037.

Dias, V., Oliveira, F., Boavida, J., Serrão, E. A., Gonçalves, J. M. S. and Coelho, M. A. G. (2020). High coral bycatch in bottom-set gillnet coastal fisheries reveals rich coral habitats in Southern Portugal. *Frontiers in Marine Science*, 7: 603438. doi:10.3389/fmars.2020.603438

Douglas, R. and Djamgoz, M. (eds.) (1990). *The Visual System of Fish*. Springer, Dordrecht. doi:10.1007/978-94-009-0411-8_4

Everhart, W. H., Eipper, A. W. and Youngs, W. D. (1975). *Principles of Fishery Science*. Ithaca, NY: Cornell University Press.

Field, R., Crawford, R., Enever, R., Linkowski, T., Martin, G., Morkūnas, J., Morkūnė, R., Rouxel, Y. and Oppel, S. (2019). High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. *Global Ecology and Conservation*, 18: e00602. doi:10.1016/j.gecco.2019.e00602

Govardovskii, V. I., Fyhrquist, N., Reuter, T., Kuzmin, D. G. and Donner, K. (2000). In search of a visual pigment template. *Visual Neuroscience*, 17, 509-528.

Grant, S. M. and Brown, J. A. (1998). Nearshore settlement and localized populations of age 0 Atlantic cod (*Gadus morhua*) in shallow coastal waters of Newfoundland. *Canadian Journal of Fisheries and Aquatic Sciences*, 55(6), 1317-1327. doi:10.1139/f97-310

Guy, R. W. (1994). *From the Straight Shore*. St. Johns, NL: Harry Cuff Publications.

Hanamseth, R., Barry Baker, G., Sherwen, S., Hindell, M. and Lea, M. A. (2018). Assessing the importance of net colour as a seabird bycatch mitigation measure in gillnet fishing. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28(1), 175-181. doi:10.1002/aqc.2805

Hedd, A., Regular, P. M., Wilhelm, S. I., Rail, J. F., Drolet, B., Fowler, M., Pekarik, C. and Robertson, G. J. (2015). Characterization of seabird bycatch in eastern Canadian waters, 1998-2011, assessed from onboard fisheries observer data. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26(3), 530-548. doi:10.1002/aqc.2551

Henson, S. A., Dunne, J. P., and Sarmiento, J. L. (2009). Decadal variability in North Atlantic phytoplankton blooms. *Journal of Geophysical Research*, 114: C04013. doi:10.1029/2008JC005139

Humborstad, O-B., Utne-Palm, A. C., Breen, M. and Løkkeborg, S. (2018). Artificial light in baited pots substantially increases the catch of cod (*Gadus morhua*) by attracting active bait, krill (*Thysanoessa inermis*). *ICES Journal of Marine Science*, 75(6), 2257-2264. doi:10.1093/icesjms/fsy099

Hutchings, J. A. and Myers, R. A. (1994). What can be learned from the collapse of a renewable resource? Atlantic Cod, *Gadus morhua*, of Newfoundland and Labrador. *Canadian Journal of Fisheries and Aquatic Sciences*, 51, 2126-2146.

Krag, L. A., Herrmann, B. and Karlsen, J. (2012). Quantifying fish escape behaviour through large mesh panels in trawls based on catch comparision data - model development and a case study from Skagerrak. *ICES (2012) Report of the ICES-FAO Working Group on Fishing Gear Technology and Fish Behaviour (WGFTFB)*, 23-27. Lorient, France. ICES CM 2012/SSGESST:07

Kratzer, I. M. F., Brooks, M. E., Bilgin, S., Özdemir, S., Kindt-Larsen, L., Larsen, F. and Stepputtis, D. (2021). Using acoustically visible gillnets to reduce bycatch of a small cetacean: first pilot trials in a commercial fishery. *Fisheries Research*, 243: 106088. doi:10.1016/j.fishres.2021.106088

Large, P. A., Graham, N. G., Hareide, N-R., Misund, R., Rihan D. J., Mulligan M. C., Randall P. J., Peach, D. J., McMullen, P. H. and Harlay, X. (2009). Lost and abandoned nets in deep-water gillnet fisheries in the Northeast Atlantic: retrieval exercises and outcomes. *ICES Journal of Marine Science*, 66(2), 323-333. doi:10.1093/icesjms/fsn220

Larsen, R. B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J. and Tatone, I. (2018). Could green artificial light reduce bycatch during Barents Sea Deep-water shrimp trawling? *Fisheries Research*, 204, 441-447. doi:10.1016/j.fishres.2018.03.023

Levine, J. and MacNichol, E. (1982). Color vision in fishes. *Scientific American*, 248(2), 140- 149. doi:10.1038/scientificamerican0282-140

Mann, K. H. and Lazier, J. R. N. (1991). *Dynamics of Marine Ecosystems: Biological-Physical Interactions in the Oceans*. Malden, MA: Blackwell.

McEneaney, C. (June 14, 2017). The Dying of the Light: Men Who Fish with Fire. *Culture Trip*. Retrieved October 16, 2018, from www.theculturetrip.com/asia/taiwan/articles/thedying-of-the-light-men-who-fish-with-fire

McMahon, T. E. and Holanov, S. H. (1995). Foraging success of largemouth bass at different light intensities: implications for time and depth of feeding. *Journal of Fish Biology*, 46(5), 759-767. doi:10.1111/j.1095-8649.1995.tb01599.x

Meintzer, P., Walsh, P. and Favaro, B. (2017). Will you swim into my parlour? *In situ* observations of Atlantic cod (*Gadus morhua*) interactions with baited pots, with implications for gear design. *PeerJ*, 5: e2953. doi:10.7717/peerj.2953

Meintzer, P., Walsh, P. and Favaro, B. (2018). Comparing catch efficiency of five models of pot for use in a Newfoundland and Labrador cod fishery. *PLoS ONE*, 13(6): e0199702. doi:10.1371/journal.pone.0199702

Migaud, H., Cowan, M., Taylor, J. and Ferguson, H. W. (2007). The effect of spectral composition and light intensity on melatonin, stress and retinal damage in post-smolt Atlantic Salmon, *Salmo salar*. *Aquaculture*, 270, 390-404. doi:10.1016/j.aquaculture.2007.04.064

Milich, L. (1999). Resource mismanagement versus sustainable livelihoods: The collapse of the Newfoundland cod fishery. *Society and Natural Resources*, 12(7), 625-642. doi:10.1080/089419299279353

Mobley, C. D. (1994). *Light and Water: Radiative Transfer in Natural Waters*. San Diego: Academic Press.

Montevecchi, W. A. (2023). Interactions between fisheries and seabirds: Prey modifications, discarding and bycatch. In: Young, L. and Vander Werf, E. (eds.) *Conservation of Marine Birds*. Elsevier.

Montevecchi, W. A., Lamarre, J., Rouxel, Y., Montevecchi, M. W., Blackmore, R. J., Bourne, C., and Spiegel, C. (2023). High-contrast banners designed to deter seabirds from gillnets reduce target fish catch. *Marine Ornithology* 51, 119-126.

Montgomerie, M. (2015). *Basic fishing methods: a comprehensive guide to commercial fishing methods*. SEAFISH, Edinburgh UK, 106p.

Morgan, M. J., Koen-Alonso, M., Rideout, R., Buren, A. D. and Parsons, D. M. (2017). Growth and condition in relation to the lack of recovery of northern cod. *ICES Journal of Marine Science,* 75(2), 631-641. doi:10.1093/icesjms/fsx166

Myers, R. A., Hutchings, J. A. and Barrowman, N. J. (1996). Hypotheses for the decline of cod in the North Atlantic. *Marine Ecology Progress Series*, 138, 293-308.

Myers, R. A., Hutchings, J. A. and Barrowman, N. J. (1997). Why do fish stocks collapse? The example of cod in Atlantic Canada. *Ecological Applications*, 7(1), 91-106.

Nguyen, K. and Winger, P. (2018). Artificial light in commercial industrialized fishing applications: A review. *Reviews in Fisheries Science & Aquaculture*, 27(1), 106-126. doi:10.1080/23308249.2018.1496065

Nguyen, K. Q., Winger, P. D., Morris, C., and Grant, S. M. (2017). Artificial lights improve the catchability of snow crab (*Chionoecetes opilio*) traps. *Aquaculture and Fisheries*, 2, 124-133. doi:10.1016/j.aaf.2017.05.001

Northridge, S. P. (1991). Driftnet fisheries and their impacts on non-target species: a worldwide review. *FAO Fisheries Technical Paper*, No.320. Rome, FAO. ISBN 92-5-103098-7

O'Keefe, C. E., Cadrin, S. X., Glemarec, G., and Rouxel, Y. (2021). Efficacy of time-area fishing restrictions and gear-switching as solutions for reducing seabird bycatch in gillnet fisheries. *Reviews in Fisheries Science & Aquaculture*, 31(1). 29-46. doi:10.1080/23308249.2021.1988051

Ortiz, N., Mangel, J. C., Wang, J., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., Swimmer, Y., Carvalho, F. and Godley, B. J. (2016). Reducing green turtle bycatch in small-scale fisheries using illuminated gillnets: The cost of saving a sea turtle. *Marine Ecology Progress Series,* 545, 251-259. doi:10.3354/meps11610

Reeves, R. R., McClellan, K. and Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97. doi:10.3354/esr00481

Regular, P., Montevecchi, W., Hedd, A., Robertson, G. and Wilhelm, S. (2013). Canadian fishery closures provide a large-scale test of the impact of gillnet bycatch on seabird populations. *Biology Letters*, 9(4): 20130088. doi:10.1098/rsbl.2013.0088

Rose, G. A. (2019). *Atlantic Cod: A Bio-Ecology*. John Wiley & Sons Ltd., Hoboken, NJ, U.S.A. ISBN: 9781119460633

Rouxel, Y. and Montevecchi, W. (2018). Gear sustainability assessment of the Newfoundland inshore northern cod fishery. *Ocean and Coastal Management*, 163, 285-295.

Rouxel, Y., Crawford, R., Cleasby, I. R., Kibel, P., Owen, E., Volke, V., Schnell, A. K. and Oppel, S. (2021). Buoys with looming eyes deter seaducks and could potentially reduce seabird bycatch in gillnets. *Royal Society Open Science*, 8: 210225. doi:10.1098/rsos.210225.

Rowe, S. and Rose, G. (2017). Don't derail cod's comeback in Canada. *Nature*, 545, 412. doi:10.1038/545412b

Shelton, P. A., Sinclair, A. F., Chouinard, G. A., Mohn, R. and Duplisea, D. E. (2006). Fishing under low productivity conditions is further delaying recovery of Northwest Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Sciences,* 63(2), 235-238. doi:10.1139/f05-253

Shester, G. G. and Micheli, F. (2011). Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. *Biological Conservation*, 144(5), 1673-1681. doi:10.1016/j.biocon.2011.02.023

Sierra-Flores, R. (2014). Environmental management of Atlantic cod (*Gadus morhua*) and turbot (*Scophthalamus maximus*): Implications of noise, light and substrate. Ph.D. thesis Sterling University, United Kingdom. doi:10.13140/RG.2.1.3304.3040

Sigurdsson G. M. (2023). Increase in bycatch rates of plunge- and surface-feeding seabirds observed while setting and hauling bottom set gillnets equipped with LED lights. *Marine Ecology Progress Series*, 720, 191-194. doi:10.3354/meps14408

Slooten, E. (2013). Effectiveness of area-based management in reducing bycatch of the New Zealand dolphin. *Endangered Species Research*, 20(2), 121-130. doi:10.3354/esr00483

Stien, L., Fosseidengen, J. E., Malm, M. E., Sveier, H., Torgersen, T., Wright, D. W. and Oppedal, F. (2014). Low intensity light of different colours modifies Atlantic Salmon depth use. *Aquacultural Engineering*, 62, 42-48. doi:10.1016/j.aquaeng.2014.05.001.

Tabor, R., Bell, A., Lantz, D., Gregersen, C. and Berge, H. (2015). Artificial Lighting Experiments in Lake Washington (2014) and Lake Sammamish (2015). U.S. Fish and Wildlife Service. Retrieved October 16th, 2018 from https://www.govlink.org/watersheds/8/committees/15TechFrm/Artificial-Lighting-Experiments-RTabor-USFWS-2015.pdf

Tasker, M. L., Camphuysen, C. J., Cooper, J., Garthe, S., Montevecchi, W. A. and Blaber, S. J. M. (2000). The impacts of fishing on marine birds. *ICES Journal of Marine Science*, (57), 531-547. doi:10.1006/jmsc.2000.00714

Utne-Palm, A. C., Breen, M., Løkkeborg, S. and Humborstad, O. B. (2018). Behavioural responses of krill and cod to artificial light in laboratory experiments. *PLoS ONE*, 13(1): e0190918. doi:10.1371/journal.pone.0190918

Valen, R., Edvardsen, R. B., Søviknes, A. M., Drivenes, Ø. and Helvik, J. V. (2014). Molecular evidence that only two opsin subfamilies, the Blue Light- (SWS2) and Green Light-Sensitive (RH2), drive Color Vision in Atlantic cod (*Gadus morhua*). *PLoS ONE*, 9(12): e115436. doi:10.1371/journal.pone.0115436.

Winger, P. D., Løkkeborg, S. and Pol, M. (2016). Fish capture by baited pots: A review of fish behaviour. *Journal of Ocean Technology*, 11(4), 1-12.

Woodhead, P. M. J. (1966). Effects of light upon behaviour and distribution of demersal fishes of the North Atlantic. *ICNAF Environmental Symposium Special Publication*, 6. Originally Contribution No. A-IS.ICNAF Environmental Symposium, Rome 27 January-l February 1964.

Žydelis, R., Small, C. and French, G. (2013). The incidental catch of seabirds in gillnet fisheries: A global review. *Biological Conservation*, 162, 76-88. doi:10.1016/j.biocon.2013.04.002

1.8 Co-authorship Statement

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The following is a list of co-authors and their contributions to the publication:

Robert J. Blackmore: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization, Funding acquisition.

Paul D. Winger: Writing - review and editing, Project administration, Funding acquisition.

Pierre-Paul Bitton: Conceptualization, Methodology, Resources, Writing - review and editing, Supervision, Funding acquisition.

Shannon Bayse: Validation, Formal analysis, Visualization.

Kira Whittaker: Investigation.

William A. Montevecchi: Conceptualization, Methodology, Investigation, Writing - review and editing, Supervision, Funding acquisition.

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The following is a list of co-authors and their contributions to the publication:

Robert J. Blackmore: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization, Funding acquisition.

Ryan F. B. Hawkins: Software, Writing - review and editing

William A. Montevecchi: Conceptualization, Writing - review and editing, Supervision, Funding acquisition.

Pierre-Paul Bitton: Conceptualization, Methodology, Resources, Writing - review and editing, Supervision, Funding acquisition.

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Robert J. Blackmore: Conceptualization, Writing - original draft, Visualization, Funding acquisition.

William A. Montevecchi: Conceptualization, Writing - review and editing, Supervision, Funding acquisition.

Pierre-Paul Bitton: Conceptualization, Writing - review and editing, Supervision, Funding acquisition.

Chapter 2: Effects of LED Attachments on Handline Catch Efficacy in the Newfoundland Inshore Cod Fishery

2.1 Abstract

Catch efficacy and bycatch are critical factors that determine the sustainability, practicality, and profitability of fishing gears. Inshore Atlantic cod (*Gadus morhua*) fisheries commonly use gillnets, cod-pots, longlines and handlines. Owing to their efficiency, species-selectiveness, and low effort, gillnets are the most widely used gear. Gillnets however are prone to entanglement and low-quality catch. Handlines benefit from low capital investment, live high-quality (better-priced) fish, and low bycatch. Enhancements to handlines that could increase catch rate or size of catch would be considered beneficial and could promote uptake by harvesters using other gear types. Previous pilot research has shown that green LED handline attachments that target the visual sensitivity of cod increased the catch rate of Atlantic cod. The present study builds upon this finding, incorporating three participating commercial crews and vessels. I found no significant effect of green LED handline modifications on catch efficacy for Atlantic cod or bycatch. The bycatch of Atlantic wolffish (*Anarhichas lupus*) decreased with the use of green LEDs, but the data precludes complex statistical analysis. I discuss how these findings are relevant to small-scale fishers and provide empirical evidence regarding the use of such devices in the commercial fishery.

2.2 Introduction

Following the collapse of Atlantic cod (*Gadus morhua*) stocks in eastern Canada, the commercial fishery was closed in 1992 (Hutchings and Myers 1994). Explanations for the collapse are varied, but it appears overfishing was compounded by biophysical and socio-economic factors (Hutchings and Myers 1994, Myers et al. 1996, Milich 1999). A major contributing influence was increasing technological advancement, such as rapid improvements in vessel design, fish-finding capability, and fishing gear technology, including the widespread use of monofilament nylon gillnets (Hutchings and Myers 1994, Myers et al. 1996, Montgomerie 2015). Gillnets are prone to bycatch, which is the incidental catch of non-target fish (Shester and Micheli 2011), corals (Dias et al. 2020), turtles (Alfaro-Shigueto et al. 2018), marine mammals (Reeves et al. 2013), and seabirds (Tasker et al. 2000, Žydelis et al. 2013, Hedd et al. 2015). Efforts to reduce bycatch have investigated acoustic and visual deterrents and reduced soak times (Melvin, Parrish and Conquest 1999; Rouxel et al. 2021) but effective means to reduce bycatch in gillnets remain elusive (Field et al. 2019, Montevecchi et al. 2023, Sigurdsson 2023). Gillnet removal and gear-switching is a viable and effective option for bycatch mitigation (Northridge 1991, Regular et al. 2013, Slooten 2013, O'Keefe et al. 2021). Baited cod pots have proven to be effective in both Canada (Meintzer et al. 2017, 2018) and western Europe (Bryhn et al. 2014, Anders et al. 2017), however uptake has been slow due to higher capital investments required.

Handlining is a traditional fishing practice still used today (Hutchings and Myers 1994, Montgomerie 2015), with high quality catch and sustainability compared to gillnets.

Handlines eliminate seabird and marine mammal bycatch, however they have the potential for low catch rates and undersized fish (Rouxel and Montevecchi 2018). In the Northwest Atlantic, handlines may infrequently catch wolffish (*Anarhichas* spp.), of which all three species that can occur in the region are Species of Concern (COSEWIC 2012).

Artificial light has been used in fishing practices for centuries to exploit the visual capabilities of target species (review by Nguyen and Winger 2018). Modern commercial applications of light in fisheries include squid, shrimp, snow crab, and Atlantic cod (Bryhn et al. 2014, Nguyen et al. 2017, Humborstad et al. 2018, Larsen et al. 2018). Fishes are influenced by the visual environments they inhabit, whereby the habitat light-scape influences the evolution and development of physiological and behavioural characteristics. The visual systems of fishes inhabiting specific pelagic zones have evolved such that visually-driven behaviours maximize the potential use of available light. Marine light environments are relatively constant and predictable, given the absorption of the available ambient light through the water column (Levine and MacNichol 1982; Mann and Lazier 1991), so visual ecology can be useful for understanding the interactions of animals and fishing gears (Blackmore, Montevecchi, and Bitton 2021, see Supplementary Material S.1), particularly those modified with artificial light devices.

Northern or Atlantic cod (*Gadus morhua*) is a typical benthopelagic fish species that inhabits both demersal and open ocean environments throughout its life (Rose 2019). The visual system of adult cod contains blue (446 nm) and green (517 nm) sensitive photopigments corresponding to the light availability below 50 metres (Anthony and Hawkins 1983, Douglas and Djamgoz 1990, Bowmaker 2008, Valen et al. 2014). Cod's dichromatic visual system provides sensitivity for specific wavelengths of light (colours) to carry more information that is behaviourally relevant (Gerl and Morris 2008). Utne-Palm et al. (2018) tested the influence of light on both cod and krill, a common prey, with respect to their interactions with light stimuli in a lab setting and found krill to interact with green light sources but found no significant results for the behaviour of cod toward the same lights. Cod interact with passive fishing gear modified with artificial light (Bryhn et al. 2014) and the krill surrounding the gear. Some bycatch reduction studies have shown different behavioural responses of cod to active gears such as trawls modified with green light (Grimaldo et al. 2018, Melli et al. 2018, Southworth et al. 2020). The behaviour of wild adult Atlantic cod to various wavelengths of light has not been assessed for handline fishing gear.

The economic and cultural significance of cod prioritizes research with the goal of enhancing sustainable gear options for the cod fishery. Handlines modified with a light attachment that is attractive to Atlantic cod, such that catch rate is increased, could benefit the fishery, and valuable basic knowledge about the species' behavioural traits could be gained. Research on modifications to handlines that target Atlantic cod's visual ecology might also promote a viable gear option with marketable benefits for small-scale inshore fishers and fill important knowledge gaps regarding the applicability of such modifications. Increasing handline catch rates and potentially catch size would be highly economical for handline fishers through a reduction in fuel use (fewer, shorter trips to catch quotas), reductions in bait use, and increased profitability and marketability for sustainably harvested catch.

A recent pilot study in Newfoundland, Canada, investigated the catch rates of handlines modified with green light-emitting diode (herein LED, emittance peak at 520 nm) attachments and obtained promising results that suggested a substantial increase in catch rates of handlines using green LED devices (Blackmore 2019). An inshore commercial cod stewardship fishery is ongoing in Newfoundland and Labrador, wherein bottom-set gillnets are the primary gear owing to their catch efficiency (Rouxel and Montevecchi 2018). Handlines are a common gear used in the off-time between setting and hauling gillnets to achieve quotas and are the sole gear type permitted for use in the recreational “food” fishery (DFO 2021b: see also Arlinghaus and Cooke 2009). In order for paradigm shift to occur in the favoured gear type of the Newfoundland and Labrador cod fishery, a highly efficient, sustainable, and profitable gear type would be required to replace or supplement gillnets. Owing to their high-quality live catch, handlines are the gear of choice to promote widespread gear-switching, and to reduce gillnet fishing effort. The pilot study was performed with small samples in both the recreational and commercial fishery, with various gear types and fishing methods (Blackmore 2019), thus the present study was designed to assess the same devices in a commercial, standardized setting, to test the effects of green LED attachments on handlines on catch rates, bycatch rates, and size of catch for commercial fishers.

2.3 Methods and Materials

2.3.1 Study Design and Procedure

In this study, three commercial fishing vessel owners were contracted to fish with and without handline enhancements. Experimental light treatments were applied to vessels, as opposed to individual lines, where the light catch basin of a line using the LED could influence the catch rate of nearby control lines from the same vessel. This allowed assessment of the effectiveness of LED lights on parameters of fishing efficacy and simulated how the LEDs might be used in practice. For logistical reasons, all lines fishing aboard each vessel either used LED handline attachments or not for the entire trip, and light use was randomized across the season for each vessel. To account for day effect, when possible, multiple vessels fished on the same days. Fishing activities were recorded for 62 days, from 13-Sep-2020 to 6-Nov-2020 in Motion Bay, Newfoundland and Labrador, Canada (47.466397, -52.695966). Three vessels were selected to participate in the research study by random draw from the Petty Harbour Fishermen's Cooperative (PHFC): RB (three crew members, 10 x 3.5 m vessel), BC (three crew members, 10 x 3.5 m vessel) and DK (two crew members, 6.7 x 2.5 m vessel). The PHFC has banned gillnet fishing in their area, allowing us to test handline fishing applications with crews who could directly implement gear modifications.

Fishing occurred 4-5 days each week, depending on weather and crew schedules, or until the weekly license quota was reached (DFO 2021a). All fishing was done from an anchored position, in different locations within Motion Bay, at depths ranging from 30-100 m, with an average daily fishing time of 317 minutes (sd = ±87.96 mins). Log sheets were filled out on every trip by either on-board researchers or the skipper, and included data on the crew and recorder, date, light treatment, number of lines fishing, time spent fishing, total catch weight, and bycatch (number of individuals and species ID, with photos taken and sent to me if the recorder was unsure). On return to port and while fishers were filleting and processing their catch, the length and weight of a subsample of the catch (approximately 50 haphazardly selected individuals) was recorded. Lengths were measured as total length using a ribbon tape, in centimetres rounded to the nearest cm. Weights were measured using a Pesola spring scale in kilograms, rounded to the nearest 0.1 kg. The weight of Atlantic cod varies with length at a predictable allometric growth relationship (Árnason et al. 2009), and thus the results of weight measurements could be considered redundant for presentation alongside length, but I chose to include all analyses, with weight being the more relevant measurement to fishers. Researchers attended different vessels each day, fishing with the crew, overseeing the crews' fishing methods and participation in the study, as well as training the skippers to fill out log sheets. For applicability to the inshore commercial fishery, no variables were altered with regard to the fishing practices of the participant crews, such that data recorded on days without using lights represented a true control for "normal" fishing.

Experiments were performed with approval from the Memorial University of Newfoundland Animal Care Committee under Animal Use Protocol 20181915.

2.3.2 Fishing Gear and Devices

All three crews fished using the same gear: traditional handlines consisting of a 200 lb-test fishing line with an 8-10 oz lead weight and #12 hook, baited with capelin, mackerel, herring, or squid (configuration shown in Figure 2.1a). Each crew member fished with 2 lines each, totaling 4 or 6 lines per vessel, unless a researcher was aboard the vessel in which case 5 or 7 lines were deployed. The LEDs used were ProGlow UltraBright LEDs (FishTek Marine, Devon, U.K.), which were attached directly to the line between the hook and swivel and have an automatic submersion switch that emits green light peaking at 524 nm when in contact with water (emission profile shown in Figure 2.1b). Throughout the experiment, one device stopped working and was replaced. The light emission profile for LED devices was measured before experimentation began using a Jaz® spectrophotometer (OceanInsight, Orlando, U.S.A.) fitted with a cosine-corrected optic fibre (CC-3-UV, Ocean Insight) in scope mode. Six LEDs were measured at full battery, positioned 1 m from the cosine corrector, with an integration time of 200 milliseconds (Figure S.2).

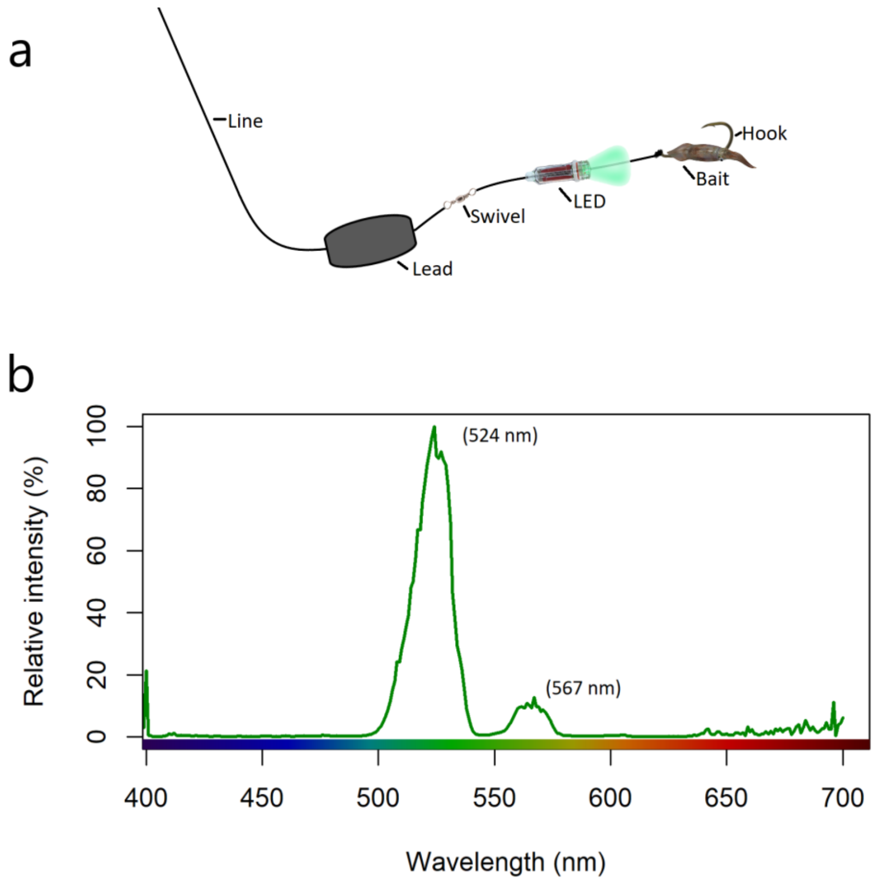


Figure 2.1. (a) Experimental handline configuration showing the position of the LED attachment on the line, and (b) the light profile of the LED as measured by spectrophotometry, showing its peak relative intensity at 524 nm (maximum intensity set to 100%).

2.3.3 Statistical Analysis

I tested the influence of LED handline attachments on Catch Rate (kg/hr/line), Bycatch Rate (organisms/hr/line), Catch Weight (kg), and Catch Length (cm). To determine the factors influencing the dependent variables I performed generalized linear mixed model (GLMM) analyses that included 'Light treatment' and 'Fisher' as fixed factors, and

‘Fishing date’ as a random factor. The Total Catch model was fitted using a negative binomial distribution, and Bycatch Rate data were normal and fitted using a Gaussian distribution model. Catch Length and Catch Weight data were log-transformed prior to analysis and subsequent models were fitted using a Gaussian distribution. Degrees of freedom were calculated from the GLMMs and residuals were checked for homogeneity and independence, then fitted to Q-Q plots to check normality. Models were compared using AIC (Akaike 1974), using the *anova* function in the car package (Fox and Weisberg 2019). All model assumptions were evaluated using the DHARMa package and assigned a model distribution that best fit the residuals. Cook’s distances were plotted to identify any outliers, and any values above a precalculated maximum acceptable value (4/(n-k-1)), where n = sample size and k = number of parameters in the model, were flagged. Analyses were performed with and without flagged outliers, and the outliers were kept in the presented data if the interpretation of the subsequent results remained unchanged. When applicable, post hoc Tukey’s contrasts tests were performed using the “multcomp” package in R (R Development Core Team 2017). All statistical analyses were performed, and all plots were produced, using R statistical software (R Development Core Team 2017). For boxplots produced using the *ggplot* function in ggplot2 package, default settings for the interquartile range and whiskers were used, such that the box represents the 25th, 50th (median), and 75th percentiles, whiskers represent 1.5 times the interquartile range, and dots represent outlying values outside of 1.5 times the range.

2.3.4 Size selectivity analysis

Atlantic cod length data were analyzed using the unpaired method in the selfisher package (Brooks et al. 2022). Relative retention probability between both treatments was modelled as a function of length class (per cm). Logistic generalized linear models (GLMs) were used to fit the expected proportions of Atlantic cod caught with and without lights using a binomial error. Flexible models were fit by maximum likelihood of proportions retained, including low order polynomials (degree 0-4) and splines (3-5 degrees of freedom; using the *ns* function in the splines package (Bates and Venables 2011)). The model was scaled up to incorporate the subsampling ratio. The best model was considered to have the lowest AIC (Akaike 1974), using the function *AICtab* in the bbmle package (Bolker 2017). If retention was 0.5 at a given length class, then there was no difference in catch between treatments at that particular length class. If retention was 0.75, then 75% of Atlantic cod at the given length class was captured by fishers using lights and 25% by fishers not using lights. Confidence intervals (CIs) for the model were generated with the *bootSel* function in selfisher, and 1,000 bootstrap simulations were used to generate 95% CIs that account for within and between trip variation (Millar 1993). Retention was considered significantly different between treatments if 0.5 was not contained within the CIs.

2.4 Results

To determine the effect of LEDs on catch parameters, the experimental treatment was randomized across the season with lights used n = 33 days and control n = 29 days. Partitioned by crew: n = 15 lights, n = 9 control for BC; n = 4 lights, n = 10 control for

DK; and n = 14 lights, n = 10 control for RB. Due to human error and insufficient data, some fishing days had to be discounted from the analyses. A complete description of the number of replicates for each variable tested is in Table 2.1.

Table 2.1. Summary of replicates performed for tests of catch efficacy variables in the Newfoundland inshore cod fishery.

Variable	Replicates of experimental treatment		Average value	Factor	χ^2	df	p
Catch Rate N = 46	Light	21	14.65 kg/hr/line	Lights	0.5039	1	0.4778
	Control	25	17.69 kg/hr/line	Fisher	9.9121	2	0.0070
Bycatch Rate N = 47	Light	22	0.141 ± 0.154 organisms/hr/line	Lights	0.0557	1	0.8134
	Control	25	0.115 ± 0.086 organisms/hr/line	Fisher	3.9277	2	0.1403
Catch Length N = 767	Light	478	56.05 ± 9.37 cm	Lights	0.0088	1	0.9254
	Control	289	55.93 ± 8.61 cm	Fisher	15.0122	2	0.0005
Catch Weight N = 767	Light	478	2.16 ± 0.38 kg	Lights	0.1823	1	0.6693
	Control	289	2.23 ± 0.58 kg	Fisher	9.7391	2	0.0076

2.4.1 Catch Rate

The influence of lights and fisher on catch rate was investigated using a negative binomial GLMM and showed that the mean catch rate of lines using lights was 14.65 kg/hr/line, whereas the mean catch rate of lines without lights was 17.69 kg/hr/line ($p = 0.4778$; Figure 2.2). BC and DK had increased catch rates when using LEDs, whereas RB showed a decrease. The influence of fisher on catch rate was statistically significant at a predetermined $\alpha = 5\%$ ($p = 0.0070$), so a post hoc Tukey's contrasts test was performed to identify which harvesters had significant differences in catch rate. RB was shown to differ from DK ($p = 0.0048$) (Figure 2.2). The results were qualitatively the same with and without a possible outlier ($x = 38.90$ kg/hr/line), which therefore remains in the analysis.

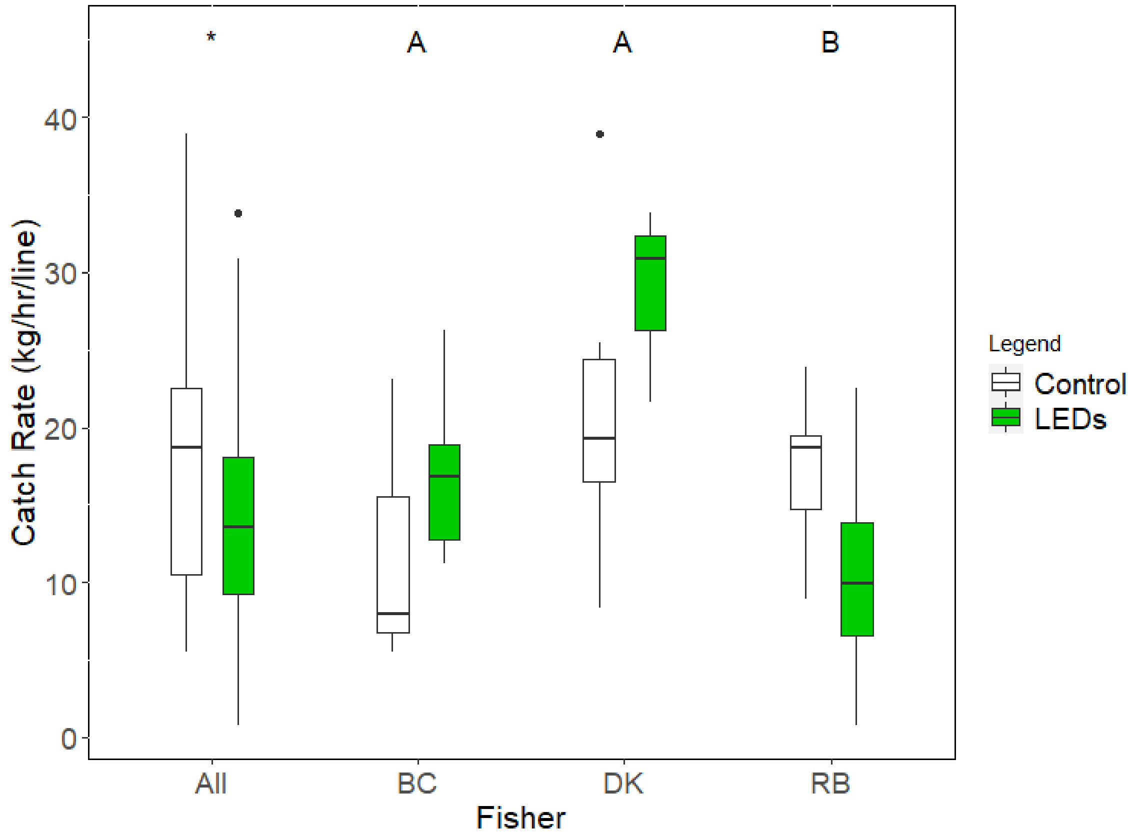


Figure 2.2. The effect of green LED handline attachments on catch rates (kg/hr/line) of Petty Harbour inshore fishers (n = 25 days control, 21 days using LEDs). Results of the Tukey's contrast test for multiple comparisons of means are shown as annotated labels, where * denotes the overall results, A denotes non-significant individual results and B denotes statistically significant individual results (α = 5%).

2.4.2 Bycatch Rate

The GLMM investigating the influence of lights on bycatch rate showed that the mean bycatch rate for lines with lights was 0.113 ± 0.088 organisms/hr/line, whereas the mean bycatch rate for lines without lights was 0.115 ± 0.086 organisms/hr/line (p = 0.8134; Figure 2.3). Fisher had no significant effect on rate of bycatch between conditions (p = 0.1403). Table 2.2 shows a complete list of bycatch occurrences. One outlier remains in the analysis; its removal quantitatively changed the mean bycatch rate for lines with lights but qualitatively changes nothing with regards to the statistical significance or interpretation of subsequent results, justifying its inclusion.

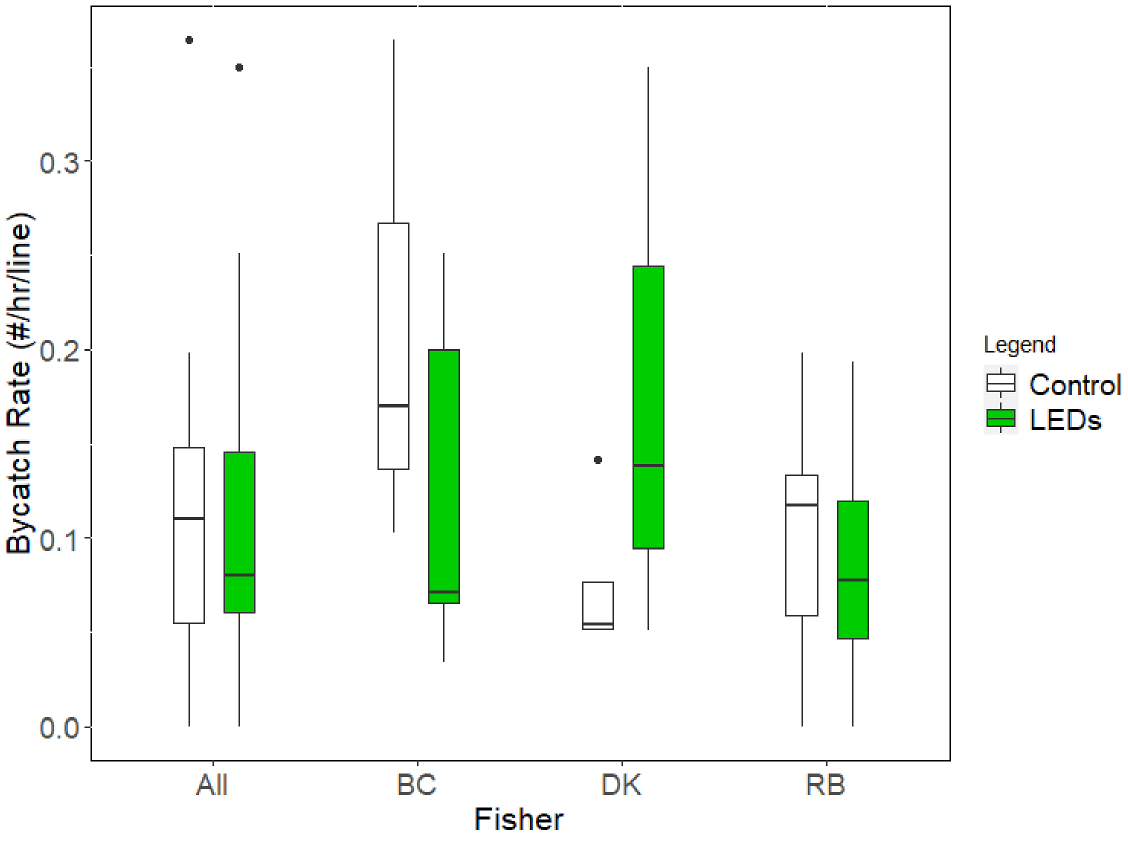


Figure 2.3. The effect of LED handline attachments on bycatch rate for Petty Harbour inshore fishers (n = 25 days control, 22 days using LEDs).

Table 2.2. List of all bycatch species encountered and the number of occurrences throughout the study (X denotes that encounters with this species were not quantified).

Species name	**Occurrences**
Shorthorn Sculpin - *Myoxocephalus scorpius*	149
Longhorn Sculpin - *Myoxocephalus octodecemspinosus*	5
Atlantic Wolffish - *Anarhichas lupus*	20
Winter Flounder - *Pseudopleuronectes americanus*	2
Blue Shark - *Prionace glauca*	1
Atlantic Lyre Crab - *Hyas araneus/alutaceus*	2
Northern Basket Star - *Gorgonocephalus arcticus*	5
Daisy Brittle Star - *Ophiopholis aculeata*	3
Spiny Sunstar - *Crossaster papposus*	1
Green Sea Urchin - *Strongylocentrotus droebachiensis*	1
Sea Strawberry - *Gersemia rubiformis*	2
Ascidia sp.	1
Irish Moss - *Chondrus crispus*	X
Various epibionts, such as isopods, copepods, etc	X

The only wolffish bycatch throughout the study was *A. lupus*, which was caught 20 times (Table 2.2). Fourteen instances of *A. lupus* bycatch occurred when lights were not used (control), whereas six occurred when lights were used (experimental). This sample size precludes complex statistical modelling, but running a binomial test for the cumulative probability of the control lines catching 14 wolffish of the total 20 ($Pr|X \geq x$) returns a likelihood of $p = 0.057$ for that outcome. This signifies that this outcome is unlikely due to chance alone, and that the light condition of experimental lines may have influenced the catch of wolffish.

2.4.3 Catch Length

To investigate the effects of lights on catch length of Atlantic Cod, a Gaussian GLMM was used and showed that overall, the average length of catch using lights was 55.93 ± 8.61 cm, whereas the average catch length without lights was 56.05 ± 9.37 cm ($p = 0.9254$, Figure 2.4). The influence of fisher on catch length was statistically significant ($p < 0.001$) and the conditional model showed that DK was significantly different from the reference ($p = 0.0072$), so a post-hoc Tukey's contrasts test was performed, showing that DK significantly differed from RB ($p < 0.001$) and BC ($p = 0.0195$) (Figure 2.4).

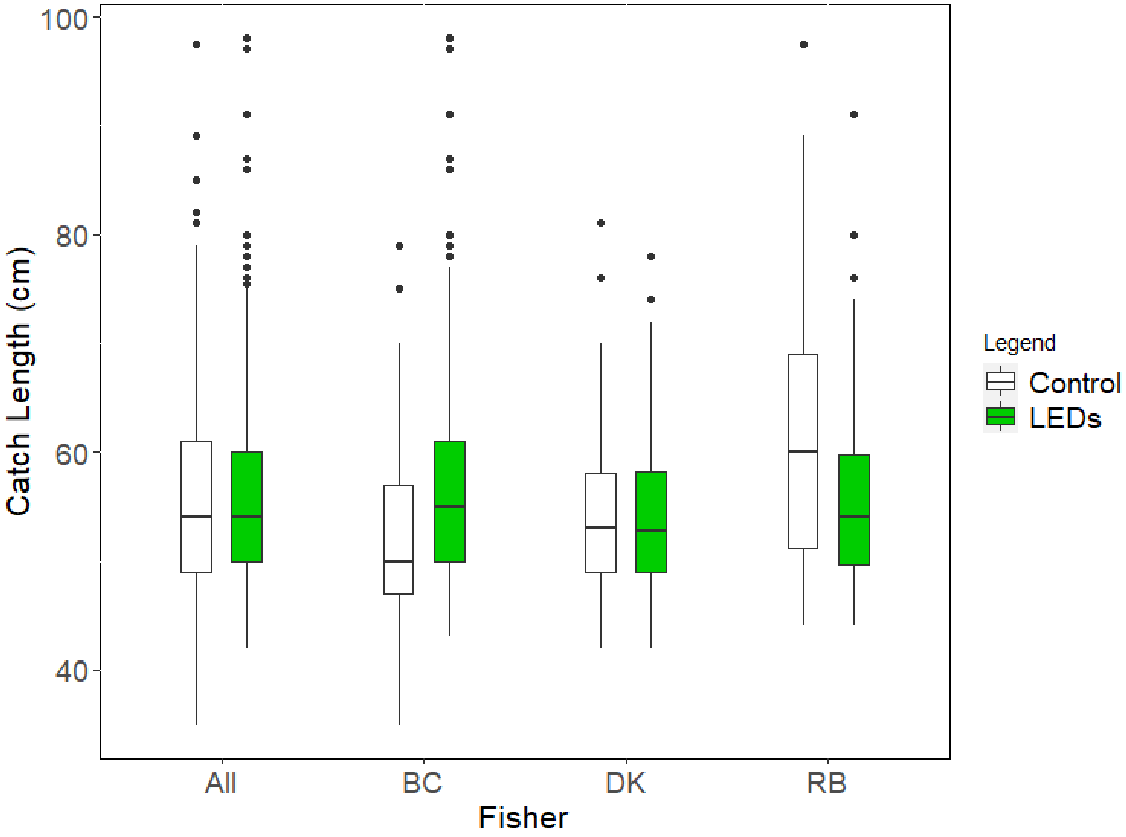


Figure 2.4. The effect of LED handline attachments on catch length (cm) for Petty Harbour inshore fishers (n = 289 control, 478 LEDs).

A size selectivity analysis on the catch length data was performed using a spline model with three degrees of freedom. The analysis showed that confidence intervals at every length class included 0.5 proportion (Figure 2.5), indicating no significant difference in size selectivity for handlines with or without green LEDs.

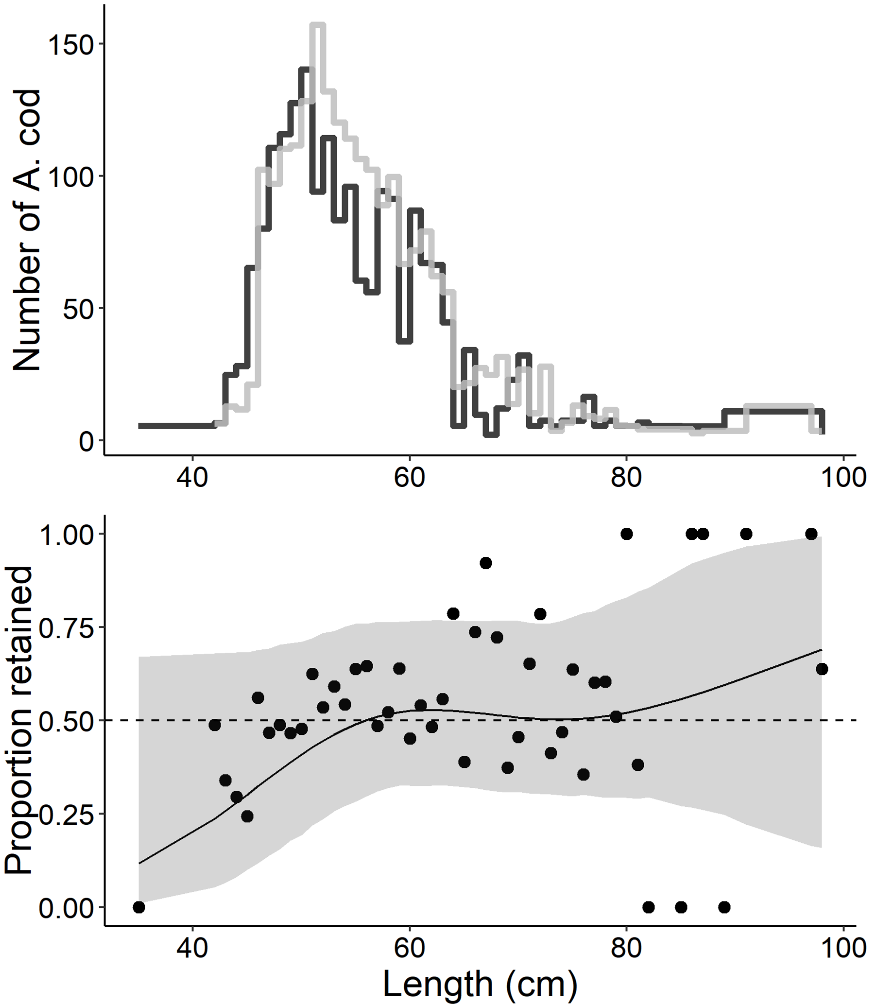


Figure 2.5. Size selectivity analysis of modified handlines. At each length class, the frequency of individuals caught is shown in black for control and grey for experimental treatments. Retention probability for the experimental treatment is calculated from 0-1 such that 1.00 indicates a 100% probability of catch by LED-modified handlines, 0.00 indicates a 0% probability of catch by LED-modified handlines (100% probability of catch by unmodified gear), and 50% indicates an equal probability of catch for both gears, at a given catch length-class. Confidence intervals are shown by the shaded area, with the trendline as a solid black line-of-best-fit.

2.4.4 Catch Weight

The GLMM investigating the influence of lights on catch weight showed that the mean catch weight for lines using lights was 2.16 ± 0.38 kg, whereas the mean catch weight of lines without lights was 2.23 ± 0.58 kg (p = 0.569; Figure 2.6). The influence of fisher on catch weight was statistically significant (p = 0.0076) and the conditional model showed that DK was significantly different from the reference (p = 0.0374), so a post-hoc Tukey's contrasts test was performed, showing that DK significantly differed from RB (p = 0.0078), but not BC (p = 0.0929) (Figure 2.6).

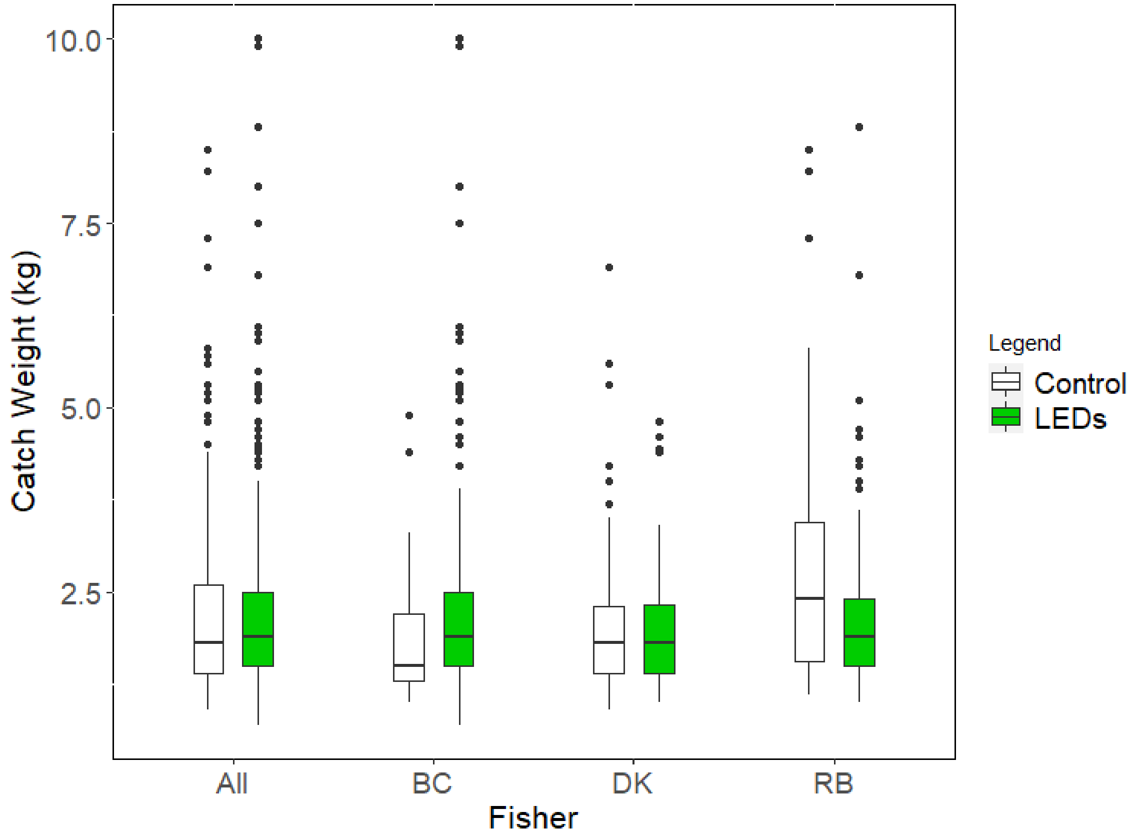


Figure 2.6. The effect of LED handline attachments on catch weight (kg) for Petty Harbour inshore fishers (n = 289 control, 478 LEDs).

2.5 Discussion

My results found no significant difference in the catch rate, bycatch rate, or average weight or length of catch between days fished with or without green LED handline attachments (Figures 2.2, 2.3, 2.4 and 2.6, respectively). This information is important to rural commercial fisheries, as the harmful effects of gillnets such as frequent bycatch and poor-quality catch are well-known and frustrating to small-scale harvesters (Rouxel and Montevecchi 2018). A gear enhancement that could increase the CPUE of sustainable gear alternatives would be useful to many rural commercial fishers seeking more sustainable fishing methods. Non-significant results like these indicate that the investment in this particular gear attachment, which is available in marine supplies stores locally for ~$7.50, may not be worthwhile for those using handlines or those considering switching gears. These results contrast with those of a pilot study which showed that catch rates of individual lines using green LEDs effectively doubled when compared to handlines that fished simultaneously without lights (Blackmore 2019). By using a more rigid study design with a much larger sample size, I am confident that the null effect reported in this study are reflective of the lack of effect that these LEDs have on catch parameters.

Targeting the visual ecology of Atlantic cod, I designed my study using green LED handline attachments as a tool for enhancing handline CPUE. The use of light in bycatch research has focused on artificial light devices to deter the species of concern from fishing gear (Ortiz et al. 2016, Field et al. 2019, Darquea et al. 2020), or to a portion of the gear that has been modified to release incidentally-caught individuals (Larsen et al.

2018, Grimaldo et al. 2018, Melli et al. 2018, Southworth et al. 2020). This method of bycatch reduction has been quite successful for some species in some fisheries, but variable and often with harmful side-effects such as diminished target-catch yields in others (Montevecchi et al. 2023). Instead of trying to balance a reduction in non-target catch while attempting to maintain or augment target catch, I opted to rethink the use of light in this study. By choosing to modify traditional handline gear with low bycatch potential, I was able to target a species' visual system while monitoring the LED's effect on bycatch frequency. My study design incorporated the fishing practices of commercial fishers who fish exclusively with handlines to ensure that the methods were consistent with practices already in place. A major strength in this design and working with this group of harvesters was that the results were not hindered by the design in terms of their applicability and could be immediately implemented and relevant to the demographic who might incorporate the results of my study into their daily fishing practices. In short, the control for this study was no different than the standard fishing practices of the commercial harvesters with whom I worked. The LED attachment was the only altered variable during normal fishing activities, and any resulting differences in CPUE will inform harvester's decision on gear choices in the future.

I recognize inherent limitations in my experimental design. Foremost, the 2020 fishing season in Motion Bay was widely regarded as one of the most anomalous fishing seasons by members of the Petty Harbour Fishermen's Cooperative. This was based on many reports by local harvesters returning to port with low catch, sometimes fishing for 6+ hours and returning with only a few fishes as compared to the hundreds of pounds of catch that would normally be expected. Fisheries and Oceans Canada (DFO) reported the lowest total catch of Atlantic cod for inshore vessels across Newfoundland and Labrador in 2020 compared to the previous five years (DFO 2021c). This situation was beyond my control when designing this study, as the variability of fish available in the region can fluctuate widely due to a myriad of factors. Daily variation in factors such as water current in the fishing location, and sea surface temperature affect the local dispersal of cod, particularly throughout the water column (Freitas et al. 2015, Staveley et al. 2019). Other environmental factors like prey dispersal and availability across the season are also likely drivers of the distribution of Atlantic cod in the area (Tamdrari et al. 2012). Other factors, including overfishing and climate change would drastically impact the stock size for inshore cod across years. These factors likely affected the results and their interpretation by producing considerable variation in the data. Nevertheless, my results mirror findings from cod behavioural studies using light (Utne-Palm et al. 2018).

Though quantifiably lower than many other gear types, handlines nonetheless produce bycatch of non-targeted groundfish species. The effects of light modifications to gear for enhancing the catch of target species likely also produce similar effects in non-target species. Of concern in the Atlantic cod fishery is the Atlantic wolffish (*Anarhichas lupus)*, an endangered species in the Eastern Atlantic (HELCOM 2013). In Canada, all four *Anarhichas* species are possible bycatch in groundfish fisheries and are listed as Species of Concern by the Species at Risk Act (SARA; COSEWIC 2012). In my trials, only *A. lupus* was caught incidentally, and it was the second-most frequently caught bycatch species throughout the study (Table 2.2). Interestingly, wolffish were caught 14 times by control handlines, and less than half as often (n = 6) by handlines using green LEDs. This sample size is quite low but suggests a potential use of LEDs for reducing bycatch of this species of concern and warrants further research on the deterrence capability of LEDs with regards to wolffish behaviour. Since the target catch parameters of lines with and without green LED attachments were effectively unaltered, the use of LEDs as a bycatch reduction technology for wolffish is intriguing. A handline fishery would allow for bycaught wolffish to be returned to the ocean alive and hopefully sustaining minimal injury (as mandated in the Canadian Fisheries Act; DFO 2021a). Wolffish are prone to getting bycaught in cod gillnets (Kulka, Hood, and Huntington 2007), where they are likely to be moribund or dead. Gillnet modifications have reduced wolffish and Atlantic cod bycatch in the west Greenland Lumpfish (*Cyclopterus lumpus*) fishery (Post et al. 2023), but these nets carry other unwanted consequences (see Post et al. 2023), therefore the possibility of wolffish deterrence using LEDs carries conservation implications with respect to various gear types. The visual sensitivities of adult Atlantic wolffish may differ from those of Atlantic cod, due to their sedentary lifestyle and feeding habits, and thus minute differences in sensitivity could be important in assessing the potential effectiveness of LEDs on deterring wolffish from fishing gears that target Atlantic cod.

I was unable to record the occurrence of undersized (< 40cm total-length) cod catch due to limitations with data collection and logistical constraints, but this should be included as non-target catch and considered bycatch. The spectral sensitivity and genotypic expression of photopigments changes ontogenetically throughout the lifespan of Atlantic cod (Valen et al. 2014), therefore it is important to record undersized catch in studies testing visual gear modifications in the future. An effect of LEDs on the catch of undersized cod would be important information to small-scale harvesters, as current fishery regulations prohibit the retention of undersized groundfish catch. Discarding catch wastes time, effort, and bait, often leaves the bycatch injured or dead as they are unhooked, and encourages large apex predators such as Atlantic bluefin tuna (*Thunnus thynnus*), sharks, and seabirds to congregate in areas of high fishing activity (Montevecchi 2023) to feed on the discards. Groundfish are not a common natural prey item of pelagic predators such as tuna (NOAA 2021), thus their predation of cod via fishery discards introduces a potential novel threat to the fish stock. More importantly however, large predators pose a dangerous risk to fishers if they become entangled or caught by the gear. The effect of LED attachments on handline fishing effort with respect to catch weight also informs fishery management, as the most sustainable fishing practice for exerting pressure on a threatened stock like Atlantic cod is to target the mid-range ages and sizes of biomass (Myers et al. 1997, Darby 2019). Undersized catches are often outside this target age and size, and do not form part of the super spawning stock biomass. New technology capable of improving size-selectivity to the centre of biomass of target catch, while decreasing rate of catch of non-target juveniles, has conservation implications for the target species, particularly on a large scale with regards to international fisheries discards policies.

Overall, the findings of this study are important for cod fisheries and research. Continuation of this research across multiple years would help account for the variation in fish availability within commercial seasons, which is the greatest limitation to the current study. The study is informative with respect to how visual ecology can be used as a tool in fishing practices and research. I encourage the continued study of visual modifications to fishing gears, especially methods that consider the sensory ecology of the target species. Future research into the sensory ecology of Atlantic cod and their behaviour will inform and shape the choice of devices deployed both in industrial and fisheries research applications. Researchers who work with gear technology in small-scale fisheries need to consider the applicability of their research to the fishery during the design phase of the study (Blackmore, Montevecchi, and Bitton 2021, see Supplementary Material S.1). Testing gear designs before application to industry and focusing on gear likely to be incorporated into fishing practices will benefit researchers and fishers alike.

2.6 References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*. 19, 716-723. doi:10.1109/TAC.1974.1100705

Alfaro-Shigueto, J., Mangel, J. C., Darquea, J., Donoso, M., Baquero, A., Doherty, P. D. and Godley, B. J. (2018). Untangling the impacts of nets in the southeastern Pacific: Rapid assessment of marine turtle bycatch to set conservation priorities in small-scale fisheries. *Fisheries Research*, 206, 185-192. doi:10.1016/j.fishres.2018.04.013

Anders, N., Fernö, A., Humborstad, O-B., Løkkeborg, S., and Utne-Palm, A. C. (2017). Species specific behaviour and catchability of gadoid fish to floated and bottom set pots. *ICES Journal of Marine Science*, 74, 769-779. doi:10.1093/icesjms/fsw200

Anthony, P. D. and Hawkins, A. D. (1983). Spectral sensitivity of the cod, *Gadus morhua* L. *Marine Behaviour and Physiology,* 10(2), 145-166. doi:10.1080/10236248309378614

Arlinghaus, R. and Cooke, S. J. (2009). Recreational Fisheries: Socioeconomic Importance, Conservation Issues and Management Challenges. In: Dickson, B., Hutton, J., and Adams, W. M. (eds.) *Recreational Hunting, Conservation and Rural Livelihoods: Science and Practice*, 4, 39-58. Wiley-Blackwell.

Árnason, T., Björnsson, B. and Steinarsson, A. (2009). Allometric growth and condition factor of Atlantic cod (*Gadus morhua*) fed to satiation: Effects of temperature and body weight. *Journal of Applied Ichthyology*, 25(4), 401-406. doi:10.1111/j.14390426.2009.01259.x

Bates, M. D., Venables, B. and Team, M. R. C. (2011). Package 'splines'. R Version, 2(0).

Blackmore, R. J., Montevecchi, W. A. and Bitton, P-P. (2021). In the eye of the beholder: visual ecology in fisheries research design. *Journal of Ocean Technology*, 16(2), 32-41. ISSN: 1718-3200

Blackmore, R. (2019). Testing Handline Catch Efficacy for Atlantic Cod (*Gadus morhua*) in the Inshore Newfoundland Fishery: Two Studies of Short-Wavelength Modifications. [Unpublished Bachelor of Science Honours thesis]. Memorial University of Newfoundland and Labrador.

Bolker, B. (2017). Package Bbmle. https://cran.r-project.org/web/packages/bbmle/bbmle.pdf.

Bowmaker, J. (2008). Evolution of vertebrate visual pigments. *Vision Research*, 48, 2022-2041. doi:10.1016/j.visres.2008.03.025

Brooks, M. E., Melli, V., Savina, E., Santos, J., Millar, R., O'Neill, F. G., Veiga-Malta, T., Krag, L. A., and Feekings, J. P. (2022). Introducing selfisher: Open source software for statistical analyses of fishing gear selectivity. *Canadian Journal of Fisheries and Aquatic Sciences*, 79(8): 1189-1197. doi:10.1139/cjfas-2021-0099

Bryhn, A. C., Konigson, S. J., Lunneryd, S. G. and Bergenius, M. A. J. (2014). Green lamps as visual stimuli affect the catch efficiency of floating cod (*Gadus morhua*) pots in the Baltic Sea. *Fisheries Research*, 157, 187-192. doi:10.1016/j.fishres.2014.04.012

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). (2012). *COSEWIC assessment and status report on the Atlantic wolffish Anarhichas lupus in Canada*. Retrieved from: https://species-registry.canada.ca/index-en.html#/consultations/1133

Darby, B. (2019). *Changing Course: A New Direction for Canadian Fisheries*. St. John's. Retrieved from: http://docplayer.net/170604916-Changing-course-a-new-direction-for-canadian-fisheries-barry-darby-st-john-s-nl.html

Darquea, J. J., Ortiz-Alvarez, C., Córdova-Zavaleta, F., Medina, R., Bielli, A., Alfaro-Shigueto, J. and Mangel, J. C. (2020). Trialing net illumination as a bycatch mitigation measure for sea turtles in a small-scale gillnet fishery in Ecuador. *Latin American Journal of Aquatic Research*, 48(3), 446-455. doi:10.3856/vol48-issue3-fulltext-2428

Dias, V., Oliveira, F., Boavida, J., Serrão, E. A., Gonçalves, J. M. S. and Coelho, M. A. G. (2020). High coral bycatch in bottom-set gillnet coastal fisheries reveals rich coral habitats in Southern Portugal. *Frontiers in Marine Science*, 7, 1-16. doi:10.3389/fmars.2020.603438

Department of Fisheries and Oceans Canada (DFO). (1985). *Status of Fisheries Cooperatives in Newfoundland and Labrador*. Retrieved from: https://waves-vagues.dfo-mpo.gc.ca/Library/102144.pdf

Department of Fisheries and Oceans Canada (DFO). (2021a). *2021 Conservation harvesting plan (CHP) - 2J3KL Stewardship cod fishery*. Retrieved from: https://www.dfo-mpo.gc.ca/fisheries-peches/decisions/fm-2021-gp/atl-36-eng.html

Department of Fisheries and Oceans Canada (DFO). (2021b). *2021 Newfoundland and Labrador recreational groundfish fishery*. Retrieved on January 19th, 2022 from https://www.dfo-mpo.gc.ca/fisheries-peches/decisions/fm-2021-gp/atl-28-eng.html

Department of Fisheries and Oceans Canada (DFO). (2021c). *Landings and Landed Value by Species: Newfoundland and Labrador Region - Preliminary Data - Subject to revision*. Retrieved on June 13th, 2021 from: http://www.nfl.dfo-mpo.gc.ca/publications/reports_rapports/land_inshore_debarquer_cotiere_2020_eng.htm

Douglas, R. and Djamgoz, M. (eds.) (1990). *The Visual System of Fish*. Springer, Dordrecht. doi:10.1007/978-94-009-0411-8_4

Field, R., Crawford, R., Enever, R., Linkowski, T., Martin, G., Morkūnas, J., Morkūnė, R., Rouxel, Y. and Oppel, S. (2019). High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. *Global Ecology and Conservation*, 18: e00602. doi:10.1016/j.gecco.2019.e00602

Fox, J. and Weisberg, S. (2019). An R Companion to Applied Regression, Third Edition, Sage.

Freitas, C., Moland Olsen, E., Moland, E., Ciannelli, L. and Knutsen, H. (2015). Behavioral responses of Atlantic cod to sea temperature changes. *Ecology and Evolution*, 5(10), 2070-2083. doi: 10.1002/ece3.1496

Grimaldo, E., Sistiaga, M., Herrmann, B., Larsen, R. B., Brinkhof, J., and Tatone, I. (2018). Improving release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery by stimulating escape behaviour. *Canadian Journal of Fisheries and Aquatic Sciences*, 75(3), 402-416.

Hedd, A., Regular, P. M., Wilhelm, S. I., Rail, J. F., Drolet, B., Fowler, M., Pekarik, C. and Robertson, G. J. (2015). Characterization of seabird bycatch in eastern Canadian waters, 1998-2011, assessed from onboard fisheries observer data. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26(3), 530-548. doi:10.1002/aqc.2551

Helsinki Commission (HELCOM). (2013). HELCOM Red List of Baltic Sea species in danger of becoming extinct. *Baltic Sea Environment Proceedings* No. 140. ISSN 0357-2994

Humborstad, O-B., Utne-Palm, A. C., Breen, M. and Løkkeborg, S. (2018). Artificial light in baited pots substantially increases the catch of cod (*Gadus morhua*) by attracting active bait, krill (*Thysanoessa inermis*). *ICES Journal of Marine Science*, 75(6), 2257-2264. doi:10.1093/icesjms/fsy099

Hutchings, J. A. and Myers, R. A. (1994). What can be learned from the collapse of a renewable resource? Atlantic Cod, *Gadus morhua*, of Newfoundland and Labrador. *Canadian Journal of Fisheries and Aquatic Sciences*, 51, 2126-2146.

Larsen, R. B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J. and Tatone, I. (2018). Could green artificial light reduce bycatch during Barents Sea Deep-water shrimp trawling? *Fisheries Research*, 204, 441-447. doi:10.1016/j.fishres.2018.03.023

Levine, J. and MacNichol, E. (1982). Color vision in fishes. *Scientific American*, 248(2), 140- 149. doi:10.1038/scientificamerican0282-140

Mann, K. H. and Lazier, J. R. N. (1991). *Dynamics of Marine Ecosystems: Biological-Physical Interactions in the Oceans*. Malden, MA: Blackwell.

Meintzer, P., Walsh, P. and Favaro, B. (2017). Will you swim into my parlour? *In situ* observations of Atlantic cod (*Gadus morhua*) interactions with baited pots, with implications for gear design. *PeerJ*, 5: e2953. doi:10.7717/peerj.2953

Meintzer, P., Walsh, P. and Favaro, B. (2018). Comparing catch efficiency of five models of pot for use in a Newfoundland and Labrador cod fishery. *PLoS ONE*, 13(6): e0199702. doi:10.1371/journal.pone.0199702

Melli, V., Krag, L. A., Herrmann, B., and Karlsen, J. D. (2018). Investigating fish behavioural responses to LED lights in trawls and potential applications for bycatch reduction in the *Nephrops*-directed fishery. *ICES Journal of Marine Science*, 75(5), 1682-1692.

Melvin, E. F., Parrish, J. K. and Conquest, L. L. (1999). Novel tools to reduce seabird bycatch in coastal gillnet fisheries. *Conservation Biology*, 13, 1386-1397.

Milich, L. (1999). Resource mismanagement versus sustainable livelihoods: the collapse of the Newfoundland cod fishery. *Society and Natural Resources*, 12(7), 625-642. doi:10.1080/089419299279353

Millar, R. B. (1993). Incorporation of between-tow variation using bootstrapping and nonparametric estimation of selection curves. *Fishery Bulletin*, 91, 564-572.

Montevecchi, W. A. (2023). Interactions between fisheries and seabirds: Prey modifications, discarding and bycatch. In: Young, L. and Vander Werf, E. (eds.) *Conservation of Marine Birds*. Elsevier.

Montevecchi, W. A., Lamarre, J., Rouxel, Y., Montevecchi, M. W., Blackmore, R. J., Bourne, C. and Spiegel, C. (2023). High-contrast banners designed to deter seabirds from gillnets reduce target fish catch. *Marine Ornithology* 51, 119-126.

Montgomerie, M. (2015). Basic fishing methods: A comprehensive guide to commercial fishing methods. *SEAFISH*, Edinburgh UK, 106p.

Myers, R. A., Hutchings, J. A. and Barrowman, N. J. (1996). Hypotheses for the decline of cod in the North Atlantic. *Marine Ecology Progress Series*, 138, 293-308.

Myers, R. A., Hutchings, J. A. and Barrowman, N. J. (1997). Why do fish stocks collapse? The example of cod in Atlantic Canada. *Ecological Applications*, 7(1), 91-106.

National Oceanic and Atmospheric Administration (NOAA). (2021). Western Atlantic Bluefin Tuna. Retrieved from: https://www.fisheries.noaa.gov/species/western-atlantic-bluefin-tuna

Nguyen, K. and Winger, P. (2018). Artificial light in commercial industrialized fishing applications: A review. *Reviews in Fisheries Science & Aquaculture*, 27(1), 106-126. doi:10.1080/23308249.2018.1496065

Nguyen, K. Q., Winger, P. D., Morris, C., and Grant, S. M. (2017). Artificial lights improve the catchability of snow crab (*Chionoecetes opilio*) traps. *Aquaculture and Fisheries*, 2, 124-133. doi:10.1016/j.aaf.2017.05.001

Northridge, S.P. (1991). Driftnet fisheries and their impacts on non-target species: A worldwide review. *FAO Fisheries Technical Paper*, No.320. Rome, FAO. ISBN 92-5-103098-7

O’Keefe, C. E., Cadrin, S. X., Glemarec, G., and Rouxel, Y. (2021). Efficacy of time-area fishing restrictions and gear-switching as solutions for reducing seabird bycatch in gillnet fisheries. *Reviews in Fisheries Science & Aquaculture*, 31(1): 29-46. doi:10.1080/23308249.2021.1988051

R Development Core Team. (2017). R: A language and environment for statistical computing. Vienna, Austria. ISBN 3-900051-07-0. URL http://www.R-project.org.

Reeves, R. R., McClellan, K. and Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97. doi:10.3354/esr00481

Regular, P., Montevecchi, W., Hedd, A., Robertson, G. and Wilhelm, S. (2013). Canadian fishery closures provide a large-scale test of the impact of gillnet bycatch on seabird populations. *Biology Letters*, 9(4): 20130088. doi:10.1098/rsbl.2013.0088

Rose, G. A. (2019). *Atlantic Cod: A Bio-Ecology*. John Wiley & Sons Ltd., Hoboken, NJ, U.S.A. ISBN: 9781119460633

Rouxel, Y. and Montevecchi, W. (2018). Gear sustainability assessment of the Newfoundland inshore northern cod fishery. *Ocean and Coastal Management*, 163, 285-295.

Rouxel, Y., Crawford, R., Cleasby, I. R., Kibel, P., Owen, E., Volke, V., Schnell, A. K. and Oppel, S. (2021). Buoys with looming eyes deter seaducks and could potentially reduce seabird bycatch in gillnets. *Royal Society Open Science*, 8: 210225. doi:10.1098/rsos.210225.

Shester, G. G. and Micheli, F. (2011). Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. *Biological Conservation*, 144(5), 1673-1681. doi:10.1016/j.biocon.2011.02.023

Sigurdsson G. M. (2023). Increase in bycatch rates of plunge- and surface-feeding seabirds observed while setting and hauling bottom set gillnets equipped with LED lights. *Marine Ecology Progress Series*, 720, 191-194. doi:10.3354/meps14408

Silk, V. (2006). *Sustainability in a Newfoundland Fishing Community Petty Harbour: Managing the Commons*. Digital Library of the Commons, Indiana University. Retrieved October 18, 2021, from https://dlc.dlib.indiana.edu/dlc/bitstream/handle/10535/2128/Silk_victoria.pdf?sequence=1&isAllowed=y

Slooten, E. (2013). Effectiveness of area-based management in reducing bycatch of the New Zealand dolphin. *Endangered Species Research*, 20(2), 121-130. doi:10.3354/esr00483

Staveley, T. A. B., Jacoby, D. M. P., Perry, D., van der Meijs, F., Lagenfelt, I., Cremle, M. and Gullström, M. (2019). Sea surface temperature dictates movement and habitat connectivity of Atlantic cod in a coastal fjord system. *Ecology and Evolution*, 9, 9076-9086. doi:10.1002/ece3.5453

Southworth, L. K., Ratcliffe, F. C., Bloor, I. S. M., Emmerson, J., Watson, D., Beard, D. and Kaiser, M. J. (2020). Artificial light improves escapement of fish from a trawl net. *Journal of the Marine Biological Association of the United Kingdom*, 100(2), 267-275. doi:10.1017/S0025315420000028

Tamdrari, H., Castonguay, M., Brêthes, J-C., Galbraith, P. S. and Duplisea, D. E. (2012). The dispersal pattern and behaviour of Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence: results from tagging experiments. *Canadian Journal of Fisheries and Aquatic Sciences*, 69, 112-121. doi:10.1139/F2011-137

Tasker, M. L., Camphuysen, C. J., Cooper, J., Garthe, S., Montevecchi, W. A. and Blaber, S. J. M. (2000). The impacts of fishing on marine birds. *ICES Journal of Marine Science*, (57), 531-547. doi:10.1006/jmsc.2000.00714

Utne-Palm, A. C., Breen, M., Løkkeborg, S. and Humborstad, O. B. (2018). Behavioural responses of krill and cod to artificial light in laboratory experiments. *PLoS ONE*, 13(1): e0190918. doi:10.1371/journal.pone.0190918

Valen, R., Edvardsen, R. B., Søviknes, A. M., Drivenes, Ø. and Helvik, J. V. (2014). Molecular evidence that only two opsin subfamilies, the blue light- (SWS2) and green light-sensitive (RH2), drive color vision in Atlantic cod (*Gadus morhua*). *PLoS ONE*, 9(12): e115436. doi:10.1371/journal.pone.0115436

Žydelis, R., Small, C. and French, G. (2013). The incidental catch of seabirds in gillnet fisheries: A global review. *Biological Conservation*, 162, 76-88. doi:10.1016/j.biocon.2013.04.002

Chapter 3: The Influence of Light Colour on the Behaviour of Atlantic Cod in an Experimental Setting

3.1 Abstract

The behaviour of animals is influenced by many environmental factors, including the ambient light environment. Fishes adapted to low-light conditions are sensitive to specific wavelengths of light based on the physiological capacity of their visual system. Technologies that target visual sensitivities can alter behaviours, with both exploitative and conservation implications. Atlantic cod (*Gadus morhua*) are an economically important species, commonly targeted by fisheries in the North Atlantic. Though fishing gears may employ light stimuli to improve catch, the visual ecology of target species are often overlooked in an effort to quickly apply enhancements directly to industry. The behaviour of adult Atlantic cod in reaction to the simultaneous presentation of various light stimuli has not been assessed in an isolated setting to determine if there is a preference for certain light qualities. To assess the influence that artificial light may have on the behaviour of Atlantic cod, I investigated the movement and space use of wild-caught cod in a laboratory setting. Green, blue, and white light were presented with a blank control in paired choice tests, and overhead videos were recorded to track the position of 25 cod in an arena. I predicted that green light would have the greatest influence on cod behaviour, and that I would observe a higher proportion of time spent in the zone illuminated with green light over other conditions. My findings show that cod behaved consistently across trials and across experimental sessions, and that the right side

of the arena was preferred. Colour of light had no influence on the time that cod spent on either side of the arena. These findings indicate that cod do not prefer to spend more time in proximity to certain colours of light in an artificial environment, which has direct implications for animal husbandry, fisheries research, and behavioural ecology.

3.2 Introduction

Atlantic cod (*Gadus morhua*) are a culturally and economically important species throughout the world and are currently listed by the International Union for Conservation of Nature and Natural Resources (IUCN) as Vulnerable as of 1996. Once a major fishery, the depletion of cod stocks in the northwest Atlantic Ocean led to the imposition of a moratorium for groundfish in Canada. Cod populations in the Newfoundland and Labrador Designatable Unit are considered Endangered by the Committee on the Status of Endangered Wildlife in Canada as of 2010 (COSEWIC 2010). All that remains is a small-scale inshore fishery, with gillnets and handlines as the ubiquitous gear types used.

Light may play an important role in the efficiency and effectiveness of fishing gears in small-scale fisheries like the Northwest Atlantic cod. Technologies can be used to intentionally manipulate the natural behaviours of animals. In fisheries, this often involves modifying or baiting fishing gears in ways that aim to attract (or repel, in some cases) specific taxa or species groups. Due to the natural role that vision plays in many harvested fishes, light modifications to gears are often used for such purposes. Bait and other lures are sensory stimuli that act to draw the target species toward or away from the gear and manipulate their behaviour to allow for their capture or avoidance. Though fishing gears often employ light stimuli in an attempt to improve catch, the visual ecology of the target species is sometimes overlooked in efforts to quickly apply enhancements directly to industry.

There have been varying results regarding the behaviour of Atlantic cod with respect to light. Some studies indicate that cod are attracted to light (Bryhn et al. 2014), while other studies have shown that light has no effect on the behaviour of cod (Grimaldo et al. 2017, Melli et al. 2018, Utne-Palm et al. 2018, Blackmore et al. 2022). To investigate the visual ecology of Atlantic cod and to inform the use of artificial lights as lures in fishing practices, the behaviour of Atlantic cod needs to be studied in response to various light stimuli in tandem.

Like all environmental constraints, an organism's light environment shapes its life history, physiology, and behaviour. The light environment at depth in the ocean is restricted to a range including only short-wavelength light, due to the absorption of light as it travels through the water column (Levine and MacNichol 1982). Adult Atlantic cod are well-adapted to their environment, living primarily in coastal and continental waters between tens to a few hundred metres depths (COSEWIC 2003), and have developed opsin pigments in their retina that allow maximum sensitivity and discrimination of wavelengths in the blue-green light range (Valen et al. 2014) associated with these coastal marine environments. Cones in the eyes of adult Atlantic Cod are maximally sensitive to 446 nm and 517 nm (Douglas and Djamgoz 1990, Figure 3.1), respectively. The broad absorption spectra of these photopigments and incorporation of rods for light detection allow cod to see in the low-light levels of the deep Atlantic Ocean. However, it is possible that colours of light that do not naturally occur within the range of natural light conditions could be perceived by cod, due to the broad absorption capabilities of their visual system and cause behavioural changes when presented via artificial stimuli.

3.3 Objectives and Hypotheses

The aim of this study is to examine the effect of three light conditions on the activity and movement of adult Atlantic cod in a controlled laboratory setting.

Atlantic Cod have spectral sensitivities adapted to pursue prey efficiently in blue-green limited light environments, and as such, can distinguish different light stimuli against a background that mimics natural light conditions. I predicted that green light emitted at 510 nm would be the light quality to best stimulate a phototactic response by Atlantic Cod, as the wavelength of light closest to the peak sensitivity of the cone in the retina of cod. As such, I predicted that cod would spend more time in proximity to the green light stimulus than to other colours of light.

3.4 Methods and Materials

Experiments were performed at the Joe Brown Aquatic Research Building (JBARB) of Memorial University of Newfoundland's Ocean Sciences Centre in Logy Bay, Newfoundland from August 26th to December 3rd, 2020. Thirty-four wild-caught Atlantic cod (acquired from Arnold's Cove, Newfoundland on November 28, 2019) were housed at low density in a 3 m diameter x 3 m tall surface-input flow-through aquarium (holding tank) beginning December 1, 2019, with regulated temperatures between 7-9 °C. Two individuals were removed and euthanized on December 12, 2019, due to exophthalmia. Following their removal, the remaining fish (n = 32) were treated with anti-parasite formalin (Parasite-S) treatments for three days, starting December 17, 2019, as a preventative measure against further disease or parasitic infection. This treatment was advised by the JBARB staff as a well-studied chemical treatment but can lower the dissolved oxygen levels in the aquarium. Its application was not thought to affect the behaviour of cod as long as the controlled oxygenation levels of the holding tank remained high (see Leal et al. 2016 for a summary of its use in aquaculture of other fishes). Following the treatments, the behaviour of cod was monitored by JBARB staff to ensure no abnormalities such as loss of appetite or decreased activity were observed. Before trials were able to begin, COVID-19 safety protocol for research on campus at Memorial University was established, restricting access to the JBARB and temporarily postponing this research project. Access to the building was not given to the research team until late August 2020. Experimental trials began October 1, 2020, by which time seven more cod had perished, leaving 25 apparently healthy individuals for experimentation.

A nearly identical aquarium next to the holding tank with the same water parameters was used as the experimental arena. The light environment was altered in both tanks using a lighting filter (Lagoon Blue #172, LEE Filters Canada ™) that absorbs light above 550 nm (Figure 3.2a) to mimic the natural light environment of Atlantic cod at depth (see McMahon and Holanov 1995, Harant and Michiels 2017). Photoperiod was automated to follow a natural day-light cycle. For 7 fish (~20 % of the sample population) I measured the fork-length to the nearest 0.1 cm using a metre stick (visible in Figure 3.3) and measured weight to the nearest gram using a Pesola spring scale (values in

Supplementary Material S.3). The Atlantic cod were fed a standard diet of a food mixture (40 % Atlantic mackerel, 40 % Atlantic herring, and 20 % squid) thrice weekly, rationed at 0.5 % of the average body weight per day (approximately 23 g per fish per week).

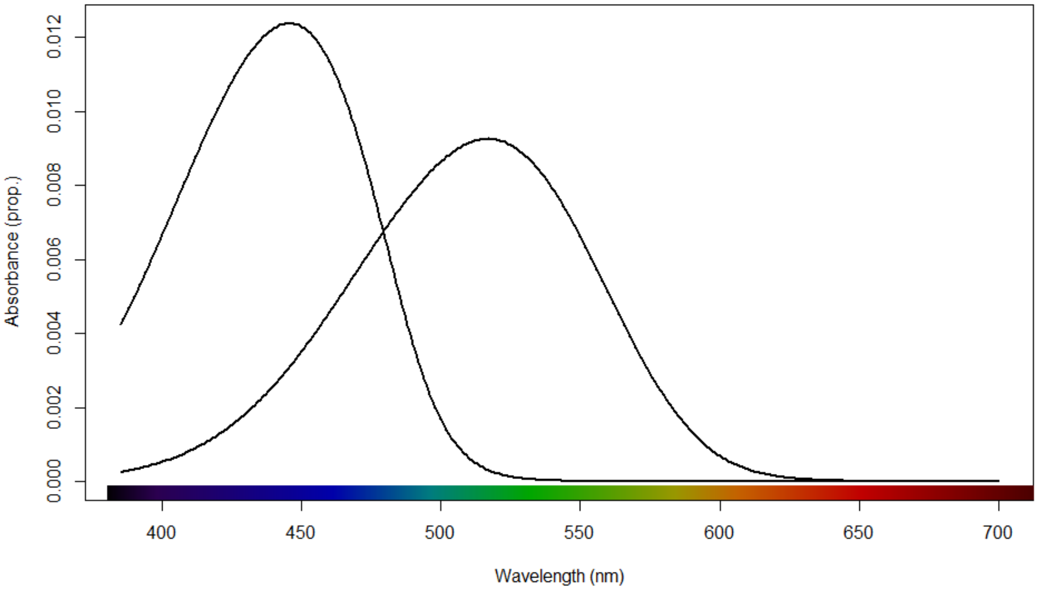
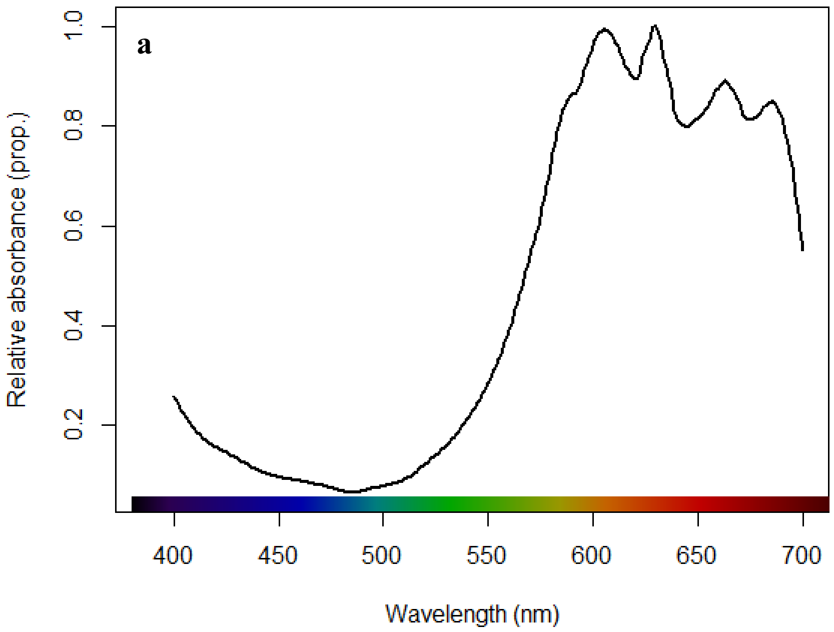
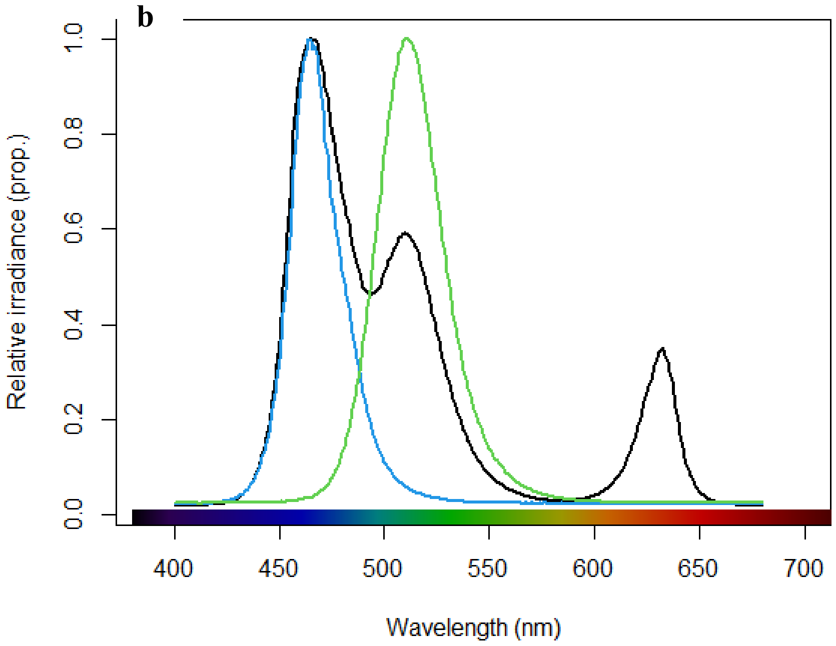


Figure 3.1. Spectral sensitivities of cones from *Gadus morhua* as measured by microspectrophotometry; λmax SWS = 446 nm, λmax RH2A = 517 nm (Douglas and Djamgoz 1990). These probability curves were produced using a vertebrate template (Govardovskii et al. 2000) and may not accurately reflect true cod vision capabilities, because the range in the short wavelength may be cut off by ocular media in the eye (e.g., lens).


a
Relative absorbance (prop.)
0.2
0.4
0.6
0.8
1.0
400
450
500
550
600
650
700
Wavelength (nm)


b
Relative irradiance (prop.)
0.0
0.2
0.4
0.6
0.8
1.0
400
450
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700
Wavelength (nm)

Figure 3.2. Spectrophotometric measurements of a) the relative intensity of light transmitted via LEE Filter #172 “Lagoon Blue” using a calibrated light source and b) the relative intensity of light output from UNPAD LED devices on the “White” (black line), “Green” (green line) and “Blue” (blue line) settings.

The behaviour of cod was assessed when presented with four conditions: green, blue, and white light, as well as a control with no light. Wireless waterproof multicolour LED devices (UNPAD, Figure 3.2b) were used, which have settings for blue, green, and white light emittance. The devices were measured using a spectrophotometer (Jaz® spectrophotometer, OceanInsight, Orlando, U.S.A.) fitted with a cosine-corrected optic fibre (CC-3-UV, Ocean Insight) in scope mode (shown in Figure S.2). The filter was measured using the same spectrophotometer in absorbance mode, using a bare optic fibre from the output (the internal light source), and a cosine corrector on the receiving fibre. The ends of each fibre were placed facing each other with a spacing of 1 cm, with the full light cone contained within the cosine corrector. The reference measurement was taken using the light only, the dark reference was measured while covering the cosine corrector completely, and the measurement of the filter was taken by applying it directly to the cosine corrector. Integration time was set during the reference measurement to automatic with dark noise correction.

The green LED was measured to emit light at a peak intensity of 510 nm (Figure 3.2b). The blue LED was measured to emit light at a peak intensity of 464 nm (Figure 3.2b). The white LED is produced by a combination of the blue and green light, in addition to a red light with a peak emission at 633 nm. The relative intensity of light emitted from each

LED used on the "white" setting was lower for those with longer wavelengths, in order to create equal perceived brightness across all three LEDs and mimic white light to a human eye, such that compared to the blue (465 nm) emittance, the green (509 nm) light was emitted at 59.12 % intensity and the red (633 nm) light was emitted at 34.77 % intensity (Figure 3.2b), optimized by the device itself.

3.4.1 Study Design and Procedure

Our chosen four light conditions were tested in pairwise combination, such that all six possible combinations of green, blue, white, and no light were presented. These six combinations were tested in random order and random sides of the tank, forming six 10-minute experimental trials. For clarity throughout, we refer to an experimental "session" as consisting of these six 10-minute trials, and a flow-chart diagram below (Figure 3.3) shows the order of operations. All Atlantic cod were subjected to two experimental sessions. For their first session, twenty-five cod were individually tested by haphazard selection, transferred from the holding tank to the arena using a dip-net and allowed to acclimatize to the arena for 5 minutes. All cod were tagged with a subdermal ID tag (Floy T-bar Anchor Fish Tag, Figure 3.4) near the first spine of the dorsal fin for individual recognition immediately prior to their first experimental session. Each trial was initiated by the lowering of LEDs into the tank, where LED devices were attached to weights and simultaneously lowered into the tank to allow the presentation of each light condition from opposite sides of the arena (Figure 3.4). Trials involving the control condition still began with the lowering of both LEDs, but the LED being used as the control was turned off. A colour CCD infrared camera (National Electronics Inc. DN-IR36) was placed above the centre of the experimental tank to record all trials. Once each fish finished their first experimental session, it was returned to the holding tank with the others. Once all 25 fish had completed one session, they were haphazardly selected for a second experimental session, in which the order and side that light conditions were presented were randomized to control for order effects. The first experimental sessions occurred in September and October 2020, and the second sessions occurred in November and December 2020. Cod were not fed on the days that testing took place to account for satiation as a factor affecting behaviour. All cod were euthanized by blunt-force trauma to the head following the completion of their second session.

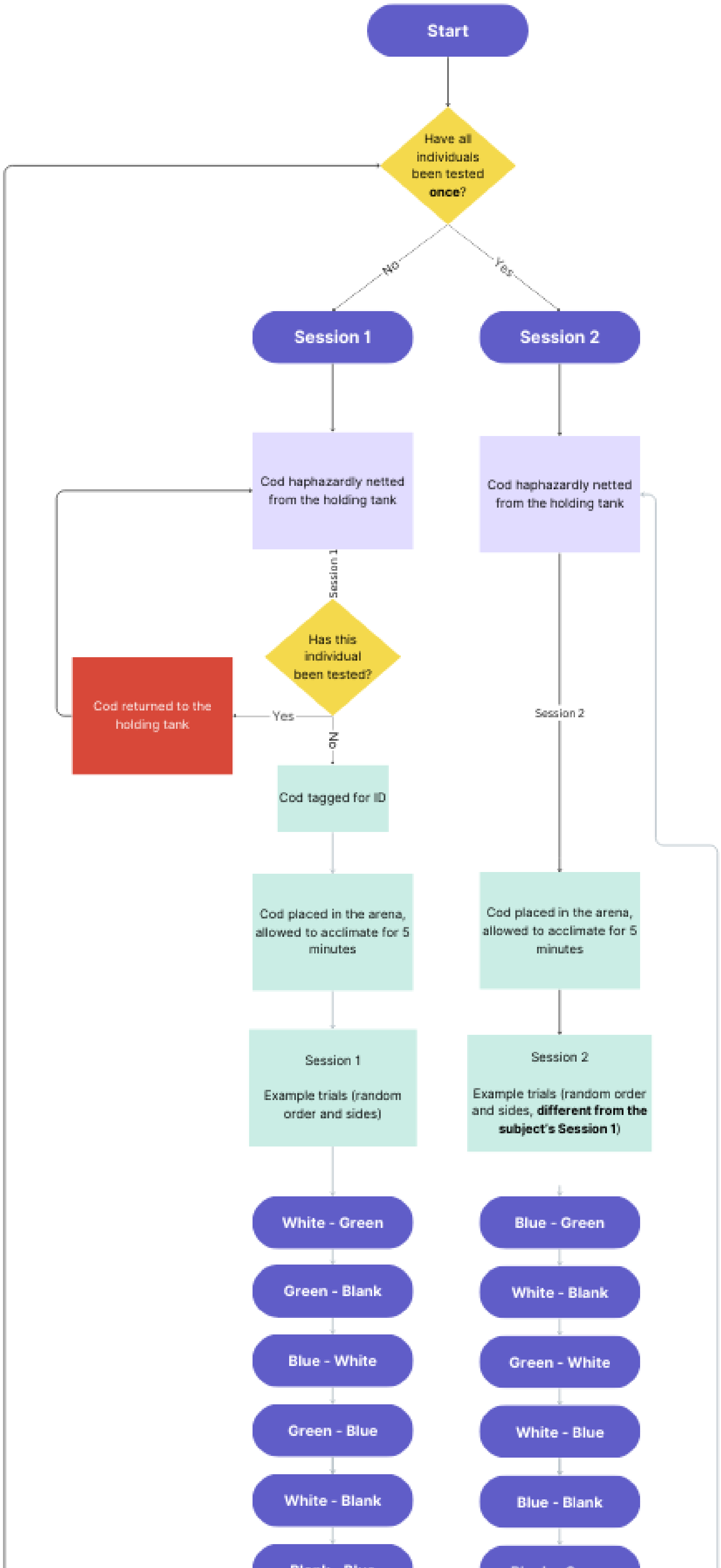
Start
Have all individuals been tested once?
No
Yes
Session 1
Session 2
Cod haphazardly netted from the holding tank
Cod haphazardly netted from the holding tank
Session 1
Has this individual been tested?
Yes
No
Cod returned to the holding tank
Session 2
Cod tagged for ID
Cod placed in the arena, allowed to acclimate for 5 minutes
Cod placed in the arena, allowed to acclimate for 5 minutes
Session 1
Example trials (random order and sides)
Session 2
Example trials (random order and sides, different from the subject's Session 1)
White - Green
Green - Blank
Blue - White
Green - Blue
White - Blank
Blue - Green
White - Blank
Green - White
White - Blue
Blue - Blank

Figure 3.3. Flow-chart showing the procedural order of events throughout which all 25 Atlantic cod were subjected to two experimental sessions.

Figure 3.4. Example of Floy T-bar Anchor Fish Tag used to identify Atlantic cod and its placement on an individual.

3.4.2 Analysis of videos

Behavioural data were extracted from videos of the trials by trained assistants who were blind to the treatments and to the research question. A custom-built program (found here: https://github.com/rfh473/fish) allowed assistants to extract positional data from videos.

Assistants were tasked with placing their cursor above the centre of mass of the fish and following the fish's movements for the duration of each trial. The user's cursor position was normalized to 0-1, where the origin was the upper left corner of the video frame. The relative position of the cursor to the bounds of the recording was therefore equivalent to the relative position of the fish to the bounds of the arena. For each frame of the video (1080 x 720p, 48 fps), the normalized x and y coordinates were written to a comma-separated-value (.csv) file for each test.

Positional data were categorized for proximity to the light sources presented on the right side of the tank (right zone) or the left (left zone, Figure 3.5a). These zones were created as equal tangent circles, where the positions of each light source were the origins and the radii were half the distance between the light sources. The proportion of total time that fish spent in the left and right zones was used as a measure of time spent in proximity to each light source.

Proportion of time values were calculated for each 10-minute trial, as well as for the first 60 seconds of each trial. The initial minute of behaviour was assessed separately from the entire trial to capture the immediate reactive behaviours of cod upon being presented with lights.

In cases where data were missing for one of the two sessions, or the behaviour of the fish changed such that it was determined to not meet the participation requirements for the experiment (i.e., an individual moved considerably during its first session, but floated at the top of the tank during the entire second session, which may have been caused by some sort of trauma), that session was considered to be an outlier and was excluded, with the remaining session chosen for analysis. While all fish were subjected to two experimental sessions, many had missing or excluded data. Such that all 25 cod could be assessed, including those with an excluded session, fish with two valid sessions (n = 7) had one session picked by random assortment, and that same session was then used for all subsequent modelling exercises.

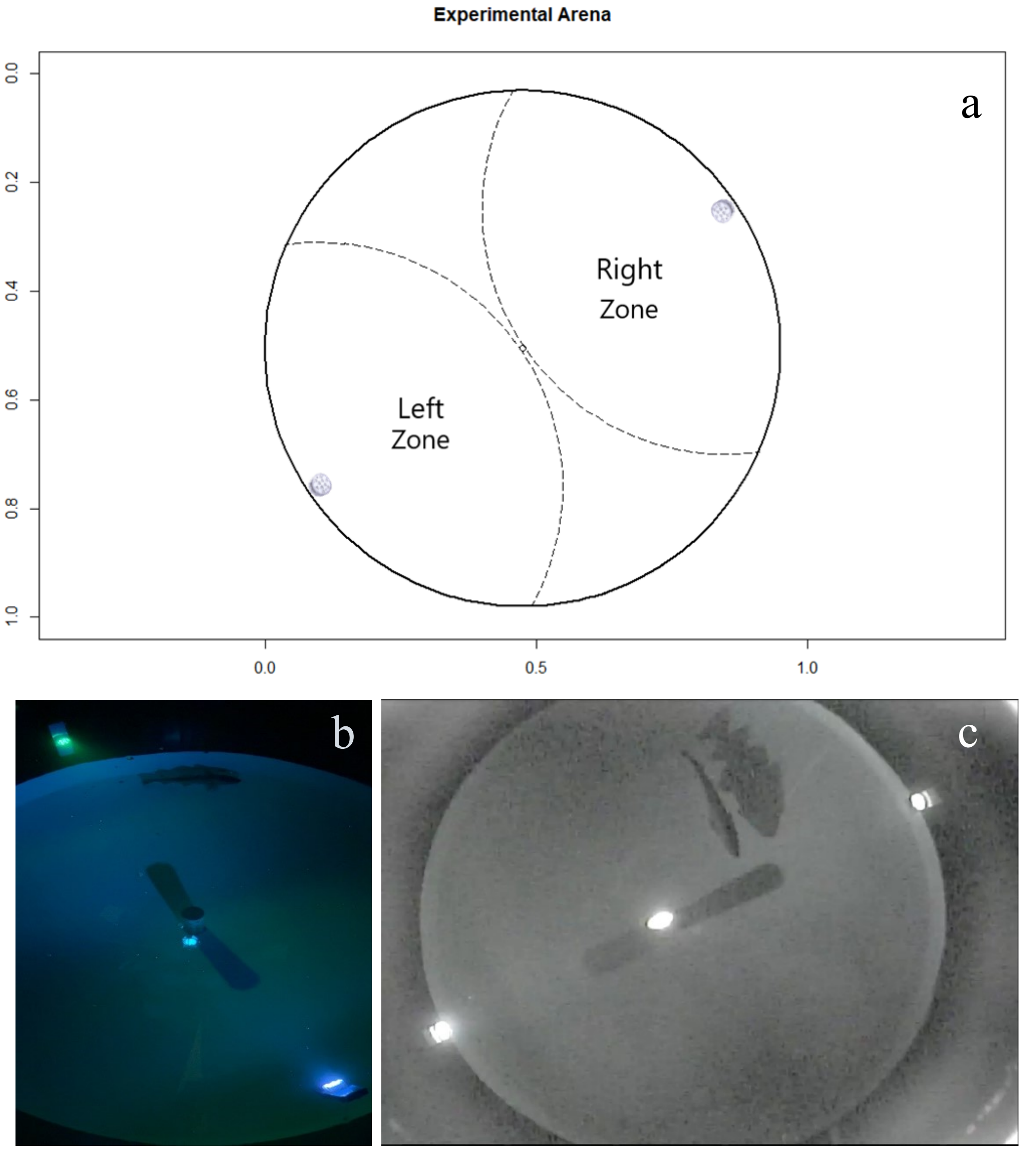

Figure 3.5. a) The design of the arena, showing the right and left zones associated with each light source. b) The view of the arena from the perspective of the researcher. c) The view of the arena from the overhead infrared camera.

3.4.3 Statistical Analysis

A measure of individual activity was calculated using the *spDists* function in R (sp v. 1.6-0 package, Pebesma and Bivand 2005) as the mean absolute deviation of total distance travelled throughout the arena during a single session by each fish. With the exception of those excluded from analyses due to a lack of movement, all fish spent the ten minutes of each trial moving in some capacity, so time spent moving could not be used as a way to correct other metrics, so we used distance moved as an approximation for activity. Every individual had a total distance travelled for their one session, and this value was subtracted from the grand mean of all individuals to get a mean absolute deviation for each subject. To assess behavioural repeatability during trials, the activity measure for each fish was analyzed using the *rpt* function in R (rptR v. 0.9.22 package, Stoffel, Nakagawa and Schielzeth 2017). The repeatability measure was calculated to determine if the behaviour of activity differed among fish (n = 25) and then differed for individual fish between sessions (n = 7). The sample size available for the between-session analysis was low, and did not involve all 25 cod, due to the aforementioned exclusions due to erroneous behaviour or faults in the video capture accounting for the loss or removal of one of the two sessions, leaving only seven individuals with two entirely valid sessions. Each of these analyses were generated with 1,000 bootstrap simulations to create 95 % confidence intervals around the estimated repeatability measures.

Two dependent measures were modelled; the proportion of time that fish spent in each zone during the first minute of each trial, and the proportion of time that fish spent in each zone during the 10-minute trial, to investigate differences in the initial response against a prolonged response to the light conditions. Twenty-five fish were included in both models, where fish identity was treated as a random factor, and the colour of light, side of the tank the light was presented on, and individual activity measure were treated as fixed factors.

Data were fitted to generalized linear mixed models using the glmmTMB package (v. 1.15, 2022, Brooks et al. 2017) in R (R Core Team 2022). Models were first fit using a Gaussian distribution of residuals and were assessed for fit using the *simulateResiduals* function of the DHARMa package (v. 0.4.6, Hartig 2022), which assesses homogeneity and fits the residuals to Q-Q plots to check normality. Both models were zero-inflated and otherwise normally distributed, bound at 0 and 1, so I built a model using a Tweedie distribution, as well as a hurdle modelling approach with a zero-inflation parameter paired with a student's t-distribution for the error structure. Akaike information criteria (AIC, Akaike 1974) were used to compare the two models through the *anova* function in the car package (Fox and Weisberg 2019). P-values associated with each explanatory variable in the model were assessed through the *anova* and determined to be significant if less than $\alpha = 0.05$. *Post hoc* investigations of a variable were performed if the p-value was less than $\alpha = 0.10$.

For boxplots produced using the *ggplot* function in ggplot2 package, default settings for the interquartile range and whiskers were used, such that the box represents the 25th, 50th (median), and 75th percentiles, whiskers represent 1.5 times the interquartile range, and dots represent outlying values outside of 1.5 times the range.

3.4.4 Ethics and Permits

Cod were held under General Broodstock Holding IAC Protocols DB 18-01. Experiments were performed with approval from Memorial University of Newfoundland Animal Care Committee under Animal Use Protocol 20-01-WM.

3.5 Results

3.5.1 Repeatability tests

The repeatability of activity, as measured by the total distance travelled by each individual, was calculated between trials within a session ($n = 25$ individuals, 6 replicates each), as well as between sessions ($n = 7$ individuals, 2 replicates each). Repeatability estimates showed that, within a single session, behaviour was highly repeatable ($R^2 = 0.794$, log-Likelihood = -601.1, $p >> 0.001$). Between sessions, behaviour was also repeatable but the sample size was too low for the p-value to be considered significant ($R^2 = 0.472$, log-Likelihood = -78.87, $p = 0.128$). Bootstrapping models corroborated the results of the repeatability estimates, with $\mu_{1000} = 0.783$ between trials and $\mu_{1000} = 0.436$ between sessions.

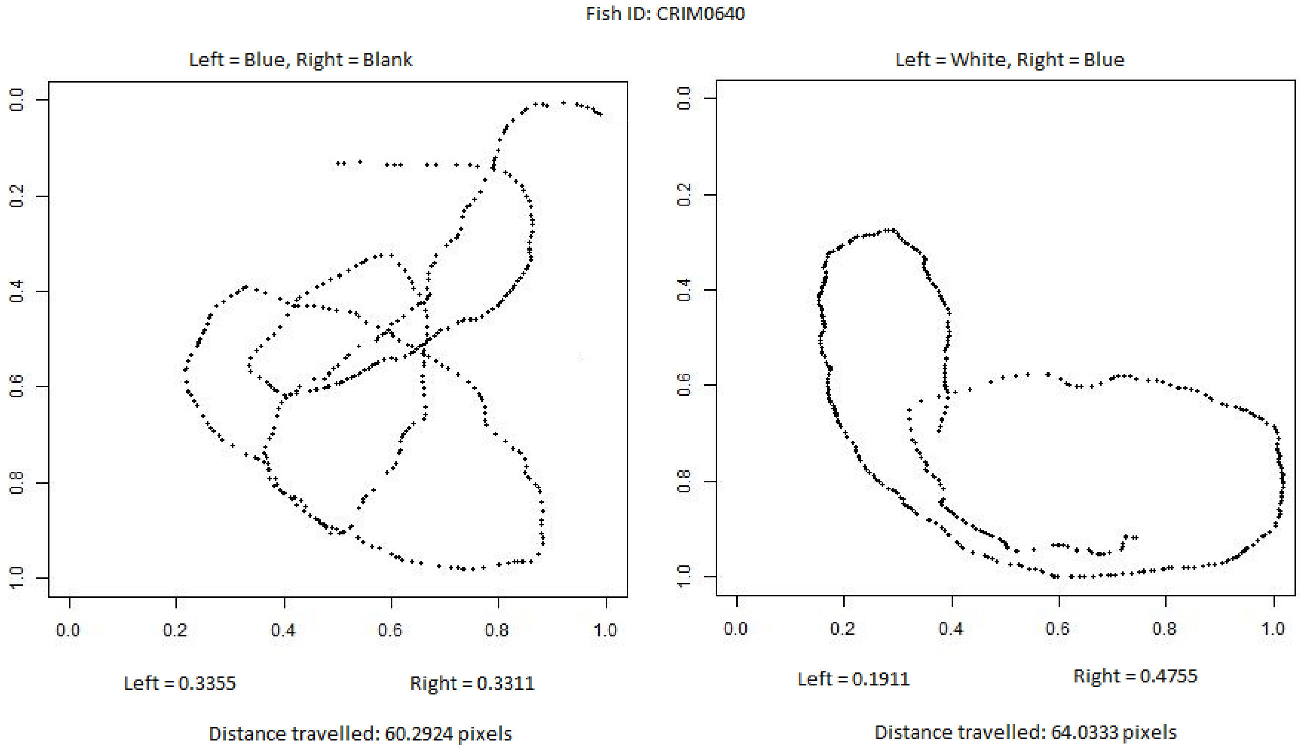

Figure 3.6. Two example movement paths of Atlantic cod "CRIM0640" around the arena during experimental trials within one session. X- and Y-axes represent the coordinates of the video frame from 0 to 1, points represent the centre of mass of the cod for each frame of video. The proportion of time spent in the left and right zone are labelled below each graph, as well as the distance measures for both trials.

3.5.2 The effect of light on space use

A model evaluation using AICs showed that the hurdle model factors for the colour of light presented, side of the tank, individual activity measure, and fish ID was the best fit for the first minute of trials. I found that the right zone was preferred overall ($\beta = 0.121 \pm$

0.012, df = 1, $p < 0.001$), but that the three light treatments were not preferred to the control condition (blue: $\beta = -0.002 \pm 0.018$, df = 3, $p = 0.931$, green: $\beta = -0.001 \pm 0.018$, df = 3, $p = 0.972$, white: $\beta = -0.005 \pm 0.017$, df = 3, $p = 0.791$). Activity was not a significant factor for 1-minute trials ($p = 0.745$, df = 1).

The model with the best fit for the 10-minute trials was also a hurdle model. The proportion of time that fish spent in proximity to green ($\beta = -0.003 \pm 0.019$, df = 3, $p = 0.889$), blue ($\beta = 0.005 \pm 0.019$, df = 3, $p = 0.710$), and white ($\beta = 0.0001 \pm 0.019$, df = 3, $p = 0.90$) light did not differ significantly from the control throughout all conditions. The proportion of time that a fish spent near a given light condition was not-significantly influenced by their activity ($p = 0.079$, df = 1), but fish spent significantly more time in the right zone, regardless of the light condition that was presented ($\beta = 0.122 \pm 0.0127$, df = 3, $p < 0.001$).

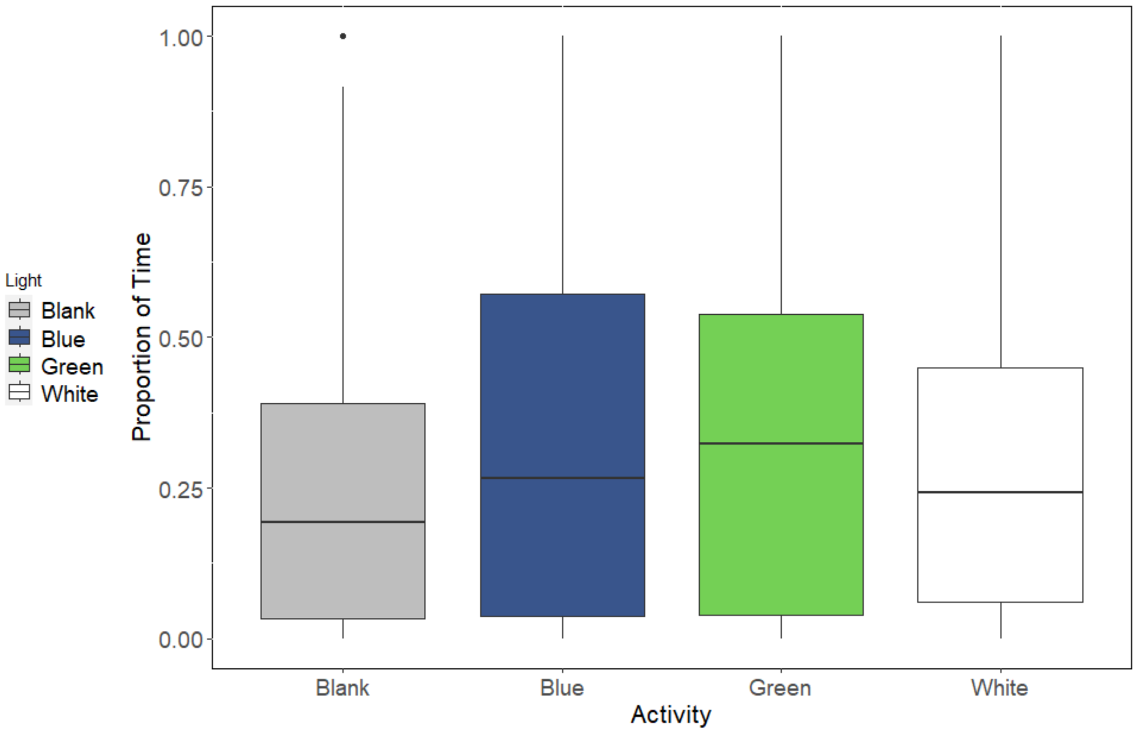

Figure 3.7. The influence of light condition on the proportion of time that Atlantic cod spent in proximity to that condition.

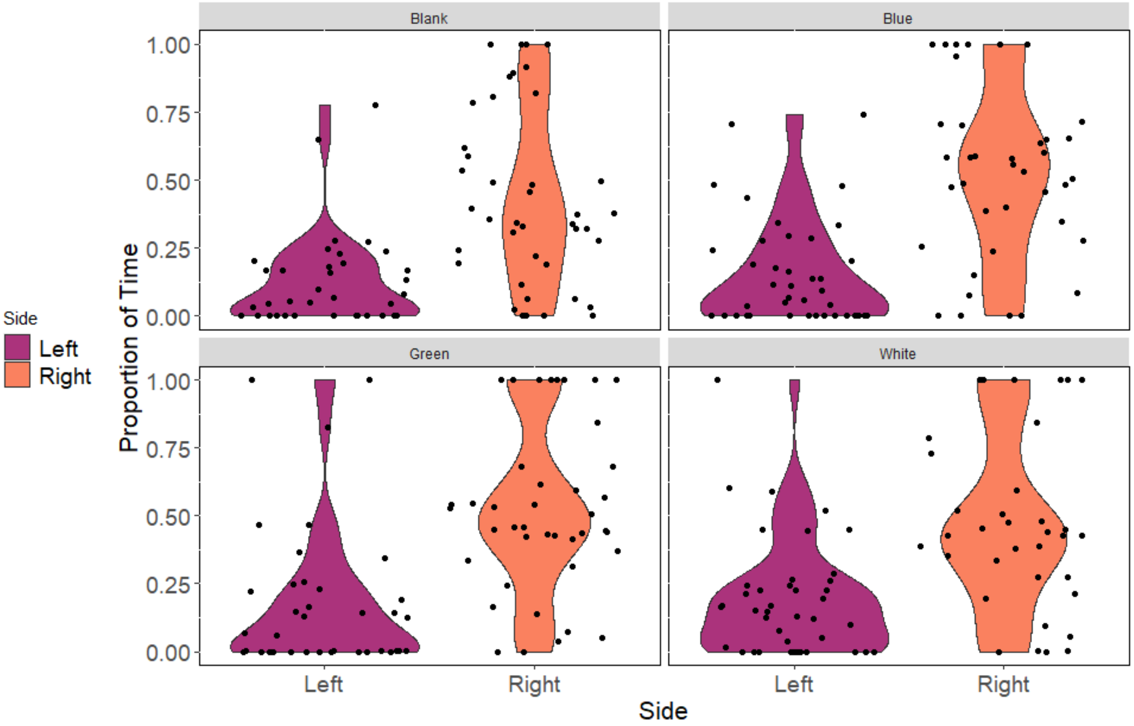

Figure 3.8. Proportion of time that Atlantic cod spent in either the right or left zone, split by light condition present on that side of the arena. The data show consistent biases by cod toward the right side of the arena, regardless of light condition.

3.6 Discussion

Though within the visual sensitivity range for this species, this study found no evidence that the presentation of blue (465 nm), green (510 nm) or broad-spectrum white LEDs influence the movement behaviour of Atlantic cod. No significant differences were observed during the first minute of each trial, nor throughout the entire 10-minute duration of trials, and the colour of light presented did not affect the time that Atlantic cod spent in proximity to the stimuli. Light is used in many contexts in fisheries worldwide but is primarily and historically used as an attractive feature of fishing gear meant to lure target fishes into capture (Nguyen and Winger 2018). Some examples of lights being used in fisheries targeting Atlantic cod have shown that they are attracted to light (Bryhn et al. 2014), while other studies have shown that lights do not affect cod behaviour (Grimaldo et al. 2017, Melli et al. 2018, Blackmore et al. 2022). Light can also be used in artificial settings, to modify the physiology (e.g., Taranger et al. 2006), as well as the behaviour or distribution (Pavlov et al. 2005, Stien et al. 2014, Hansen et al. 2018, Xu et al. 2022) of fish in aquaria, which can have direct husbandry implications. In a similar study, Utne-Palm et al. (2018) found no evidence that wild-caught cod were attracted to light between 448-560 nm in an artificial setting. The findings presented here expand on the results of Utne-Palm et al. (2018) by providing further information on the effect that light has on the movement behaviour of Atlantic cod in a laboratory setting. However, the potential range of spectral sensitivity in Atlantic cod ranges from <400 to >650 nm, so other qualities of light could influence the behaviour and movements of cod. Our study could not replicate the true depth at which cod would naturally forage and was restricted to a 3 m aquarium. As such, there may not have been sufficient differentiation in the perception of light stimuli across such a short distance when presented in pairwise combination. Within these restrictions, however, the implications of the results are still relevant to fishing efforts, husbandry, and the basic visual ecology of Atlantic cod, as their tendency to approximate to one colour of light over another would have applications across these fields at that distance. Our study aimed to understand the component of behaviour associated with phototaxis, therefore, cod were not fed on days that experimentation took place, and we did not present food alongside the lighting conditions, so as not to introduce satiation levels and food-association as factors into the experimental design.

In these experiments, the right side of the tank was preferred ($p < 0.001$) and the time spent on either side of the tank was unequal. This could be due to the position of extraneous components of the tank setup. The tanks used as the holding tank and experimental arena were identical, with a seawater input flow from the left side at the water's surface and a drain in the centre of the tank floor (Figure 3.5). The movement of surface water from this inflow could have caused an avoidance of this area, meaning that fish spent more time in the right side of the tank. Temperature gradients can be stronger stimuli for inducing behavioural changes in fish than lighting (Pavlov et al. 2005, Stien et al. 2018), therefore although likely minimal, it is possible that minor differences in water temperature near the inflow compared to the right side of the tank may have affected the potential distribution effects of light stimuli in this study. Ideally, the water input would have been positioned in the centre of the camera's point-of-view, such that any disturbance that it caused would be evenly distributed across the two "zones" of the tank. Similarly, the soundscape throughout the laboratory was not controlled for in our experiment, lending variation in noise from areas of the space that may have altered behaviour in our focal individuals. Cod are able to hear sounds in their environment and use noise to forage (Hawkings and Picciulin 2019, Hawkins and Popper 2020), as well as to communicate with conspecifics during courtship and spawning behaviour (Rowe and Hutchings 2006, Hawkings and Picciulin 2019), and anthropogenic noise is known to elicit a startle response in larval Atlantic cod (Nedelec et al. 2015), therefore their sensitivity to background anthropogenic noise should have been considered for its contribution to differences in observed behaviour throughout this experiment.

The activity of fish, modelled as mean absolute deviation of distance travelled, also significantly affected the time that fish spent in the left or right zones. However, since the distance measure was calculated using the distance travelled by a fish throughout the entire 60-minute session, this differs from the fish's behaviour within the first minute of each trial.

The repeatability of behaviour of Atlantic cod in a laboratory setting has been studied greatly (Meager, Fernö, and Skjæraasen 2018), in both juveniles (Beukeboom et al. 2022) and adults (Zimmermann, Purchase, and Fleming2012, Reynisson and Ólafsdóttir 2018, Villegas-Ríos et al. 2018) as measures of animal personality. Prior studies have found consistent individual differences in behavioural traits of Atlantic cod for both boldness and exploration (Zimmermann, Purchase, and Fleming 2012, Reynisson and Ólafsdóttir 2018, Villegas-Ríos et al. 2018, Beukeboom et al. 2022). Within-individual repeatable behavioural differences in animals affect spatio-temporal dynamics (Spiegel et al. 2016), and thus management and conservation strategies for the species (Collins et al. 2022). With Atlantic cod there are direct implications of movement behaviours for interactions with fishing gears (Olsen et al. 2012, Bøe 2013) and space use, i.e., distribution and migration (Thorsteinsson et al. 2012, Reynisson and Ólafsdóttir 2018, Villegas-Ríos et al. 2018, Beukeboom et al. 2022). The findings of this study show variation among individuals, and that individual cod behaved consistently across trials ($R^2 = 0.794$), as well as across the two experimental sessions ($R^2 = 0.472$), showing aspects of animal personality. The repeatability of movement behaviour within individuals in this study validates the experimental design and is compatible with the study by Villegas-Ríos et al. (2018). Consistent individual behaviours have implications for the outcomes of the study, in that light preference may have been influenced by an individual's tendency to roam. Highly active individuals, particularly if they had been considered to be exploring the arena as a novel environment, may not have spent more time in one zone near a certain colour of light over another and spent the entirety of the trials moving throughout the arena. The reverse is also true, in that inactive individuals may have preferred one light quality over another, but this preference was masked by their inactivity. Due to the high repeatability of behaviour across trials and across sessions within individuals, light had no effect on the measure of activity, and that activity was consistent across all combinations of light colours presented. If this experimental arena is considered a novel environment, it would be of interest to perform a similar test for proximity to light in a familiar environment or *in situ* within the natural home range of a wild population (e.g. Thorsteinsson et al. 2012).

The design of these experiments was created without insight into whether wild-caught cod from the Northwest Atlantic would behave consistently across trials nor what degree of activity differences would be observed between individuals. Therefore, the behavioural tests were designed in such a way that reproducible preferences in light conditions could be captured given any possible consistent among-individual variation in movement behaviours. The experimental tank is not unique enough from the holding tank in which the sample population is housed to constitute a novel environment, therefore the measured trait is solely referred to as “activity”, since “exploration” requires a novel environment (Reale et al. 2007). Though these two traits are often referred to in conjunction with one another as a behavioural syndrome, movement behaviours differ in Atlantic cod when in a known vs. unknown environment (Beukeboom et al. 2022). The experimental design also included randomizing the sampling of subjects, randomizing the order and side of the presentation of light variables, and testing all individuals in two sessions at different times. This approach allows for variation in behavioral attributes (heterogeneity) in the sample population while being tested in a single laboratory setting and still accounts for the influence of time and experience of the individuals tested (von Kortzfleisch et al. 2020).

No covariates were assessed to explain the repeatability measurements but given that all individuals were caught simultaneously and housed in the holding tank for nearly a year prior to experimentation, randomization justifies the covariation. Cod show individual differences in behaviour linked to sex (Hutchings, Bishop and McGregor-Shaw 1999) and by association, size (Villegas-Rios et al. 2018), which can influence personality traits including movement behaviours linked to activity and exploration (Chapman, Hegg, and Ljungberg 2013). Cod were tested alone, in an experiment where sex and other physiological characteristics were not considered, so I acknowledge this as a potential oversight and encourage its investigation in future research. The length of time that cod were kept in housing may also have affected their behaviour, as they had nearly a year to acclimate and adjust to their holding tank. However, since all fish were kept for the same length of time, and the parameters (temperature, lighting, feeding regime, etc.) remained consistent both during their time spent in the holding tank and while being tested, I do not see this as an issue with regards to the experimental design.

3.9 Concluding Remarks

I hypothesized that Atlantic cod would show distinct behavioural differences when presented with different light qualities in an artificial setting and predicted that cod would spend more time in proximity to green light over other colours. Instead, these results are consistent with similar studies, indicating that cod do not modify their behaviour or show a preference when presented with various qualities of light. This result has direct application to the Newfoundland and Labrador inshore stewardship ground-fishery and elsewhere, in that overall, light has very little effect on the movement and foraging behaviours of Atlantic cod, so modifying the light environment near fishing gears through gear modifications or attachments may not be an effective strategy of exploiting their behaviour.

3.10 References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, 19, 716-723. doi:10.1109/TAC.1974.1100705

Beukeboom, R., Morel, A., Phillips, J. S., Ólafsdóttir, G. Á., and Benhaïm, D. (2022). Activity vs exploration: Locomotion in a known and unknown environment differs in Atlantic cod juveniles (*Gadus morhua*). *Behavioural Processes*, 202: 104736. doi:10.1016/j.beproc.2022.104736

Bøe, K. (2013). You are what you get caught with: Inter-Individual variation in Coastal Atlantic Cod (*Gadus morhua*) Behavior. Master thesis. Norwegian University of Life Sciences.

Brooks, M. E., Kristensen, K., Van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Machler, M. and Bolker, B. M. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R journal*, 9(2), 378-400. doi:10.3929/ethz-b-000240890

Bryhn, A. C., Konigson, S. J., Lunneryd, S. G. and Bergenius, M. A. J. (2014). Green lamps as visual stimuli affect the catch efficiency of floating cod (*Gadus morhua*) pots in the Baltic Sea. *Fisheries Research*, 157, 187-192. doi:10.1016/j.fishres.2014.04.012

Chapman, B. B., Hegg, A., and Ljungberg, P. (2013). Sex and the syndrome: individual and population consistency in behaviour in rock pool prawn *Palaemon elegans*. *PLoS One*, 8(3): e59437. http://doi.org/10.1371/journal.pone.0059437

Collins, S. M., Hendrix, J. G., Webber, Q. M. R., Boyle, S. P., Kingdon, K. A., Blackmore, R. J., d'Entremont, K. J. N., Hogg, J., Ibáñez, J. P., Kennah, J. L., Lamarre, J., Mejías, M., Newediuk, L., Richards, C., Schwedak, K., Wijekulathilake, C., and Turner, J. W. (2023). Bibliometric investigation of the integration of animal personality in conservation contexts. *Conservation Biology*, 37(2): 14021. doi:10.1111/cobi.14021

Douglas, R. and Djamgoz, M. (1990). *The Visual System of Fish.* Springer, Dordrecht. doi:10.1007/978-94-009-0411-8_4

Fox, J. and Weisberg, S. (2019). *An R Companion to Applied Regression*. Third Edition, Sage.

Grimaldo, E., Sistiaga, M., Herrmann, B., Larsen, R. B., Brinkhof, J., and Tatone, I. (2018). Improving release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery by stimulating escape behaviour. *Canadian Journal of Fisheries and Aquatic Sciences*, 75(3), 402-416. doi:10.1139/cjfas-2017-0002

Hawkins, A. D., and Picciulin, M. (2019) The importance of underwater sounds to gadoid fishes. *The Journal of the Acoustical Society of America*, 146(5), 3536–3551. doi:10.1121/1.5134683

Hawkins, A. D., and Popper, A. N. (2020) Sound detection by Atlantic cod: An overview. *The Journal of the Acoustical Society of America*, 148(5), 3027–3041. doi:10.1121/10.0002363

Harant, U. K., and Michiels, N. K. (2017). Fish with red fluorescent eyes forage more efficiently under dim, blue-green light conditions. *BMC Ecology*, 17(1), 18. doi:10.1186/s12898-017-0127-y

Hartig, F. (2022). DHARMa: Residual diagnostics for hierarchical (Multi-level/Mixed) regression models. R package version 0.4.6. URL: http://florianhartig.github.io/DHARMa/

Hutchings, J. A., Bishop, T., and McGregor-Shaw, C. (1999). Spawning behaviour of Atlantic cod, *Gadus morhua*: Evidence of mate competition and mate choice in a broadcast spawner. *Canadian Journal of Fisheries and Aquatic Sciences*, 56, 97-104. doi:10.1139/cjfas-56-1-97

Kulka, D., Hood C., and Huntington, J. (2007). Recovery Strategy for Northern Wolffish (*Anarhichas denticulatus*) and Spotted Wolffish (*Anarhichas minor*), and Management Plan for Atlantic Wolffish (*Anarhichas lupus*) in Canada [Proposed]. Fisheries and Oceans Canada: Newfoundland and Labrador Region. St. John's, NL. x + 103 pp.

Leal, J. F., Neves, M. G. P. M. S., Santos, E. B. H., and Esteves, V. I. (2016). Use of formalin in intensive aquaculture: properties, application and effects on fish and water quality. *Reviews in Aquaculture*, 10(2), 281–295. doi:10.1111/raq.12160

McMahon, T. E. and Holanov, S. H. (1995). Foraging success of largemouth bass at different light intensities: implications for time and depth of feeding. *Journal of Fish Biology*, 46(5), 759-767. doi:10.1111/j.1095-8649.1995.tb01599.x

Meager, J. J., Fernö, A., and Skjæraasen, J. E. (2018) The behavioural diversity of Atlantic cod: insights into variability within and between individuals. *Reviews in Fish Biology and Fisheries*, 28, 153–176. doi:10.1007/s11160-017-9505-y

Melli, V., Krag, L. A., Herrmann, B., and Karlsen, J. D. (2018). Investigating fish behavioural responses to LED lights in trawls and potential applications for bycatch reduction in the *Nephrops*-directed fishery. *ICES Journal of Marine Science*, 75(5), 1682-1692. doi:10.1093/icesjms/fsy048

Nedelec, S. L., Simpson, S. D., Morley, E. L., Nedelec, B., and Radford, A. N. (2015) Impacts of regular and random noise on the behaviour, growth and development of larval Atlantic cod (*Gadus morhua*). *Proceedings of the Royal Society B*, 282: 20151943. doi:10.1098/rspb.2015.1943

Nguyen, K. and Winger, P. (2018). Artificial light in commercial industrialized fishing applications: A review. *Reviews in Fisheries Science & Aquaculture*, 27(1), 106-126. doi:10.1080/23308249.2018.1496065

Olsen, E. M., Heupel, M. R., Simpfendorfer, C. A., and Moland, E. (2012). Harvest selection on Atlantic cod behavioral traits: Implications for spatial management. *Ecology & Evolution*, 2(7), 1549-1562. doi:10.1002/ece3.244

Pebesma, E. and Bivand, R. (2005). Classes and methods for spatial data in R. *R News*, 5(2), 9-13. https://CRAN.R-project.org/doc/Rnews/

Post, S., Merkel, F., Bak-Jensen, Z., Koch, C., and Hedeholm, R. B. (2023). Bycatch mitigation in the West Greenland lumpfish (*Cyclopterus lumpus*) fishery using modified gillnets. *Royal Society Open Science*, 10, 221536. doi:10.1098/rsos.221536

R Development Core Team. (2022). R: A language and environment for statistical computing. Vienna, Austria. ISBN 3-900051-07-0. URL http://www.R-project.org.

Réale, D., Reader, S. M., Sol, D., McDougall, P. T., and Dingemanse, N. J. (2007). Integrating animal temperament within ecology and evolution. *Biological Reviews Cambridge Philosophical Society*, 82(2), 291-318. doi:10.1111/j.1469-185X.2007.00010.x

Reynisson, H., and Ólafsdóttir, G. Á. (2018). Plasticity in activity and latency to explore differs between juvenile Atlantic cod *Gadus morhua* across a temperature gradient. *Journal of Fish Biology*, 92(1), 274-280. doi:10.1111/jfb.13520

Rowe, S., and Hutchings, J. A. (2006). Sound production by Atlantic cod during spawning. Transactions of the American Fisheries Society, 135(2), 529-538. doi:10.1577/T04-061.1, ISSN:0002-8487.

Spiegel, O., Leu, S. T., Bull, C. M. and Sih, A. (2017). What's your move? Movement as a link between personality and spatial dynamics in animal populations. *Ecology Letters*, 20, 3-18. doi:10.1111/ele.12708

Stoffel, M. A., Nakagawa, S., and Schielzeth, H. (2017). rptR: Repeatability estimation and variance decomposition by generalized linear mixed-effects models. *Methods in Ecology and Evolution*, 8, 1639-1644. doi:10.1111/2041-210X.12797

Thorsteinsson, V., Pálsson, Ó. K., Tómasson, G. G., Jónsdóttir, I. G., and Pampoulie, C. (2012). Consistency in the behaviour types of the Atlantic cod: Repeatability, timing of migration and geo-location. *Marine Ecology Progress Series*, 462, 251-260. doi:10.3354/meps09852

Utne-Palm, A. C., Breen, M., Løkkeborg, S. and Humborstad, O. B. (2018). Behavioural responses of krill and cod to artificial light in laboratory experiments. *PLoS ONE*, 13(1): e0190918. doi:10.1371/journal.pone.0190918

Villegas-Ríos, D., Réale, D., Freitas, C., Moland, E., and Olsen, E. M. (2018). Personalities influence spatial responses to environmental fluctuations in wild fish. *Journal of Animal Ecology*, 87(5), 1309-1319. doi:10.1111/1365-2656.12872

von Kortzfleisch, V. T., Karp, N. A., Palme, R., Kaiser, S., Sachser, N., and Richter, S. H. (2020). Improving reproducibility in animal research by splitting the study population into several 'mini-experiments'. *Scientific Reports*, 10: 16579. doi:10.1038/s41598-020-73503-4

Zimmermann, E. W., Purchase, C. F., and Fleming, I. F. (2012). Reducing the incidence of net cage biting and the expression of escape-related behaviors in Atlantic cod (*Gadus morhua*) with feeding and cage enrichment. *Applied Animal Behaviour Science*, 141(1-2), 71-78. doi:10.1016/j.applanim.2012.07.009

Chapter 4: General Discussion and Conclusions

4.1 Implications for the Inshore Stewardship Groundfishery of Newfoundland and Labrador

The groundfishery in Newfoundland and Labrador has been federally managed since 2006 as a stewardship fishery, limited to the inshore harvest of groundfish like Atlantic cod using certain allowed gear types (DFO 2021). With the goal of increased sustainability and quality of catch, some fishers have opted to only use handlines as their preferred catch method, while most use more efficient gears such as gillnets. Knowing that handlined fish are usually of good quality, being caught alive with minimal injury, these catches are viewed as marketable and profitable, since the product can be graded at a higher price and advertised as harvested using a sustainable gear-type. Of those who use passive gears like gillnets, many fishers handline between the setting and hauling of the nets to increase their daily catch and quickly meet weekly quotas. Modifications to handlines that could affect the catch size, catch rate, or bycatch of the gear could have direct and important consequences for the strategies that fishers opt to employ. The results of the tests performed with the Petty Harbour fishing crews showed that, although there has been disagreement in the literature with regards to the effectiveness of the use of green lights in cod fishing gear (Utne-Palm et al. 2018, Humborstad et al. 2018, Bryhn et al. 2014, Blackmore 2019), there appears to be no effect for handlines. Catch rates and catch size measurements on handlines with LED attachments were not different from efforts without. This information allows fishers to decide whether or not to invest in visually-oriented gear modifications which are promoted to increase catch rates, and provides valuable insight into how these LEDs affect the catchability of benthic fishes. The bycatch of Atlantic wolffish in Mobile Bay throughout the study period was lower when lights were used compared to without, and although these results are simply descriptive and hold no statistical power, there are implied consequences both for the safe practice of the fishers in Newfoundland, as well as for the benefit of this threatened species.

4.2 The Role of Behavioural Studies in Policy and Industry Decision-making

The cognitive processes of animals dictate their behaviours and how they interact with the natural environment to coexist in various habitats. The study of animal cognition is a part of the context for how ecosystems cope with human-driven rapid environmental change. As much as holistic studies of abiotic factors of a landscape determine the outcome of how and why environmental change occurs, so too do the movements, interactions, and behaviours of animals that occupy the physical environment. Therefore, insight into animal behaviours can be used to shape how humans decide to develop and strategize plans for areas on large and small scales. Governments and international organizations consider all aspects of the environment when forming and amending major policy decisions, and studies that consider the distribution and expected movements of animals with respect to extraneous factors, namely anthropogenic change, can have large impacts on the timing, scope, and details needed for such policies (Lennox et al. 2019). International collaboration is crucial to conservation efforts when animals move beyond legislative borders. Behavioural studies can inform conservation practices, including how certain species or species groups and even specific behaviorally oriented individuals (i.e., those showing aspects of animal personality) might behave in situations altered through human influence (Sutherland 1998, Sih 2013, Villegas-Ríos et al. 2018, Lennox et al. 2019, Collins et al 2022). The areas of research in conservation that can gain the most from insight into consistent individual behaviours in animals are those with direct applications (Collins et al. 2022).

Studies on the behaviour of Atlantic cod are inherently adaptable and applicable to fisheries and related industries across the Atlantic Ocean. Cod are a culturally and economically important fish harvested primarily as a food product, but also for use in the pharmaceutical, nutritional, medicinal, cosmetic, (Gudmundsdóttir and Pálsdóttir 2005), and even pet-food industries (Malaweera and Wijesundara 2014), among others. Behavioural studies of cod can inform large-scale bioinformatics with practical input to policy, such as migration movements across oceans and international borders (Lennox et al. 2019, Hüssy et al. 2022). Studies of cod fishing practices *in situ* can have consequences for finer-scale management of the species and related stocks. The behaviour of Atlantic cod in restricted environments like in sea pens or aquaria has direct application to farming and husbandry practices, as cod are a quickly emerging species of interest in aquaculture (Nardi et al. 2021). My studies regarding the behaviour of cod when presented with LEDs in artificial and natural contexts each have applications not only to the stewardship fishery of Newfoundland and Labrador, but beyond. I found that cod behaviours and movements did not change in response to the colours of light that were presented. I also found that cod catch on handline gear did not change when using green LED lures. These results in combination suggest that, although within the range of light available in their natural environment (Levine and MacNichol 1982) and within the range of visible light for the sensitivity of the eye (Douglas and Djamgoz 1990), short-wavelength light does not induce phototactic or interactive behaviours for Atlantic cod. Other studies that have investigated the use of lights in passive gear types such as nets and pots have found that catch increased (Bryhn et al. 2014, Humborstad et al. 2018, Kim, Kim, and Kim 2022), but this seems to be due in part to a positive phototactic response of krill and other prey items, driving a predatory response (Humborstad et al. 2018). In my study, cod catch was not quicker or of higher quality on lines illuminated by green light, and cod did not spend more time in proximity to green light over other light stimuli. For fisheries that target Atlantic cod worldwide, these results suggest that active gears like handlines that attempt to exploit the behaviour of cod and attract cod directly to the fishing gear may not be improved with LED devices. Interestingly, similar LED devices seem to work well at influencing the catch of other species (Ngyuen and Winger 2018) but my results indicate that they do not facilitate the same behaviour in Atlantic cod. The results of my laboratory study also have implications directly related to the aquaculture industry, in addition to the wider body of literature on the effects of lighting in rearing cod in aquaria (van der Meeren and Ivannikov 2006, Penney et al. 2006, van der Meeren, Mangor-Jensena, and Pickova 2007, Árnadóttir 2008, Monk, Puvanendran, and Brown 2008). The retinal physiology of juvenile cod differs from that of adults (Valen et al. 2014), meaning that studies that investigate the use of lighting for the growth and development of juveniles (e.g. van der Meeren, Mangor-Jensena, and Pickova 2007, Árnadóttir 2008, Monk, Puvanendran, and Brown 2008) may not necessarily be related to the use of lighting in a holding and husbandry context. My results show that activity and movement of cod within the experimental arena were not significantly affected by the lighting conditions suggesting that light is not a useful tool in manipulating the position or behaviour of cod in this context. As such, decisions and strategies for managing wild and captive Atlantic cod can pull from these results for fine-scale examples of which methods to employ for adjusting the catchability of gears. Industry members can look to the results of this study for how to develop lures for Atlantic cod and approach the concept of visual ecology in practical applications with an understanding that one-size-fits-all ideas for lures or gear modifications should be avoided. Fishers can apply these results: when considering the use or purchase of certain products on the market aimed to enhance catch parameters; to gather a better understanding on the behaviour of their target species; and for information on how to best use gears and gear modifications in their fishing settings.

4.3 Considerations for Future Fisheries Research

There is much that can be posited from this research and adapted to future avenues of exploration. How to improve sustainability in fisheries is one of the root goals of this thesis and should continue to be investigated on all scales. Further research into how to improve the catch efficacy of handlines is imperative for improving the sustainability of inshore fisheries that primarily use other more damaging gear types and could be easily transitioned to more sustainable practices. My study showed that handline gears could not be enhanced through artificial light attachments in the Atlantic cod fishery, but how lights can be used in other fisheries for various target species should always be considered, not only in the development of LED devices, but also in their practical applications. As interest in the use of light in fisheries increases from both a commercial and scientific perspective, there is a need for proper validation of these technologies through proper research designs. With Atlantic cod, information was available on the species' visual sensitivities (Levine and MacNichol 1982, Douglas and Djamgoz 1990, Valen et al. 2014), and I was able to narrow the scope of my study to fit ecologically relevant light qualities. How the light source(s) will be perceived by the target animals is an essential consideration in these studies, yet the visual system of many commercially relevant species has not been assessed. Therefore, I encourage this approach to behavioural research regarding vision and sensory modalities in the future and highlight the need for baseline sensory information to be collected for a wider range of taxa.

Many questions can be asked about how light affects aspects of behaviour, but also other practical uses in science and industry. Some of the questions that arose during field research with fishers included how lights can be used to increase size/weight of catch by targeting specific individuals, as well as how lights can be used to decrease bycatch. Deterring animals from fishing gear can be incredibly successful in reducing bycatch (Lien et al. 1992, Ortiz et al. 2016), but an important consideration is how the bycatch reduction technology used might work without changing the natural distribution of the species it was meant to conserve (Rouxel et al. 2021). This can come about in many ways, including altering where and how the deterred species live and forage, which can have unforeseen consequences. Especially concerning are cases where deterrence mechanisms are applied to gear types designed for use in specific habitat types occupied by both the target and bycatch species of interest. These fishing gears tend to catch any organism that forages within that habitat, and if bycatch reduction technologies that only target unwanted catch force said species from their natural habitat, their ability to survive outside of that environment might be poor.

How light affects other physiological mechanisms in animals undergoing behavioural study should also be considered. As lights can cause behavioural change in animals, so too can the persistence of artificial stimuli both *in situ* and *ex situ* (including aquaria) affect the development and physiology of organisms. The effects that lighting conditions have on juvenile cod and their growth is a well-studied research question in aquaculture (van der Meeren, Mangor-Jensena, and Pickova 2007, Árnadóttir 2008, Monk, Puvanendran, and Brown 2008), but the information from those studies cannot be translated to adult Atlantic cod, or outside of an artificial environment. Pursuing these questions and considerations in future academic fisheries research will inform how light is used in artificial environments and will allow the application of light in the development of industrial practices and commercial equipment.

4.4 References

Árnadóttir, G. S. (2008). The effects of cold cathode lights on growth of juvenile Atlantic cod (*Gadus morhua* L.): Use of IGF-I as an indicator of growth. Master's thesis. University of Akureyri.

Blackmore, R. (2019). Testing handline catch efficacy for Atlantic cod (*Gadus morhua*) in the inshore Newfoundland fishery: Two studies of short-wavelength modifications. [Unpublished Bachelor of Science Honours thesis]. Memorial University of Newfoundland and Labrador.

Collins, S. M., Hendrix, J. G., Webber, Q. M. R., Boyle, S. P., Kingdon, K. A., Blackmore, R. J., d'Entremont, K. J. N., Hogg, J., Ibáñez, J. P., Kennah, J. L., Lamarre, J., Mejías, M., Newediuk, L., Richards, C., Schwedak, K., Wijekulathilake, C., and Turner, J. W. (2023). Bibliometric investigation of the integration of animal personality in conservation contexts. *Conservation Biology*, 37(2): 14021. doi: 10.1111/cobi.14021

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). (2003). *COSEWIC assessment and update status report on the Atlantic cod Gadus morhua in Canada.* Retrieved from: https://www.sararegistry.gc.ca/virtual_sara/files/cosewic/sr_atlantic_cod_e.pdf

Darquea, J. J., Ortiz-Alvarez, C., Córdova-Zavaleta, F., Medina, R., Bielli, A., Alfaro-Shigueto, J., & Mangel, J. C. (2020). Trialing net illumination as a bycatch mitigation measure for sea turtles in a small-scale gillnet fishery in Ecuador. Latin *American Journal of Aquatic Research*, 48(3), 446-455. ISSN 0718-560X. doi:10.3856/vol48-issue3-fulltext-2428

Department of Fisheries and Oceans Canada (DFO). (2021). *2021 Newfoundland and Labrador recreational groundfish fishery*. Retrieved on January 19th, 2022 from https://www.dfo-mpo.gc.ca/fisheries-peches/decisions/fm-2021-gp/atl-28-eng.html

Douglas, R. and Djamgoz, M. (1990). *The Visual System of Fish*. Springer, Dordrecht. p. 81–107. doi:10.1007/978-94-009-0411-8_4

Field, R., Crawford, R., Enever, R. Linkowski, T., Martin, G., Morkūnas, J., Morkūnė, R., Rouxel, Y. and Oppel, S. (2019). High contrast banners and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. *Global Ecology and Conservation*, 18: e00602. ISSN 2351-9894. doi:10.1016/j.gecco.2019.e00602

Gudmundsdóttir A. and Pálsdóttir H. M. (2005). Atlantic cod trypsins: From basic research to practical applications. *Marine Biotechnology*, 7(2), 77-88. doi:10.1007/s10126-004-0061-9

Humborstad, O-B., Utne-Palm, A. C., Breen, M. and Løkkeborg, S. (2018). Artificial light in baited pots substantially increases the catch of cod (*Gadus morhua*) by attracting active bait, krill (*Thysanoessa inermis*). *ICES Journal of Marine Science*, 75(6), 2257-2264. doi:10.1093/icesjms/fsy099

Hüssy, K., Albertsen, C. M., Hemmer-Hansen, J., Vinther, M., Serre, S H., Thomsen, T B., and Eero, M. (2022). Where do you come from, where do you go: early life stage drift and migrations of cod inferred from otolith microchemistry and genetic population assignment. *Canadian Journal of Fisheries and Aquatic Sciences*, 79(2), 300-313. doi:10.1139/cjfas-2020-0409

Kim, P., Kim, H., Kim, S. (2022). Application of light-emitting diode lights to Bluefin Sea Robin (*Chelidonichthys spinosus*) catch in pot fishery in the South Sea, Korea. *Applied Sciences*; 12(9):4149. doi: 10.3390/app12094149

Lennox, R. J., Paukert, C. P., Aarestrup, K., Auger-Méthé, M., Baumgartner, L., Birnie-Gauvin, K., Bøe, K., Brink, K., Brownscombe, J. W., Chen, Y., Davidsen, J. G., Eliason, E. J., Filous, A., Gillanders, B. M., Helland, I. P., Horodysky, A. Z., Januchowski-Hartley, S. R., Lowerre-Barbieri, S. K., Lucas, M. C., Martins, E. G., Murchie, K. J., Pompeu, P. S., Power, M., Raghavan, R., Rahel, F. J., Secor, D., Thiem, J. D., Thorstad, E. B., Ueda, H., Whoriskey, F. G., and Cooke, S. J. (2019). One hundred pressing questions on the future of global fish migration science, conservation, and policy. *Frontiers in Ecology and Evolution*, 7. ISSN: 2296-701X. doi:10.3389/fevo.2019.00286

Levine, J. and MacNichol, E. (1982). Color vision in fishes. *Scientific American*, 248(2), 140-149. doi:10.1038/scientificamerican0282-140

Lien, J., Barney, W., Todd, S., Seton, R. and Guzzwell, J. (1992). Effects of adding sounds to cod traps on the probability of collisions by Humpback whales. In:

Thomas, J. et al. (eds.) *Marine Mammal Sensory Systems*. Plenum Press, New York.

Malaweera, B. O., and Wijesundara, W. M. N. M. (2014). Use of Seafood Processing By-products in the Animal Feed Industry. In: Kim, SK. (ed.) *Seafood Processing By-Products*. Springer, New York, NY. doi:10.1007/978-1-4614-9590-1_15

Monk, J., Puvanendran, V., and Brown, J. A. (2008). Does different tank bottom colour affect the growth, survival and foraging behaviour of Atlantic cod (*Gadus morhua*) larvae? *Aquaculture*, 277(3), 197-202. doi:10.1016/j.aquaculture.2008.02.018

Nardi, G., Prickett, R., van der Meeren, T., Boyce, D., and Moir, J. (2021). Atlantic cod aquaculture: Boom, bust, and rebirth? *Journal of the World Aquaculture Society*, 52(3), 672-690. doi:10.1111/jwas.12811

Nguyen, K. and Winger, P. (2018). Artificial light in commercial industrialized fishing applications: A review. *Reviews in Fisheries Science & Aquaculture*, 27(1), 106-126. doi:10.1080/23308249.2018.1496065

Ortiz, N., Mangel, J. C., Wang, J., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., Swimmer, Y., Carvalho, F. and Godley, B. J. (2016). Reducing green turtle bycatch in small-scale fisheries using illuminated gillnets: The cost of saving a sea turtle. *Marine Ecology Progress Series,* 545, 251-259. doi:10.3354/meps11610

Penney, R. W., Lush, P. L., Wade, A. J., Brown, J. A., and Burton, M. P. M. (2006). Effect of photoperiod manipulation on broodstock spawning, fertilization success, and egg developmental abnormalities in Atlantic cod, *Gadus morhua*. *Journal of The World Aquaculture Society*, 37(3), 273-281. doi:10.1111/j.1749-7345.2006.00037.x

Rouxel, Y., Crawford, R., Cleasby, I. R., Kibel, P., Owen, E., Volke, V., Schnell, A. K. and Oppel, S. (2021). Buoys with looming eyes deter seaducks and could potentially reduce seabird bycatch in gillnets. *Royal Society Open Science*, 8. doi:10.1098/rsos.210225

Sih, A. (2013). Understanding variation in behavioural responses to human-induced rapid environmental change: A conceptual overview. *Animal Behaviour*, 85(5), 1077-1088. ISSN 0003-3472. doi:10.1016/j.anbehav.2013.02.017

Sutherland, W. (1998). The importance of behavioral studies in conservation biology. *Animal Behaviour*, 56, 801-809. doi:10.1006/anbe.1998.0896

Utne-Palm, A. C., Breen, M., Løkkeborg, S. and Humborstad, O. B. (2018). Behavioural responses of krill and cod to artificial light in laboratory experiments. *PLoS ONE*, 13(1): e0190918. doi:10.1371/journal.pone.0190918

Valen, R., Edvardsen, R. B., Søviknes, A. M., Drivenes, Ø. and Helvik, J. V. (2014). Molecular evidence that only two opsin subfamilies, the Blue Light- (SWS2) and Green Light-Sensitive (RH2), drive color vision in Atlantic cod (*Gadus morhua*). *PLoS ONE*, 9(12): e115436. doi:10.1371/journal.pone.0115436 van der Meeren, T. and Ivannikov, V. P. (2006). Seasonal shift in spawning of Atlantic cod (*Gadus morhua* L.) by photoperiod manipulation: egg quality in relation to temperature and intensive larval rearing. *Aquaculture Research*, 37(9), 898-913. doi:10.1111/j.1365-2109.2006.01510.x

van der Meeren, T., Mangor-Jensen, A., and Pickova, J. (2007). The effect of green water and light intensity on survival, growth and lipid composition in Atlantic cod (*Gadus morhua*) during intensive larval rearing. *Aquaculture*, 265(1-4), 206-217. doi:10.1016/j.aquaculture.2007.01.042

Supplementary Material

S.1. Using Visual Ecology in Research Design and Industry Applications

The development of fishing gear aims to increase the catchability, efficiency, ease of use, and quality of catch. To enhance catchability, gear modifications often take advantage of different sensory capabilities of the target organism. Bait, for example, is a gear modification that exploits many sensory modalities by altering the scent, shape, movement, and possibly even the sound or electrostatic field of the gear. Though multimodal stimuli can improve gear, and technologies have been developed to improve the many sensory qualities of gear, no modality has been exploited as extensively as vision.

For centuries, fishers have exploited visually-driven behaviours in their target species through the development of fishing methods and gear types. Examples involving visual cues include bonfires on beaches to attract fish close to shore and artisanal fishers in Southeast Asia lighting fires aboard their fishing boats while hauling nets. Fishers have also developed lures to attract fish, which primarily exploit the visual behaviour of the target catch. Many modern fisheries use visual attractants in lieu of, or in combination with, bait. For example, glowing phosphorescent or fluorescent materials and paints have been incorporated in lures and even into the nylon netting of gillnets and pots to enhance their visibility and attractiveness. In some fisheries, such as in the sword- fishery off the east U.S. coast, glowing light sticks have been attached to longlines. Subsequently, these have been replaced with more sustainable, longer-lasting LED lights. This use of light has transferred to other fisheries worldwide and LEDs have become a relatively common technology for increasing catch with pots, longlines, and handlines. Developing highly efficient fishing gears has, however, come with the cost of increasing the frequency and possibility of bycatch. The incidental bycatch of non-target species includes unwanted fish as well as marine mammal, sea turtle, and seabird entanglement (Figure A.1). Bycatch reduction technologies (BRTs) are any technology or gear alteration designed to mitigate incidental catch. Sensory physiology has also been at the forefront of the development of these devices and techniques. For example, acoustic alarms ("pingers") broadcast sound signals that have been shown to greatly decrease cetacean (whale & and dolphin) bycatch. Similar deterrents that exploit other sensory modalities such as chemoreception and vision have also been developed.

Figure S.1. Incidental bycatch of non-target species includes unwanted fish as well as marine mammal, sea turtle, and seabird entanglement, as shown in this photo of a gannet entangled in a herring gillnet. Credit: Marina Montevecchi.

One of the first attempts at using visual signals as BRTs were high-contrast warning panels on gillnets. The premise was that diving seabirds would see the panels and avoid the nets while foraging underwater. A recent study at Memorial University used high-contrast warning panels on surface-set herring gillnets (Montevecchi et al. 2023). The bycatch of seabirds such as gannets and murres was comparable between gillnets with and without the panels. However, herring catch was reduced significantly in gillnets with panels, which did not provide a commercially viable option for the fishery. Similar results for high-contrast flags used in the Baltic Sea were presented in a 2019 paper (Field et al. 2019). In that study, researchers additionally tested flashing white lights on gillnets but found an increase in the bycatch of Long-tailed Ducks (*Clangula hyemalis*).

Fisheries researchers are abandoning the use of high-contrast warning panels and shifting their focus to LED lights. Owing to their capability to emit specific, narrow colour ranges, LEDs are being tested as a tool to reduce bycatch and simultaneously attract commercial species. Some results have been promising. For instance, a recent paper summarized studies in which both green and violet-coloured LEDs were associated with significant reductions in sea turtle gillnet bycatch (see Darquea et al. 2020).

Results like these improve the conservation of non-target species. However, many gaps and questions remain. Why might certain light-emitting devices be successful as BRTs or at luring catch and others not? How can the effectiveness of these techniques be better evaluated? And how can ecological impacts of these techniques be assessed?

S.1.1 *A Priori* Considerations for Visual Ecology

The visual ecology of target species is an essential consideration for research in bycatch reduction and catch enhancement methods. To biologically rationalize the results of studies involving light-emitting techniques, the visual perception of target species and how light-emitting techniques might affect their behaviour needs to be understood.

Visual ecology is the study of how an organism's visual system has evolved and how animals gather information from their visual landscape, ultimately affecting their behaviour. How an animal's visual capabilities are specialized to their environment, and for specific behaviours, is the crux of visual ecology research, particularly that which deals with fisheries. Considerations from visual ecology concepts are needed in the design phase of the light-modified fishing gear research to increase the power, effectiveness, and implications of their tests.

Visual systems vary according to an animal's ecological needs. Omitting such consideration from a study design can lead to poor experimental success, and even misinterpretations of observed behaviour. One study presented a convincing argument on the pitfalls of such omissions (Bennett et al. 1994). In the past, it was assumed that animals could see the same colours that I do or that they would respond to a visual stimulus like I would, which led to key mechanisms of behaviour to be overlooked. A call for action was proposed by these authors to avoid this human bias and better understand how animals perceive their world.

This was not a novel idea. The concept of *umwelt* was first coined by Jakob Von Uexküll. He contended that even though we may experience the same conditions, each organism experiences their own self-centred world, where all features of the environment that are directly relevant to one's perception and experience shape the way that they behave. In fisheries research, the human-biased assumption of using high-contrast flags or lights to indicate the presence of a gillnet and thus deter bycatch does not take the animals umwelt into account and is an anthropomorphism. It assumes that the animal will interpret this visual cue or the net itself as a sign of danger and thus avoid it, without an *a priori* rationale for this behaviour.

S.1.2 How can Visual Ecology be Applied to Fisheries Research?

The field of visual ecology is rich and complex, and advocating an expert level understanding before conceptualizing studies would be counterproductive. As a starting point, I suggest consideration of the 'ARTS' of visual ecology:

A - Ambient light environment: the light environment(s) in which the interactions of interest take place.

R - Reflectance/irradiance of the object: the inherent spectral properties of the technology or visual signal to be used, whether it is the reflection of light from the object or the light emitted (irradiance) from the source.

T - Transmission properties of the medium: how light will interact with the medium through which it travels. Water strongly absorbs short (UV and blue) and long wavelengths (reds, oranges, and yellows) such that greenish blue light travels further.

S - Sensory system of the organism: the types and properties of the animal's photoreceptors, and other aspects of the visual system that affects its ability to detect features in its visual environment.

These can be very complicated relationships to understand and incorporate into research designs, but often some very broad assumptions can be made.

First, daytime ambient light and the transmission properties of water both make the light environment at depth relatively constant and predictable. The light profile striking the water surface is similar in sunny and cloudy conditions, except for its intensity. To a depth of about 5 metres, downwelling light (the light field coming from the surface) maintains most of its qualities such that objects of all colours are generally perceived as they would be at the surface. From 5-30 metres, ultraviolet and red/orange-yellow light are progressively absorbed and/or scattered such that they are removed from the light environment. At these depths, sidewelling irradiance (light striking objects sideways or from below due to scattering) becomes more important. This reduces shadows and makes the visual environment more similar in all directions. Below 30 m, almost only blue-green light remains.

Thus, if a red-coloured device is used at a depth of 45 metres, it will not reflect any red light because of the absence of long-wavelength light in that environment. It may appear black or dark grey. This occurs because reflected light is a product of the inherent properties of the material and the ambient light available to be reflected. A device that emits light (or a material that uses irradiance as opposed to reflectance, such as phosphorescing paint) does not rely on the ambient light to provide a signal, but water's transmission properties of light absorption/scattering also have implications on the perception of light emitting devices. Even a bright "white" light will likely be perceived as green if observed from ~20 metres away. Its quality would then change as the viewer approaches. Furthermore, a green light powered by the same amount of energy as a white light would be perceived further away since much less light would be absorbed/scattered over the same distance.

Secondly, to anticipate how a stimulus would be perceived, I need to consider the visual system of all animals influenced by the research. As a first approximation of what they may be able to see, the sensitivity of their photoreceptor (i.e., which wavelengths they can detect) can be used. For many fish of commercial interest, only two types of visual systems are likely to occur. Dichromats perceive some colours, and monochromats perceive only shades of grey. Fish that perceive a range of colours use shallower waters and are usually sensitive to the green-blue range of the light spectrum. Very few commercially important species found in deep North Atlantic waters can perceive long-wavelength colours such as yellows, oranges, and reds. Monochromats are usually deep-water species that only assess greyscale contrasts and can only use shadows and achromatic contrast against a background to detect prey or predators.

Many common bycatch species, however, are semi-aquatic predators that live part of their life at or near the surface, and often have great visual capabilities above and below water. Many marine mammals and sea turtles have numerous adaptations to their sensory systems to be able to thrive on land and in the sea. Seabirds, like most birds, have tetrachromatic vision, meaning that their visual sensitivity is highly specialized and can range from ultraviolet wavelengths through much of what is considered the visible spectrum. Diving seabirds spend much of their life above water, where the UV component of the light environment is quite informative, but as previously mentioned, these short wavelengths of light are quickly absorbed and/or scattered in water. The ability to perceive this quality of the light spectrum separates birds from other marine animals and could allow for targeted bycatch mitigation efforts. By identifying a signal that would trigger avoidance behaviour in seabirds that was outside the visible range for target catch species, bycatch reduction would be possible without reducing commercial success.

While considering ARTS and using these assumptions can help us interpret the results of studies, anecdotal evidence can also aid in understanding. Why, for example, have both green and red lures been successful in the cod fishery? It seems that green phosphorescent lures work quite well in shallow inshore fishing, whereas red lures work well at-depth. Based on what I know about the properties of light and the visual ecology of Atlantic cod, this may seem counter-intuitive as cod are dichromatic (able to perceive colours) but live in a range of depths where the light environment is quite restricted to short-wavelength blue-green light. Their visual system has evolved to suit this ambient light environment, and their photoreceptors are unable to perceive red, so why are red lures so successful at depth? Relatively near the surface, cod could be targeting the reflection of some visible wavelengths from highly reflective surfaces, particularly those of a common prey item, i.e., the shiny silvery scales of capelin. In this scenario, cod are particularly vulnerable to capture by a lure that reflects green light in a similar fashion. At greater depths, however, reflection of green light may be less important than perceiving the shadow of a prey item against the background, and so a red lure (which would likely be seen as black or grey to cod) works well as a mimic in this context, and I would expect any dark lure to work equally well.

Considering the ARTS of visual ecology and using the broad assumptions detailed above can certainly hone the focus and applicability of light modifications in any context, especially research design. At the very least, these considerations will prevent the use of devices that would obviously not be perceived by the target species and will inform assessments of their success. I do note, however, that light modifications to fishing gears should avoid being redundant and harmful in the ecosystem in which they are placed.

S.1.3 Negative Impact of Light-modified Fishing Gear

Fishing gear is a major component of marine pollution and plastic globally. Any additional materials used in the ocean to amplify the catchability of lures or generate light in general have the potential for added ecosystem harm. Ocean pollution by plastic glowsticks is one reason that LEDs became a common replacement. Fishers have historically been stewards for fisheries sustainability and promoters for the development of gear that is not easily discarded or lost. When a research objective aims to improve gear catch rates (and possibly the profitability of that gear) or influence a gear’s popularity through technology, collateral pollution effects need to be addressed from both researchers and industry, including light pollution. The ocean is an open, generally low-light environment where an intense light source suddenly appearing on fishing gear could affect a myriad of organisms, possibly even at great distances. Bioluminescent organisms occur throughout the oceans both at depth and near-surface, and additional light signals in the environment could have unintended consequences. For this reason, the visual ecology of target commercial and bycatch species needs accounting, but so does the visual ecology of any species at-risk in the area that could be harmed or influenced by this light.

In stationary, passive fishing gears, light modifications could affect the gear's propensity to self-bait by attracting prey species to the gear that would then act as a food source for other species, causing a cascading effect. Were that gear to be lost, the light enhancement could amplify ghost-fishing catches.

Finally, it is possible that the gear modification's effect on behaviour influences the distribution of animals in an area. For example, an ongoing study in the Baltic Sea is using poles, attached to the buoys that mark fishing gear, with large eyespots. Eyespots are large round markings, often displayed by small prey organisms, that are known to evoke avoidance behaviours in predators. Using this knowledge of behaviour, the poles with looming eyespots are being tested as a way to divert Long-tailed Ducks from areas of intense gillnet fishing. If this technique is effective, what does the deterrence of ducks in this foraging area mean for their ability to catch prey and for their overall distribution? Could the effects of this stimulus be detrimental to the populations of Long-tailed Ducks in the region? This example is another case where general visual ecology should be considered when conceptualizing the research and design of the BRT, because avoidance behaviour in Long-tailed Ducks in response to eyespot stimuli has never been tested. Unforeseen problems could arise that are harmful to the species in which I aim to protect.

S.1.4 Moving Forward

There is no one-size-fits-all approach to modifying gear through visual stimuli. Many considerations about the positive and negative ramifications from the use of these gear modification need to be addressed. There are many gaps in the knowledge about the visual ecology of commercially-important species and future research should focus on filling these gaps. For fisheries researchers in the North Atlantic, I suggest a program to explore the visual sensitivities of species central to inshore fisheries, such as snow crab, capelin, halibut, herring, etc. For species with basic information on visual capabilities, such as lobster or cod, field or laboratory-based studies will be needed to understand the behavioural interactions with visual stimuli used in fisheries research. Furthermore, studies on the visual systems of commonly-bycaught species will inform bycatch and conversation research.

Research planning and design must address the visual behaviour and ecology of focal and peripheral species. I suggest that fisheries researchers, industry professionals, and everyone involved in fisheries science involving visual cues and gear alterations apply visual ecology information and perspectives in fisheries research design. The incorporation of the physiology and visually-oriented behaviour of target species, and others, will help improve the design of fishing gear research, and benefit the environment.

S.1.5 References

Bennett, A. T. D., Cuthill, I. C. and Norris, K. J. (1994). Sexual selection and the mismeasure of colour. *American Naturalist*, 144(5), 848-860. URL: http://www.jstor.org/stable/2463016

Darquea, J. J., Ortiz-Alvarez, C., Córdova-Zavaleta, F., Medina, R., Bielli, A., Alfaro-Shigueto, J., & Mangel, J. C. (2020). Trialing net illumination as a bycatch mitigation measure for sea turtles in a small-scale gillnet fishery in Ecuador. Latin *American Journal of Aquatic Research*, 48(3), 446-455. ISSN 0718-560X. doi:10.3856/vol48-issue3-fulltext-2428

Field, R., Crawford, R., Enever, R., Linkowski, T., Martin, G., Morkūnas, J., Morkūnė, R., Rouxel, Y. and Oppel, S. (2019). High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. *Global Ecology and Conservation*, 18: e00602. doi:10.1016/j.gecco.2019.e00602

Montevecchi, W. A., Lamarre, J., Rouxel, Y., Montevecchi, M. W., Blackmore, R. J., Bourne, C., and Spiegel, C. (2023). High-contrast banners designed to deter seabirds from gillnets reduce target fish catch. *Marine Ornithology*, 51, 119-126.

S.2. Spectrophotometry configuration

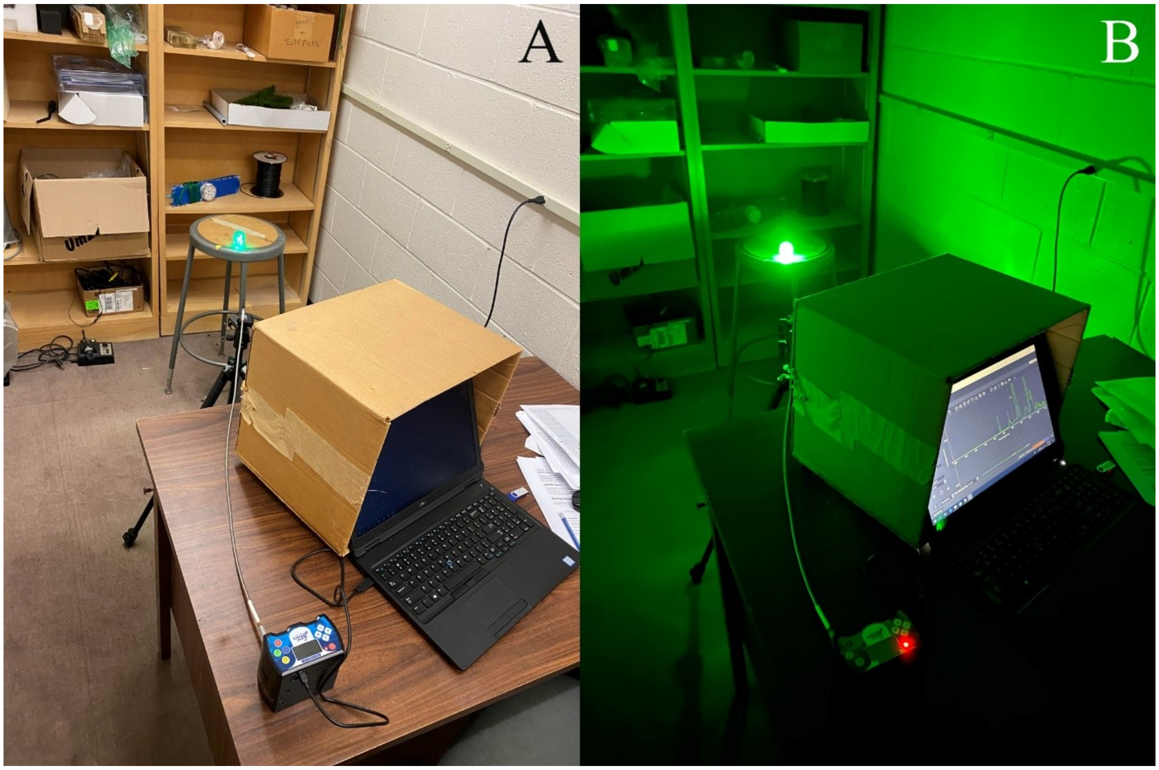

Figure S.2. Spectrophotometer setup for measuring LED spectral output, with the ambient lights on (A) and off (B). The cosine corrector at the end of the fibre optic cable was placed 1 metre from the light source and measured light input for 2000 milliseconds.

S.3. Body sizes of a subsample of fish housed in aquaria

A subsample of seven wild-caught Atlantic cod were measured for body length and weight by staff members of the Joe Brown Aquatic Research Building prior to experimentation and the values were provided as follows: the mean fork-length to the nearest 0.1 cm = 53.5 cm FL, and mean weight to the nearest gram = 1,527 g.