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Guidelines for Evaluating Artificial Light to Mitigate Unwanted Fisheries Bycatch

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ABSTRACT
Evaluating artificial light as a bycatch reduction device (bycatch reduction light, "BRL") requires a multidisciplinary approach that applies knowledge of fisheries science, fishing technology, engineering, physics, optics, vision biology, oceanography, animal behavior, economics, and social science. To support the continued evaluation of BRL, these guidelines were developed for conducting standardized and systematic studies. The guidelines highlight how information from those fields of study contributes to the efficacy of study design and the evaluation of results. The guidance is focused on four core areas: (*i*) defining the objective of using a BRL; (*ii*) understanding the context in which the BRL is applied and considering the base knowledge that is needed; (*iii*) selecting an appropriate study design (including selection and placement of the BRL) and analytical methods for measuring both behavioral responses and catch outcomes from using the BRL; and (*iv*) interpreting the data through the lens of the base knowledge, context, and study design, and evaluating the results against an established definition of success and variables that affect adoption. The purpose of these guidelines is to increase the ability of researchers and managers to determine if BRL is appropriate for a fishery and to encourage consistency in data collection among studies to support future meta-analyses and inter-study comparison. In addition, suggestions are provided on where more research and technology development are needed to support this rapidly emerging field of research.

KEYWORDS
Fish behavior; fisheries selectivity; fish vision; phototaxis; bycatch reduction; conservation engineering

1. Introduction

Lights have been used in fisheries for thousands of years. While the primary goal of using artificial light in fisheries has been to increase the target catch rate (Ben-Yami 1976, 1988; ICES 2012; Nguyen and Winger 2019a), recent research has focused on examining its effect on the behavior of marine species and its potential application in fisheries as a bycatch reduction device (BRD). Artificial lights used as a BRD (hereafter, bycatch reduction light, "BRL") have been used in multiple fisheries. In active fishing gears, BRL has been tested and used primarily on trawls, but also in flyshooting fisheries (Table 1). For these active gear fisheries, illumination has induced a positive or negative phototactic response (i.e., movement toward or away from the light source, respectively) or enhanced the visual perception of gear components; and BRL has also been used in conjunction with other BRDs to increase or decrease

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Table 1. Summary of several studies (listed alphabetically by author) evaluating bycatch reduction lights (BRL) in bottom trawls (1a), pelagic trawls (1b), gill and trammel nets (1c), and longlines (1d).

Study	BRL placement and type	BRL Color (peak wavelength in nm)	Bycatch animal	Target animal	Brief results
(a) Bottom trawls					
Cuende, Arregi, Herrmann, Sistiaga, Basterretxea (2020)	Extension: LED lights placed in front of- and over- a square mesh panel (SMP) bycatch reduction device (BRD)	White (color temperature 6500K)	Undersize hake (*Merluccius merluccius*), blue whiting (*Micromesistius poutassou*)	Mixed groundfish	Position of the lights did not significantly affect the release efficiency for either species (hake or blue whiting).
Cuende, Arregi, Herrmann, Sistiaga, Onandia (2020)	Extension/codend: LED lights attached longitudinally over a SMP	Blue (455)	Undersize hake, blue whiting, horse mackerel (*Trachurus trachurus*)	Mixed groundfish	Lights significantly reduced the release efficiency of blue whiting in the size range between 15 and 27 cm. Lights did not significantly affect horse mackerel nor hake release efficiency compared to the baseline design.
Cuende et al. (2022)	Extension: Fiber optic cable attached to a grid mounted horizontally on a separator panel in front of a split codend	Blue (450)	Horse mackerel, mackerel (*Scomber scombrus*), blue whiting	Mixed groundfish: hake, megrim (*Lepidorhombus* spp.) and anglerfish (*Lophius* spp.)	Light did not have an effect on the separation of hake and megrim from horse mackerel, mackerel, and blue whiting.
Grimaldo et al. (2018)	Extension: LED lights attached to a SMP and on the selvedge	Green	NA	Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*)	Lights triggered an evasion response in haddock when observed with illuminated cameras, meaning escape attempts were less effective. Quantitative descriptions suggest that escape likelihood is higher for undersized haddock in the light treatment, although these effects were not significant.
Hannah et al. (2015)	Trawl mouth/Extension: LED lights placed on the fishing line and on and around a rigid grate BRD	Blue (460), Green (540)	Eulachon (*Thaleicthys pacificus*)	Ocean shrimp (*Pandalus jordani*)	Addition of LEDs on the fishing line dramatically reduced bycatch of a wide number of fishes with no observed reduction of shrimp catch, and a reduction of eulachon by 91%. LEDs on the BRD increased bycatch of Eulachon with no effect on ocean shrimp.
Karlsen et al. (2021)	Tapered section: Luminous netting inserted in the aft part of the tapered section to the front of a horizontally separated codend	Green (520)	Atlantic cod, haddock, whiting (*Merlangius merlangus*), European plaice (*Pleuronectes platessa*), lemon sole (*Microstomus kitt*)	*Nephrops norvegicus*	Light altered vertical distribution of fishes and *Nephrops*. Four of the six species evaluated (roundfishes and *Nephrops*, but not flatfishes) responded to the low light level of the luminous netting, similar to that reported by Melli et al. (2018). The gadoids and large *Nephrops* entered the lower half of the codend more frequently than the control. The flatfishes did not respond.
Larsen et al. (2017)	Extension: LED lights attached around the escape hole in front of a Nordmøre grid	Green	Atlantic cod, haddock, *Sebastes* spp., Greenland halibut (*Reinhardtius hippoglossoides*)	Deep-water shrimp (*Pandalus borealis*)	Illumination around the escapement area of the grid was ineffective at stimulating fish escape. Rather, fish did not get close to the area where lights were placed.
Larsen et al. (2018)	Extension: LED lights attached to the lower part of a Nordmøre grid	Green	Atlantic cod, haddock, *Sebastes* spp., American plaice (*Hippoglossoides platessoides*)	Deep-water shrimp	Lights did not significantly affect the escape probability or the size selectivity of any of the investigated species.

(*Continued*)

Table 1. Continued.

Study	BRL placement and type	BRL Color (peak wavelength in nm)	Bycatch animal	Target animal	Brief results
Lomeli et al. (2018)	Trawl mouth: LED lights attached to the headrope	Green (540)	Groundfishes	Pacific halibut (*Hippoglossus stenolepis*)	Illuminating the headrope affected catch of groundfishes differentially by species and length. The illuminated trawl caught fewer (not significant) rex sole *(Glyptocephalus zaphirus),* arrowtooth flounder (*Atheresthes stomias*), lingcod (*Ophiodon elongatus*), and Pacific halibut; and more dover sole (*Microstomus pacificus*) 31–44 cm in length and sablefish (*Anoplopoma fimbria*) 43–61 cm in length. On average, the illuminated trawl caught more (not significant) rockfishes (*Sebastes* spp.), English sole (*Parophrys vetulus*), and petrale sole (*Eopsetta jordani*).
Lomeli et al. (2018, 2020)	Trawl mouth: LED lights attached to the fishing line	Green (519)	Eulachon, juvenile groundfishes: Pacific hake (*Merluccius productus*), *Sebastes* spp., flatfish, whitebait smelt (*Allosmerus elongatus*)	Ocean shrimp	The control (unilluminated) trawl caught significantly more eulachon than the LED configurations, and more *Sebastes* spp. and sanddab; whereas the illuminated trawl caught more hake. Overall, the illuminated trawl had reduced bycatch and no significant loss of target catch.
Lomeli et al. (2021)	Bridles and wings: LED lights attached along each of the upper wing tips and upper bridles	Green (519)	Pacific halibut	Mixed groundfish	The illuminated trawl caught significantly fewer Pacific halibut and sablefish than the non-illuminated trawl. For Dover sole (*Microstomus pacificus*), petrale sole (*Eopsetta jordani*), and lingcod (*Ophiodon elongatus*), the illuminated trawl caught fewer individuals than the non-illuminated trawl. This catch difference was not statistically significant.
Maynard and Gaston (2010)	Trawl mouth: LED lights attached across the headline	White	Ponyfishes (family Leiognathidae), biddies (family Gerridae), sweetlips (family Haemulidae), non-target prawns (family Penaeidae), and goatfishes (family Mullidae)	Tiger prawns (*Penaeus esculentus*, *P. semisulcatus*) and endeavor prawns (*Metapenaeus endeavouri*, *M. ensis*)	The bycatch ratio for the trial more than doubled when lights were used, significantly changing the catch per unit effort of ponyfishes, biddies, non-target prawns, trevallies (family Carangidae), threadfin salmon (family Polynemidae), whiting (family Sillaganidae), and cardinalfish (family Apogonidae).
Melli et al. (2018)	Tapered section: LED lights attached in front of a BRD (divided codend) on either the top or bottom netting panel	Green (540)	Atlantic cod, haddock, whiting, European plaice, lemon sole	*Nephrops*	All six species responded to the LEDs: cod and whiting responded to both LED positions, haddock, lemon sole and *Nephrops* to LED in the lower panel, plaice to LEDs in the upper panel (not tested for *Nephrops*). All species, except for haddock, increased their entrance into the lower compartment. Results were not consistent with phototaxis.
O'Neill and Summerbell (2019)	Trawl mouth: Fiber optic cable attached at the leading edge of a separator panel (a BRD), or to the fishing line	Green (530)	NA	Any available demersal fish species	Light can be used to alter the height at which some species enter a trawl gear, and the effect is dependent on natural ambient light. In Autumn, during daylight, the illuminated cable had little effect compared with Spring during night time hours when the cable had a significant effect on how haddock, whiting, European plaice, common dab (*Limanda limanda*), and gurnards (*Eutrigla gurnardus*, *Chelidonichthys cuculus*) entered the trawl (swam below the panel when the cables were illuminated).

(*Continued*)

Table 1. Continued.

Study	BRL placement and type	BRL Color (peak wavelength in nm)	Bycatch animal	Target animal	Brief results
O'Neill et al. (2022)	Extension: Fiber optic cable attached to an inclined grid which leads to two separate codends	Green (530)	NA	Any available demersal fish species	Most species were less likely to enter the upper codend half when the grid was illuminated and the results were similar regardless of whether the bottom-half, top-half, or the whole grid was illuminated. There was also a diel effect for all species with a lower proportion of haddock and whiting and a greater proportion of flatfish in the upper codend at night than during the day. The results are more subtle for some species, and for Atlantic cod, illuminating the grid had no effect during the day.
Parsons et al. (2012)	Codend: Light sticks attached around the circumference of the trawl near a BRD		Red snapper (*Lutjanus campechanus*)	Shrimp	Illuminated trawls equipped with the BRD reduced red snapper bycatch by 41.8%, whereas a non-illuminated BRD reduced red snapper bycatch by 17.5%.
Southworth et al. (2020)	Tapered section: LED lights attached to a SMP	White	Gadoids	Queen scallop (*Aequipecten opercularis*)	There is a suggestion that LED lights might enhance the SMP in deeper tows for haddock and some flatfishes.
(b) Pelagic trawls					
Lomeli and Wakefield (2012, 2014)	Extension: LED lights used with a BRD	White	Chinook salmon (*Oncorhynchus tshawytsha*), rockfish (*Sebastes* spp.)	Pacific hake (*Merluccius productus*)	Lights enhanced Chinook salmon escapement *via* a BRD and they spent more time on the illuminated side of the trawl. There was also a reduction in rockfish bycatch except for widow rockfish (*S. entomelas*).
Lomeli and Wakefield (2019)	Extension: LED lights used with a BRD	Blue (464), White	Chinook salmon	Pacific hake	Lights can influence where Chinook salmon exit out of the BRD and can be used to enhance their escapement overall.
(c) Gill and trammel nets					
Allman et al. (2021)	LED lights at 10 m and 15 m intervals on the net	Green	Sea turtles: leatherback (*Dermochelys coriacea*), olive ridley (*Lepidochelys olivacea)*, green (*Chelonia mydas*)	Primarily species in the families Carangidae (bumper fish), Clupeidae (sardines), and Engraulidae (anchovies)	Net illumination can reduce bycatch of multiple sea turtle species, including leatherback turtles, while maintaining target catch and value.
Bielli et al. (2020)	LED lights placed along the floatline	Green (500 nm)	Sea turtles: *green, olive ridley, loggerhead (Caretta caretta*); seabirds: *Spheniscus humboldti, Ardenna creatopus, Procellaria aequinoctialis;* and cetaceans: *Delphinus capensis, Lagenorhynchus obscurus, Phocoena spinipinnis, and Delphinus truncatus*	Elasmobranchs: smooth hammerhead (*Sphyrna zygaena)*, smooth hounds (*Mustelus* spp.), bronze whalers (*Carcharhinus brachyurus)*, blue sharks (*Prionace glauca),* and eagle rays *(Myliobatis* spp.)	Illumination reduced bycatch probability in multiple taxa, including sea turtles, cetaceans, and seabirds. Target species CPUE was not negatively affected by the presence of LEDs.
Darquea et al. (2020)	LED lights placed along the floatline at an interval of 12–14 m	Ultraviolet	Sea turtles: green, leatherback, olive ridley	Bony fish and sharks: skipjack tuna (*Katsuwonus pelamis)*, yellowfin tuna (*Thunnus albacares*), mahi-mahi *(Coryphaena hippurus)*, thresher shark *(Alopias* spp.), and smooth hammerhead shark	Significant reduction in sea turtle catch rates (species specific) and no impact on CPUE of target catch.

(*Continued*)

Table 1. Continued.

Study	BRL placement and type	BRL Color (peak wavelength in nm)	Bycatch animal	Target animal	Brief results
Field et al. (2019)	LED lights placed on the headline	Green (525), White (flashing)	Seabirds (e.g., long- tailed ducks, *Clangula hyemalis*, and velvet scoters, *Melanitta fusca*)	Cod, whitefish (*Coregonus lavaretus*), pikeperch (*Sander lucioperca*), flounder (*Platichthys flesus*)	Illuminated panels were ineffective at reducing bycatch and the use of flashing white lights increased bycatch of long tailed ducks.
Gautama et al. (2022)	LED lights placed along the headline	Green (500)	Sea turtles	Pomfret species	Significant reduction in sea turtle catch rates and significant increase in total catch and target catch.
Kakai (2019)	LED lights placed along the headline	Green (520)	Sea turtles: green, olive ridley, loggerhead (*Caretta caretta)*, leatherback, hawksbill (*Eretmochelys imbricate*)	Blue shark, flounder (*Paralichthys* spp.), guitarfish (*Rhinobatos planiceps*), kingfish (*Scomberomorus cavalla*), and shortfin mako shark (*Isurus oxyrinchus*)	Significant reduction in sea turtle catch rates, while maintaining target catch.
Mangel et al. (2018)	LED lights placed along the floatline	Green	Guanay cormorants (*Phalacrocorax bougainvillii)*	Flounder (Paralichtys spp.), guitarfish, rays (Batoidea superorder)	Significant reduction in seabird catch rates.
Martínez-Baños and Maynou (2018)	LED lights placed along the floatline	Green, White		Cuttlefish (*Sepia officinalis*)	The effect of lights on discard reduction was not significant.
Ortiz et al. (2016)	LED lights placed along the floatline	Green	Green turtles	Flounder, guitarfish, rays (Batoidea superorder)	Illumination resulted in the reduction of green turtle bycatch with no impact on target catch or value.
Senko et al. (2022)	LED lights placed along the floatline	Green	Elasmobranchs (multiple species), Humboldt squid (*Dosidicus gigas*), unwanted finfish (multiple species), loggerhead turtles	California halibut (*Paralichthys californicus*), grouper *(Hyporthodus* spp.), other finfish (multiple species)	There was a significant reduction in total discarded bycatch biomass rates, including significant reductions in elasmobranch, Humboldt squid, and unwanted finfish. There was no significant reduction in loggerhead turtle bycatch rates. Illuminated nets did not decrease target fish catch or value, while reducing the time required to retrieve and disentangle nets.
Virgili et al. (2018)	LED lights placed along the floatline	Ultraviolet	Loggerhead turtles	Thornback rays (*Raja clavata*), starry rays (*Raja asterias*), flatfishes: turbot (*Scophthalmus maximus)* and brill (*Scophthalmus rhombus*)	The illuminated net resulted in a significant reduction in loggerhead turtle catch rates, with no impact on target catch or value.
Wang et al. (2010)	LED lights and chemical lightsticks (separately) placed along the floatline	Green	Green turtles	Bothidae (flatfish), Pleuronectidae (flatfish), several species of Elasmobranchii (sharks, guitarfish, rays, skates)	The illuminated nets led to a significant reduction in green turtle catch rates and no significant changes to target catch rates or value. There were no significant differences between LED lights and chemical lightsticks.
Wang et al. (2013)	LED lights placed along the floatline	Ultraviolet (396)	Green turtles	Variety of taxa, primarily Pleuronectidae	The illuminated net resulted in a significant reduction in green turtle catch rates and no significant changes to target catch rates or value.
(d) Longlines					
Afonso et al. (2021)	LED lights attached near each hook	Green (525 nm), Blue (465 nm), and White	Sea turtles and blue sharks (*Prionace glauca*)	Tunas and swordfish	Gear with green lights caught more sea turtles and blue sharks than blue and white lights.
Swimmer et al. (2017)	LED lights and chemiluminescence attached near the hooks	N/A	Loggerhead turtles (*Caretta caretta*)	Tunas and swordfish	Results showed a positive linear relationship for loggerhead turtle bycatch probability and lightstick use (ratio of total number of light sticks to number of hooks per set).
Gianuca et al. (2016)	LED lights attached near each hook	N/A	Sea birds	Tunas and swordfish	The use of lights did not influence the sink rate of baited hooks with 3.5 m leaders, which could influence seabird bycatch.

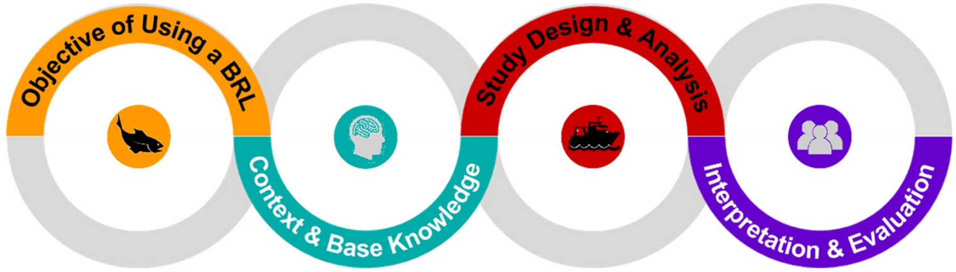

Figure 1. The four core areas to consider when testing a bycatch reduction light (BRL) described in this paper, with an emphasis on the importance of the feedback loop among these project stages.

movement toward an escapement area (Cuende, Arregi, Herrmann, Sistiaga, Basterretxea 2020; Cuende, Arregi, Herrmann, Sistiaga, Onandia 2020; Grimaldo et al. 2018). In passive fishing gears, BRL has been tested and used primarily in gillnet fisheries, but also with longlines (Afonso et al. 2021) and pots (Table 1). Artificial lights in these fisheries have additionally been used to increase catch rates of the target species (e.g., Hazin et al. 2005; Humborstad et al. 2018; Nguyen et al. 2020; Poisson et al. 2010; Sokimi and Beverly 2010).

Previous studies indicate that BRL yields mixed results (Table 1). For example, in gillnet fisheries, BRL significantly reduces the capture of sea turtles (Allman et al. 2021; Bielli et al. 2020; Darquea et al. 2020; Gautama et al. 2022; Kakai 2019; Ortiz et al. 2016; Virgili et al. 2018; Wang et al. 2010, 2013), small cetaceans (Bielli et al. 2020), seabirds (Bielli et al. 2020; Mangel et al. 2018), elasmobranchs (Senko et al. 2022), Humboldt squid (Senko et al. 2022), unwanted finfish (Senko et al. 2022), and total bycatch biomass (Senko et al. 2022). Other gillnet studies, in contrast, have shown either inconclusive or negative effects of BRL on bycatch (e.g., Field et al. 2019; Martínez-Baños and Maynou 2018). Mixed results have also been shown by attachment location (e.g., Hannah et al. 2015), species (e.g., Geraci et al. 2021; Grimaldo et al. 2018; Lomeli and Wakefield 2012; Senko et al. 2022), size of the animal (e.g., Geraci et al. 2021; Karlsen et al. 2021; Lomeli et al. 2018; Melli et al. 2018), and light properties (e.g., color, light level, and strobe rate; Yochum et al. 2022). Furthermore, environmental conditions, such as turbidity and ambient light, can dramatically alter the visual perception of BRL by target and bycatch animals and therefore influence BRL efficacy (Cuende et al. 2022). This variability highlights the need to standardize data collection on variables that may affect behavioral responses and the importance of understanding the influence of study design.

To support the continued evaluation of BRL, guidelines were developed for conducting standardized, systematic BRL studies with information that should be considered when evaluating study results. These guidelines focus on four core areas: (*i*) defining the objective of using a BRL; (*ii*) understanding the context in which the BRL is applied and considering the base knowledge that is needed; (*iii*) selecting an appropriate study design (including selection of the BRL) and analytical method; and (*iv*) interpreting the data through the lens of the base knowledge, context, and study design, and evaluating the results against an established definition of success and variables that affect adoption (either through voluntary uptake or regulation; Figure 1). The intention is for these guidelines to increase researchers' and managers' ability to determine if BRL is appropriate for a fishery (or component of a fishery). In addition, by encouraging consistency in data collection among studies, these guidelines can also support future meta-analyses and inter-study comparison.

2. Defining the objective of using a BRL

Studies evaluating BRL start by defining the specific fishery concerned and identifying the non-target animals to be selected against (hereafter, "bycatch animal") with minimal effect on the target catch (hereafter, "target animal"). Both the bycatch and target animals should be defined in terms of their key characteristics relevant to selectivity (e.g., species, size, sex; Table 2). This includes defining what is meant by a "successful" outcome of using the BRL. Success could be measured, for example, by reduction in bycatch rates (or the ratio of bycatch and target catches), an increase in harvest efficiency (e.g., decreased catch sorting time), feasibility of using the BRL (including costs and operational considerations), and/or reliability of a behavioral response. Success can also be measured by minimizing unintended consequences of the lights (see Section 8), including

Table 2. Data to collect and variables to define and consider for a bycatch reduction light (BRL) study.

Category	Variable	Description	Considerations
Defining the Objective of Using a BRL (Section 2)	Bycatch animal	Animal trying to affect using a BRL (i.e., select against).	• Define in terms of key characteristics relevant to selectivity (e.g., species, sex, size). • Consider at which life stage the bycatch animal is being caught and how that might translate into behavioral patterns (e.g., vision of an adult fish compared to their juvenile life stage). • [For animals in a laboratory study] Consider their feeding cycle and whether or not they were raised in captivity.
	Target animal	Target catch of the fishery (i.e., select for).	• Define relative to the bycatch animal.
	Desired effect	Target behavior trying to elicit using a BRL related to selectivity of the bycatch animal.	• Define behavior in non-anthropomorphized terms.
	Measures of success	Definition of a successful outcome.	• Consider variability in effect, tradeoffs with reduction in bycatch and target catch, and incidental impacts. • Consider practicability (Section 8).
Understanding the Context in which BRLs are Applied (Section 3)	Environmental Variables	Environmental variables being experienced by the bycatch animal as it experiences the BRL.	• Collect data on environmental properties (e.g., natural ambient light level, turbidity, water temperature, localized currents). • Use appropriate technology for collecting environmental data and collect the data where the BRL is experienced.
	Operational Variables	Fishing variables that likely affect animal behavior and, therefore, response to a BRL.	• Describe characteristics of the fishery (e.g., range of and common vessel types, sizes, horsepower, tow speed, fuel consumption) and fishing gear (e.g., gear type and specifications, bait type- if used). • Consider how operational variables influence animal behavior and how differences in these variables could affect inter-study comparisons. • Consider variables that limit inference based on the study design (e.g., spatio-temporal variability in fishing operations- such as time of day, season, depth). • Describe any bycatch reduction devices that will be used in conjunction with the BRL.
Considering Base Knowledge (Section 4)	Biology and physiology (4.1)	Morphology	• Consider body traits such as the cross-section of the head and girth relative to mesh; sexual dimorphism; body length.
		Physiology	• Consider physiological characteristics such as swimming capacity and the ability of the animal to react to light.
	Sensory systems (4.1)	Visual	• Consider visual spectrum and sensitivity, time required for dark/light adaptation, optical formation, accommodation, contrast sensitivity, spatial resolution/acuity, motion/flicker detection, shape discrimination, size and distance perception, and polarization sensitivity. If no information is available on the vision of the bycatch animal, inferences can be made based on their habitat and lifestyle (e.g., sedentary/ active, predator/prey). • Focus on differences in vision relative to the target animal. • Consider damage to the eye from the BRL.
		Lateral line	• Consider how water current and vibrations from the gear can interfere with the effect of the BRL.
		Auditory	• Consider how noise inside the fishing gear (e.g., trawl doors) and/or vessel can interfere with the effect of the BRL.
		Olfactory	• Consider odor plumes in relation to attraction and capture by baited gears.
		Other senses (e.g., echolocation, chemo-sensory, magneto-sensory, electro-sensory, optomotor response, stimuli that are outside of human perception)	• Consider the role of these additional sensory systems and the potential for them to interfere with the effect of the BRL.
	Behavior (4.2)	Behavior of the animal independent of and relative to the fishing process, and their response to light independent of a BRL or BRD.	• [When behavior information is missing] Seek information from studies in other fields and applications to make inferences about behavior.

(*Continued*)

Table 2. Continued.

Category	Variable	Description	Considerations
Selecting a BRL (Section 5) and Placement (Section 6)	BRL Properties (5.1)	Emitter type	• Select among types (e.g., LED, fiber optic cable, laser, phosphorescent materials, chemi-luminescence). • Consider power supply, housing (size, depth rating, rugged, attachment mechanism), directionality, programmability, accessibility, and cost.
		Light properties	• Select peak wavelength, light level, and strobe rate.
	BRL Placement	Location and Attachment	• Consider placement in relation to the objective of the study (i.e., behavior attempting to elicit). • Consider where/ when the animal will experience the BRL during the fishing process (e.g., entering the net, near a BRD) and how that relates to the state/ motivation of the animal (e.g., experiencing herding or crowding); water flow/ gear movement at that location (relative to swimming ability); factors affecting diffusion of light at that location (e.g., sediment/ turbidity); and the position relative to any selection devices in the gear. • Consider the orientation of the light (e.g., light directed aft, down, etc.) and duration of exposure. • Consider operational logistics (e.g., ease of attachment) and impact to fishing operations.
		Number	• Consider the effect of a single compared with multiple lights, either in the same area or at different locations in the fishing process. • Consider distance between lights (when multiples used).

negative impacts on fish vision for those that escape capture or changes in catch composition (e.g., increasing catch of other non-target animals).

3. Understanding the context in which BRL is applied

During the fishing process, animals are subject to stimuli that may affect their behavior in response to environmental and operational variables (e.g., herding, olfaction, turbidity). Simplified from Levitis et al. (2009), behavior can be defined as "the responses (actions or inactions) of whole living organisms (individuals or groups) to internal and/or external stimuli." Understanding the context for behavior is important for accurate interpretation of BRL study results.

3.1. Environmental variables

Knowledge of the environmental conditions in which an animal is experiencing a BRL is important for interpreting results and making inferences on the use of light for fisheries selectivity while also facilitating comparability among studies. Environmental properties (e.g., natural ambient light level – the amount of light received or measured, turbidity, water current patterns, tidal cycle patterns, range of current strengths, lunar and seasonal variations) can influence the response of the bycatch animal to a BRL by altering the appearance of the BRL (e.g., change the contrast of the light against its background) and by affecting their vision (e.g., water temperature, Fritsches et al. 2005), sensory detection range and physiological performance (Payne et al. 2016), and behavior (e.g., Kotwicki et al. 2009; Lomeli et al. 2019; Olla et al. 1997, 2000; Ortiz et al. 2016; Ryer and Barnett 2006). The light environment is affected by weather conditions (e.g., sea state, cloud cover), turbidity (i.e., loss of water transparency due to suspended organic or inorganic particles; Kalle 1966; Kirk 1976, 1994; Figure 2), depth (Dutkiewicz et al. 2019; Jerlov 1976; Johnsen and Sosik 2004; Krebs 1972; Sheppard 1982), season, time of day, and geographic region. Temporal and geographic variation in the biogeochemical composition (e.g., chlorophyll, dissolved organic matter, inorganic sediment) of the water column causes variation in water color and turbidity, and, therefore, influences visibility (Bricaud et al. 2004; Kirk 2011; Loew and McFarland 1990). For example, ocean shrimp (*Pandalus jordani*) catch was, in a study, not affected by artificial light levels, but increased turbidity did result in the illuminated trawl catching fewer individuals (Lomeli et al. 2020). Moreover, temperature can have a strong impact on physiological processes, including swimming capacity and metabolism (Brett 1971), which could affect how an animal responds to a BRL. Water flow can also influence the ability of animals to hold their position relative to an active gear as well as orientation to the current (i.e., rheotaxis). Current can also affect the distance, area, and direction animals can detect and be attracted to bait plumes (Løkkeborg 1998; Thomsen et al. 2010).

It is important to use technology that will facilitate the collection of environmental data that are representative of where and when the BRL is experienced by the animal. For example, when performing *in situ* experiments, the turbidity level can vary dramatically throughout an active gear, and the light level varies with distance from the BRL source. Some methods for data collection include the Okta for cloud cover (Ahmad et al. 2017) and Beaufort scale for sea state (Southworth et al. 2020). The ambient light level at the experimental depth can be measured using a spectroradiometer (Loew and McFarland 1990; Figure 2) or data loggers (Lomeli et al. 2018; see Section 5.2 for more detail). Temperature can be measured using underwater multi-probes, which can easily be deployed on fishing gear (e.g., CTD loggers that simultaneously measure conductivity, temperature, and pressure; Geraci et al. 2021). Water flow can be measured using flowmeters (Larsen et al. 2017) or acoustic Doppler current profilers.

Measuring turbidity is complicated. A simple method for quantifying small-scale surface turbidity is to measure the Secchi depth. Secchi disks, however, are difficult to use in rough seas and cannot be used for night experiments. The color of the oceanographic and coastal waters can be determined according to the classification system of Jerlov (1951) that is based on *in situ* attenuation measurements of oceanographic water (Akkaynak et al. 2017). Cameras can also be used to assess conditions qualitatively and supplement turbidity meter data (e.g., Cuende et al. 2022). Alternatively, satellites equipped with radiometers and underwater optical sensors to measure ocean color can give information on the overall turbidity of a water mass (e.g., Pitarch et al. 2019). Turbidity can also be automatically and continuously measured by optical sensors such as nephelometers and transmissometers. Of those only the transmissometer measures both light scattering and light absorption, characterizing transmission of light in a way that is relevant to vision (for more information, see Davies-Colley and Smith 2001; Utne-Palm 2002; Kitchener et al. 2017).

3.2. Operational variables

Operational fishing variables likely affect behavior and, therefore, the response to a BRL. These include fishery characteristics (e.g., target catch), fishing fleet

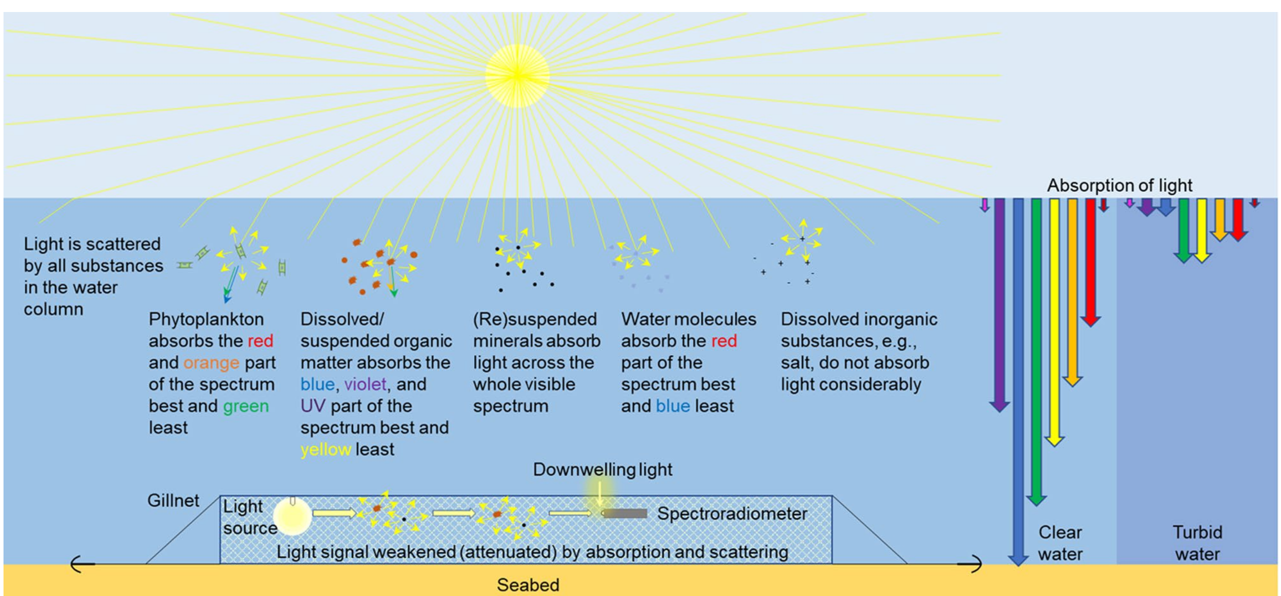

Figure 2. Natural and artificial light (illustrated here attached to a gillnet) are attenuated by absorption and scattering when traveling through water. The different types of substances in the water absorb different parts of the light spectrum to different extents, and light is attenuated more in highly turbid water. This figure was adapted from Fly Fishing Science (https://flyfishingscience.co.uk/2018/10/19/light-attenuation-in-water/); Garcia et al. (2017); and Johnsen and Sosik (2004).

information (e.g., range of and common vessel types, sizes, horsepower, tow speed), spatio-temporal variability in fishing operations (e.g., fishing during the winter season or at night, variation by depth), and fishing gear design and dynamics (e.g., the codend size, bait used, soak duration) (Table 2). These variables can affect catchability and selectivity. For example, vessel horsepower and tow speed can influence gear motion and mesh openings (Bombace and Lucchetti 2011; Wileman et al. 1996), and bait type and amount and changes in bait leaching (e.g., due to temperature changes) can affect which species are attracted to the gear and their subsequent behavior (Hazin et al. 2005; Løkkeborg et al. 2010). Moreover, if a BRL is intended for use with an additional BRD, it is useful to understand how that BRD affects selectivity in isolation. Because these factors can influence the effect of the BRL, it is important to collect data on them and to use the values to limit the scope of inference. Differences in these variables can also affect inter-study comparisons.

4. Considering base knowledge

During the fishing process, animals experience numerous stimuli as they encounter and engage with fishing gears (e.g., the sound of the boat engine, smell of the bait). Animal behavior results from the combination of the stimuli experienced (e.g., Kim and Wardle 2003) and their biology and physiology, including evolutionarily adapted responses to their environment (e.g., predator avoidance, conspecific cues). Therefore, it is important to consider how the stimulation of senses could influence or confound a behavioral response to the BRL. This includes understanding the sensitivity of the olfactory organs (Hara 1975; Løkkeborg et al. 2010; Nguyen and Winger 2019b), lateral line, echolocation organs (Kratzer et al. 2020), auditory organs (Hawkins 1973; Ona and Godø 1990; Sand and Karlsen 1986), magnetoreception, and chemosensory and electro-sensory systems. For example, the bycatch animal may respond to stimulation from water current (rheotaxis) and vibrations of the fishing gear, as well as to changes in temperature and depth. In addition to these, there are potentially other stimuli of which we are currently unaware because they fall outside of human detection capabilities (Popper and Carlson 1998). Several publications have reviewed sensory capabilities, in the context of sensory-based bycatch reduction strategies, of aquatic animals, including: teleost fishes (Atema et al. 2015); sea turtles (Southwood et al. 2008); elasmobranchs (Jordan et al. 2013); marine mammals (Dawson et al. 2013; Kratzer et al. 2021; Schakner and Blumstein 2013); birds (Martin and Crawford 2015); and invertebrates (Senko et al. 2022).

Given these dynamic interactions, a study evaluating the influence of artificial light on fisheries selectivity requires knowledge based in many scientific fields. This includes fisheries science, fishing technology, engineering, physics, optics, vision biology, oceanography, animal behavior, economics, and social science (human behavioral change) (e.g., Nguyen and Winger 2019a). It is likely that most researchers conducting BRL studies do not have an in-depth background in all these subject areas.

Here relevant base knowledge is highlighted with the aim of helping researchers appropriately design their study and interpret results (Table 2) by providing more detailed information about: (*i*) biology and physiology (Section 4.1), with a focus on vision (Section 4.1.1); and (*ii*) behavior (Section 4.2). Information about light and its properties (and measuring light) can be found in Section 5.

4.1. Biology and physiology

Biological and physiological characteristics of an animal can influence and limit their ability to respond to a BRL (Marais 1985; Reis and Pawson 1999; Table 2). This includes morphological traits such as size (e.g., the cross-section of the head and body girth relative to mesh or a BRD panel) (Herrmann et al. 2009; Marais 1985; Reis and Pawson 1999). Physiological characteristics, such as swimming capacity (Parsons and Foster 2007; Regier and Robson 1966; Yochum et al. 2021), can determine their ability to access or avoid specific areas of the fishing gear, especially in relation to towing speed and duration for active gears. Swimming speed has been broadly categorized into “sustained,” “prolonged,” and “burst” swimming; at each of these speeds, different muscle types are used to power the swimming gait (Webb 1994). Endurance negatively correlates with swimming speed (i.e., decrease in endurance with increasing speed; Coughlin 2002; Videler 1993; Webb 1994), and swimming capabilities can differ by species, size, sex (He and Wardle 1988, Videler and Wardle 1991), and ontogenetic phase (Cronin and Jinks 2001; Nguyen and Winger 2019a). There can even be significant differences in endurance at prolonged speeds between conspecifics of comparable length (Breen et al. 2004; He and Wardle 1988; Videler and Wardle 1991). Without direct information about swimming capability (e.g., swimming speed limits and endurance), inferences can be drawn based on biology and mechanisms for food capture, escape from predators, and reproduction (Videler and Wardle 1991).

4.1.1. Vision

Vision plays an important role in how an animal will respond to the presence of a BRL. Vision can vary greatly within and among species (Arimoto et al. 2010; Land and Nilsson 2012; Figures 3 and 4), by ontogenetic stage, and by the light environment to which the animal is adapted (Carlisle and Denton 1959; Shand et al. 1988; Wagner and Kröger 2005). These differences in the visual systems (both in capabilities and limitations) provide a potential mechanism for differentially affecting behavior and, therefore, capture of target- and not bycatch- animals (e.g., selecting a wavelength that is visible to one and not the other). As such, these differences should be explored and used to adjust BRL properties (e.g., flicker rate, light level; see Section 5) as well as their operational use (e.g., attachment location; see Section 6). Relevant aspects of the visual system to consider include absolute sensitivity, light/dark adaptation, color vision, spatial acuity, polarization, and motion detection.

If no information is available on the vision of the bycatch animal, inferences can be made based on the habitat, ecology, and morphology of the species (Schroer and Hölker 2016). For example, many species living deeper than 200 m have limited or no color sensitivity (Douglas et al. 1998; Munk 1964). Moreover, the field of view is a result of the placement of eyes on the head, the viewing direction, eye size and mobility (for more detail, see Arimoto et al. 2010; Wardle 1993), and position of the photoreceptors in the retina (e.g., Bozzano and Catalán 2002; Burnside and Nagle 1983).

4.1.1.1. The visual system and photoreception. The eye is a photo-sensitive sensory organ that facilitates the extraction of information from light (i.e., visible electromagnetic radiance/packages of energy called "photons"; see Johnsen 2012; Land and Nilsson 2012; Palmer 1993 for more details). Eyes of aquatic animals vary in their morphology and physiology. Here generalized overview information about the form and function of the fish eye is provided, which is broadly similar in structure to that of most other vertebrates (Wartzok and Ketten 1999) with two main functions: collection of photons and accommodation of an image on the light sensitive retina using a lens (Fernald 1990; Kröger 2013a) (Figure 5). In the retina, there is a matrix of light-sensitive photoreceptor cells (e.g., rods and cones) that convert the light into neural impulses, which are transmitted *via* the optic nerve to the optic lobes of the brain where an image is perceived (for more details see Bowmaker 1995; Lythgoe and Partridge 1989; Nakagawa et al. 1999; see Semmelhack et al. 2014 for processing light information in the retina).

4.1.1.2 Sensitivity and light-dark adaptation. Absolute sensitivity is the ability of the eye to detect light and process visual information in given light levels. Adaptation to different light levels involves several physiological, biochemical, and morphological processes that should be considered when selecting BRL light level (Ali 1959; Barbur and Stockman 2010). In brief, most fish have no eyelid, and a fixed pupil size. For these animals, adjusting the optics of the eye (i.e., retinomotor movements; Burnside and King-Smith 2017) to accommodate sudden changes in light level, for example, by introducing an artificial light source, is not possible (Douglas et al. 1998). Disrupting a dark-adapted fish with sudden exposure to a bright light (Figure 6) in fishing gear or a laboratory setting (i.e., transitioning from scotopic to photopic vision), even for a brief pulse (Wagner and Douglas 1983; Muntz and Richard 1982), can leave them temporarily visually impaired and therefore less likely to be able to detect a net or any other visual stimuli (Field et al. 2019). There is a transition at intermediate light levels where both rods and cones are active, and the fish will have twilight ("mesopic") vision. This form of visual plasticity enables fish to function visually over the range of light levels found in its natural environment; however, morphological transition from photopic to scotopic vision can take up to 20–30 min (or more) (Burnside and King-Smith 2010; Wagner and Douglas 1983).

4.1.1.3. Color vision and polarisation. Many fishes, marine mammals, seabirds, marine turtles, and invertebrates likely have the capability to recognize color (Figure 3). Color vision is the perception of differences in wavelength (or frequency) of photons striking the retina independent of image brightness. Each photoreceptor cell in the retina contains a specific visual pigment, which absorbs photons of particular wavelengths more efficiently than other wavelengths (Land and Nilsson 2012; Nakagawa et al. 1999). Spectral sensitivity, or visual pigment absorbance, indicates wavelengths most likely to be absorbed (see Figure 5; e.g., Anthony and Hawkins 1983). Rods are sensitive to low light intensities, with a single photon (amplified in the neural pathway)

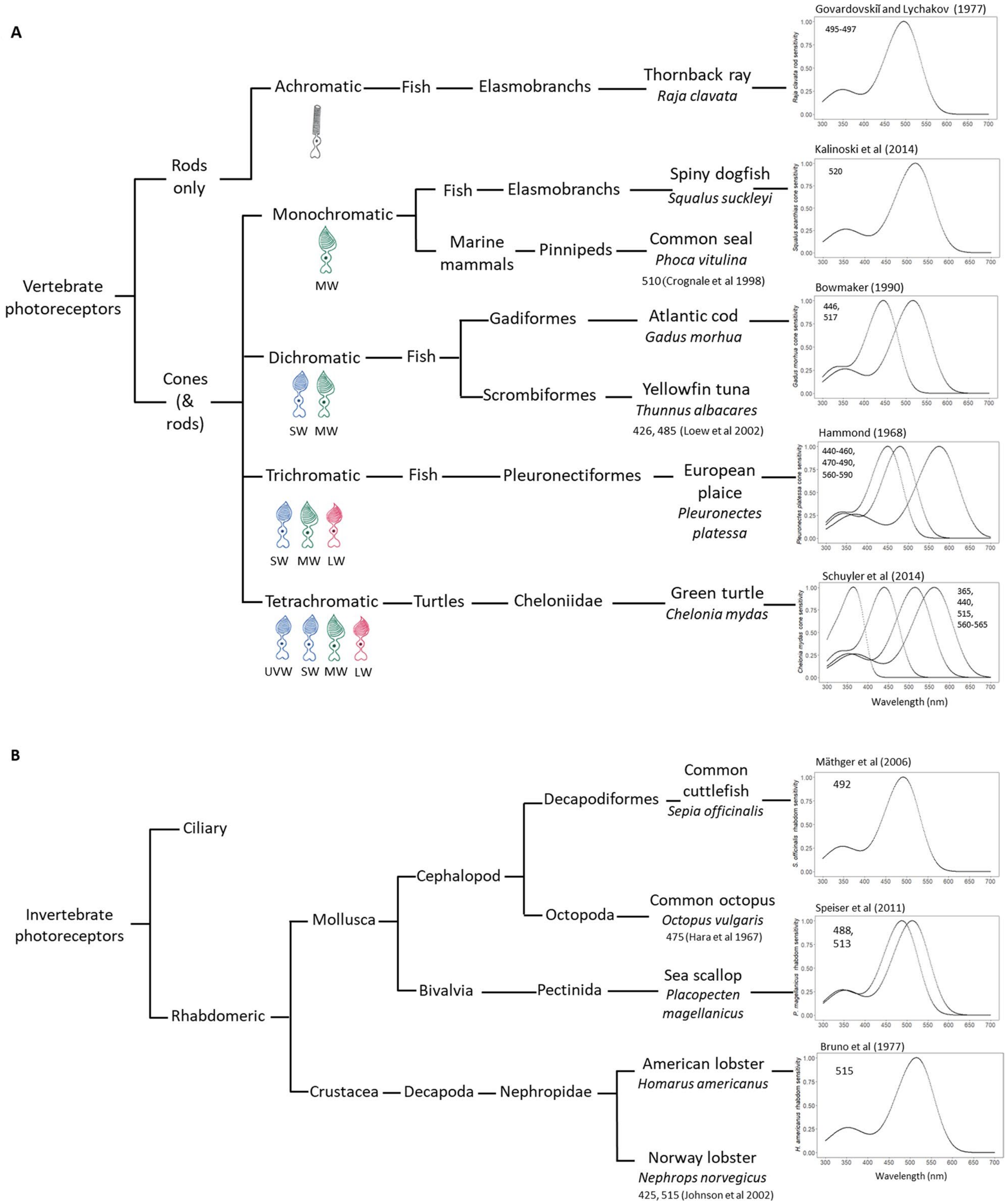

Figure 3. Vertebrate (3A) and invertebrate (3B) examples of spectral photoreceptor sensitivity curves (peak wavelengths given). While rod-cone interactions can result in color vision, monochromatic (one cone pigment) and achromatic (no cones) species will not be able to see color as they only possess one wavelength discrimination channel (photopigment type). Species that possess two or more cone cell types are likely to be able to discriminate colors (Collin and Trezise 2002, 2004). Mono-, di-, and tri- chromatic vision is common in the marine world (Marshall et al. 2015), with some species possessing even more (e.g., mantis shrimp; Marshall et al. 1991). Not all species within an order or family have the same visual capabilities, which is demonstrated within the elasmobranchs in this figure. For example, some ray species are trichromatic (Marshall et al. 2015), compared to the achromatic ray shown here. Photoreceptor combinations in 3A are examples; combinations can change with species (e.g., some monochromatic species may possess a SW cone type rather than a MW). Figure by Jasmine Somerville.

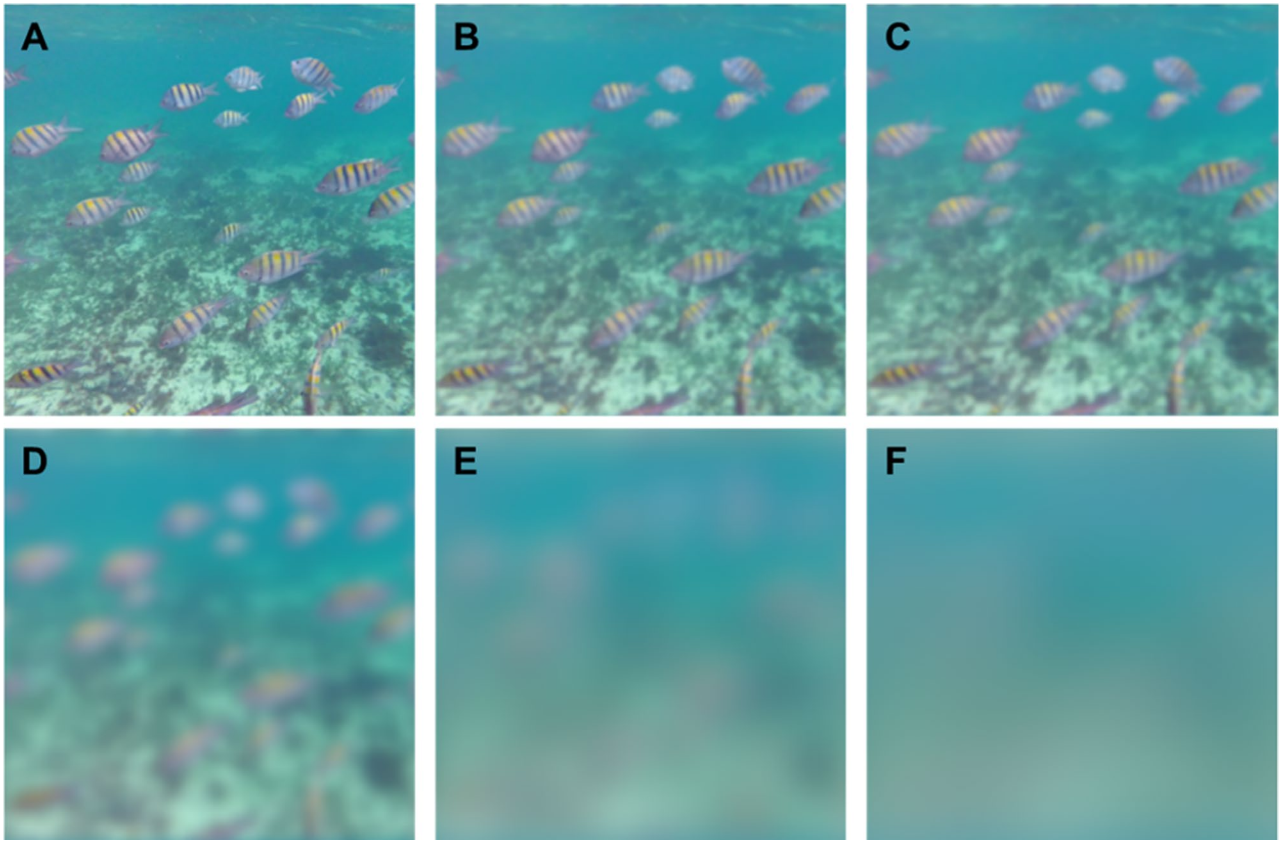

Figure 4. The predicted visual scene for six species (A–F) based on their visual acuities, using the R package AcuityView (Caves and Johnsen 2017; https://eleanorcaves.weebly.com/acuityview-software.html). The scene is viewed from a distance of 3 m from the closest fish, which is approximately 15 cm in length. The visual acuities of the six species (measured in minimum resolvable angle) are as follows: (A) yellowfin tuna, *Thunnus albacares*, 0.06 degrees (Nakamura 1979); (B) walleye pollock, *Gadus chalcogrammus*, 0.166 degrees (Zhang and Arimoto 1993); (C) European plaice, *Pleuronectes platessa*, 0.2 degrees (Neave 1984); (D) common octopus, *Octopus vulgaris*, 0.588 degrees (Hanke and Kelber 2019); (E) blue crab, *Callinectes sapidus*, 1.8 degrees (Baldwin and Johnsen 2011); and (F) great scallop, *Pecten maximus*, 3.33 degrees (Land 1981). The scenes do not account for the different spectral sensitivities of each species.

capable of triggering a response, and therefore used for dim (scotopic) low-resolution vision (black and white, contrast vision). Rods typically contain the visual pigment rhodopsin with peak sensitivity (λ_{max}) between 470 nm and 510 nm (Lythgoe and Partridge 1989). It was previously thought that color vision could not be mediated by rods, but recent research indicates that it may be possible through shared neural pathways between rods and cones (Musilova et al. 2019). Cones are less sensitive, but provide (photopic) color vision at higher light levels. Thus, shallow-water fish have a higher proportion of cones than deep-water species. Cones usually contain one of several visual pigments that are only sensitive at higher light intensities, but with absorption peaks over a wider spectral range (~300 nm to 650 nm, Carleton et al. 2020). In cones, the protein of the visual pigment is called opsin, of which there are three types: (*i*) red, (*ii*) green, and (*iii*) blue, also known as L (long), M (medium), and S (short), respectively (Land and Nilsson 2012). Cones cannot detect color by themselves. Rather, color vision requires a comparison of the relative strength of the signal across different cone types, thus, one needs at least two different spectral cone types (dichromat) to detect color.

Knowledge of color sensitivity of the bycatch animal, alone and relative to that of the target animal, can inform the choice of the peak wavelength (i.e., color) and wavelength range for the BRL (see Section 5). In making this selection, it is important not to assume the bycatch animal will perceive a BRL the same way as a human. For example, some animals can see outside of the electromagnetic spectrum perceived by the human eye (λ: 380–780 nm; “visible light”; CIE 1990). Ultraviolet (UVA; 300–400 nm wavelength) visual cone pigments are present in many fishes (Douglas et al. 1995), making it possible for some species (e.g., Mullidae, Scombridae, Labridae) to detect ultraviolet radiation (Arimoto et al. 2010;

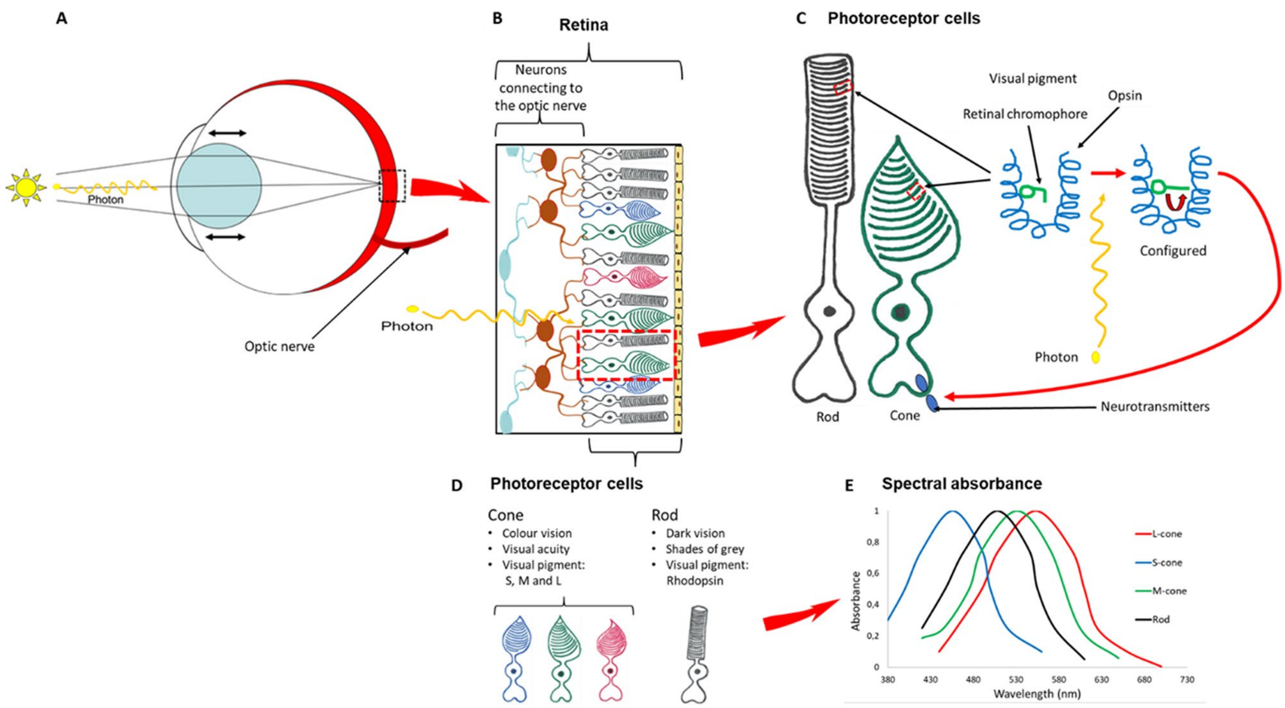

Figure 5. A simplified cartoon of the structure and function of the teleost eye. Light entering the eye through the cornea (A) and pupil ultimately leads to the formation of an image on the light sensitive retina. The retina contains an outer section (B) holding a matrix of light-sensitive photoreceptors (rods and cones) interconnected by inner neurons that connect to the optic nerve, which sends information to the optic lobes in the brain. Photoreception (C) whereby visual pigment in the outer folded membrane of the photoreceptor cells is triggered by photons. Each visual pigment molecule consists of a protein (opsin) that holds a chromophore within a pocket-like space. Photons cause the chromophore to change shape inside the pocket and separate from the opsin, which affects transmitter release (for more details, see Bowmaker 1995; Nakagawa et al. 1999). Photoreceptor cells (D): rods (highly light sensitive and therefore largely used for dim light, or scotopic, vision) and cones (less light sensitive and largely provide high-resolution color vision). Spectral absorbance (E) of the visual pigments of a shallow water dwelling goby (*Gobiusculus flavescens*; redrawn from Utne-Palm and Bowmaker 2006) showing the different photoreceptor wavelength sensitivities (efficiency at absorbing photons of different frequencies). S, M, and L cones are short, medium, and long wavelength sensitive, also called blue, green and red cones, respectively. Drawings by Anne Christine Utne-Palm.

Bowmaker and Kunz 1987; Kröger 2013b; Losey et al. 1999; Swimmer and Brill 2006). In coastal gillnet fisheries, for example, UV light has been used to reduce sea turtle bycatch while maintaining target fish catch (Virgili et al. 2018; Wang et al. 2013). Some fishes with the ability to detect UV light are also capable of detecting polarized light (Hawryshyn 2000; Hawryshyn and McFarland 1987; Losey et al. 1999; Marshall and Cronin 2011), and some species may also have near-infrared vision (Matsumoto and Kawamura 2005; Meuthen et al. 2012; Shcherbakov et al. 2013).

4.1.1.4. Spatial and temporal resolution. When selecting light level and flicker rate for the BRL (see Section 5), which can affect behavioral responses (Yochum et al. 2022), it is helpful to be aware of visual-spatial resolution (i.e., visual acuity) and temporal resolution (i.e., time taken to process the image) of the bycatch animal (Arimoto et al. 2010). Spatial resolution is related to the angular distance between cones, similar to the pixel resolution of a picture, and influences capacity to discriminate detail (for more information, see Eggers 1977; Utne-Palm 1999, 2002; Ware 1973; Figures 4 and 5). The higher the visual acuity of the retina, the less movement is potentially needed for an object (image) to be detected. The temporal resolution of this moving image, also referred to as persistence time, is related to the ability to identify sequential images as separate. At relatively low frequencies, a series of images are identifiable as separate, while at higher frequencies, only one apparently continuous "fused" image is identifiable. The threshold frequency at which the images fuze is the "critical flicker frequency" or "flicker fusion threshold" and it is dependent on light level and temperature (Arimoto et al. 2010; Douglas and Hawryshyn 1990). For a more comprehensive review of motion detection and how it is measured, see Arimoto et al. (2010) and Douglas and Hawryshyn (1990).

Visual detection of an object (e.g., netting) is dependent on visual acuity, along with the ability to detect a difference in contrast between the object and background. The relative importance of color and perceived brightness contrast is determined by visual pigments, the reflectance characteristics of the object, the radiance level, and the spectral distribution of the ambient light, as well as visual sensitivity to these properties (Douglas and Hawryshyn 1990; Lythgoe 1968; Munz and McFarland 1977). Because water absorbs long- and short-wavelengths more than middle-wavelengths (e.g., 530 nm for coastal temperate water, 480 nm for tropical coastal water; Jerlov 1968; Figure 2), light tends to be near monochromatic at moderate depths (Lythgoe 1975). Brightness contrast is, therefore, most often the determining factor, compared to color contrast, for the visibility of objects underwater (Hemmings 1965; Lythgoe 1975).

4.2. Behavior

To determine whether behavior of the bycatch animal was affected by the addition of a BRL, it is necessary to understand their behavior *(i)* independent of the fishing process; *(ii)* in response to the fishing gear/process without a BRL; and *(iii)* in the presence of artificial light independent of fishing.

Behavioral responses to light can vary among and within species (e.g., Engås et al. 1998) and are based on ontogeny and biology (e.g., maturity stage or sex) (Blaxter and Batty 1987; Nguyen and Winger 2019a). For example, behavioral responses to towed gears under different natural light conditions can be species-specific, as demonstrated by diurnal differences in catch rates (e.g., Glass and Wardle 1989; Walsh 1991; Walsh and Hickey 1993). Responses can also vary based on ecological factors and relative to the catch phase. In trawl fisheries, for example, behavior can vary among processes of herding, fall-back, and encountering a BRD. These phases reflect the changing combinations of stimuli experienced and changes in swimming performance. For example, at later stages of the catch process in active gears, a stressed and fatigued animal may be unable to maintain pace with the gear (e.g., Larsen et al. 2018). Likewise, behavior during haul-back can be influenced by changes in water flow (Engaas et al. 1999), changes in the codend netting (e.g., pulsing or changing shape), and natural ambient light (e.g., Grimaldo et al. 2009). Understanding these differences in behavior can help inform where to attach the BRL (see Section 6) and how to interpret behavior (see Section 7). In passive gears, behavior may be affected by what is already caught and/or the ability of the animal to see or be attracted to bait in the near field (e.g., Anders et al. 2017; Hedgärde et al. 2016; Humborstad et al. 2018; Swimmer and Brill 2006; Utne-Palm et al. 2018). For those reasons, it can be helpful to collect information on the response of the animal to light separate from the fishing process, being mindful of how the process of collecting these data could affect behavior (e.g., camera lights when collecting behavior information). This can include responses to light in other gear models or types, laboratory studies, or with caution from studies in other fields (e.g., changing light level at culverts; Jones et al. 2017; Jones and Hale 2020; or fish deterrents at dams; Johnson et al. 2005).

5. Selecting a BRL

When selecting an appropriate BRL to influence the behavior of a bycatch animal in a defined way, four interconnected elements should be considered in addition to the visual system of the bycatch animal described in Section 4.1.1: (*i*) the properties of the light source; (*ii*) changes in light properties during light propagation from the point of illumination to the bycatch animal; (*iii*) background characteristics that influence the contrast between the BRL and the ambient environment; and (*iv*) placement in the gear and the anticipated time the bycatch animal will experience the light during the fishing process (see Section 6).

Modern artificial light sources include light emitting diodes (LEDs), fiber optic cables, lasers, charged phosphorescent materials (e.g., luminous netting with strontium aluminate, $SrAl_2O_4$), and chemiluminescent lights (e.g., "glow sticks"). Each BRL type has practical advantages and disadvantages for implementation in a fishery, which includes environmental impacts (An et al. 2017), usability, durability, technical appropriateness, and cost (see also Section 8; Table 2). Regardless of the BRL type or design, the housing must be easy to handle during fishing operations, tolerate saltwater exposure (for marine applications), and withstand pressure from the maximum fishing depth. The housing must also sufficiently resist the abrasion and impact it will experience (e.g., damage from the gear, seabed, or vessel), not entangle in the fishing gear, resist biofouling, and require minimal maintenance (e.g., replacement of o-rings).

5.1. BRL properties

When selecting a BRL, properties to consider include light level, spectral characteristics (wavelength composition), directionality (beam angle), polarization, strobing (flicker rate or duty cycle), power consumption, and duration. Compromises might be required to achieve the desired properties. For example, phosphorescent materials (e.g., luminous netting; Karlsen et al. 2021) are usually produced in green because strontium aluminate gives the strongest and longest-lasting glow. For this material, the light level decreases more rapidly with time, does not allow for strobing, and is not programmable like some LED lights. There are, however, advantages to this BRL type, such as not requiring batteries. Similarly, lighted gillnet buoys can be solar powered (Senko et al. 2020), but have reduced operational time. Moreover, strobing lights with a reduced duty cycle might be considered to reduce battery costs and ease operational logistics (e.g., replacing batteries) to influence broad adoption in a fishery. For example, a BRL with a 20% duty cycle flashes on for 1 s and off for 4 s, allowing the power source to last five times longer than when used with continuous light.

5.1.1. Light level

There is a wide range of light levels for a BRL, from chemiluminescence (Wang et al. 2010) to powerful LEDs (e.g., Lomeli and Wakefield 2012). Typically, the light level increases with the size, complexity, and power demand of the light. The light level of a BRL often decreases over time (e.g., chemical glow sticks: Wang et al. 2007, 2010; luminous netting: Karlsen et al. 2021; LEDs: Ingólfsson et al. 2021). These decreases can go undetected by a human observer, which highlights the need to measure the decay pattern of a light source for the temperature range of application.

A high light level is not necessarily required to obtain a response in animals (Karlsen et al. 2021; Lomeli et al. 2018; Wang et al. 2007, 2010; Yochum et al. 2022) and can have adverse effects. In turbid water, for example, high light levels can make it difficult to see gear components due to backscattering (Benfield and Minello 1996; Utne-Palm 2002; see Section 3.1). If the objective of using a BRL is to illuminate portions of the gear to make it more apparent to bycatch animals (e.g., to avoid the gear or perceive an opening; e.g., Bielli et al. 2020; Ortiz et al. 2016; Senko et al. 2022; Wang et al. 2010, 2013) then it is relevant to investigate the optical properties of the water in which the BRL will be applied. Moreover, the sensitivity and expected adaptive state of the eyes of the bycatch animal (see Section 4.1.1) should be considered when selecting the BRL light level. If a BRL is applied under conditions where the eyes of the bycatch animal are dark adapted and thus have a higher sensitivity, there is a potential risk of temporary or permanent damage to the eyes of the animals (Field et al. 2019; Magel et al. 2017; Meyer-Rochow 2001). This is especially a concern when animals are forced to pass closely by a BRL (e.g., as animals move aft in a trawl where the space becomes constrained).

5.1.2. Light spectrum

Spectral characteristics of a BRL (i.e., wavelength peak and range) should be selected based on the spectral sensitivity of the bycatch animal, especially relative to that of the target animal (e.g., if only one can see UV light, Southwood et al. 2008). Because there is limited range in the visual spectrum, and species inhabiting the same visual environment are likely to have some overlap in spectral sensitivity, spectral segregation of species can be limited. Therefore, visual capabilities other than spectral sensitivity should also be explored (see Section 4.1.1).

Researchers have selected BRL that emits light at wavelengths to which the bycatch animal has maximum spectral sensitivity (Wang et al. 2010) to maximize detection; however, a behavioral response should not be assumed only based on the ability of an animal to detect the light. Rather, spectral characteristics of the animal may be helpful in understanding how the animal is experiencing the light. When vision information is unavailable, researchers have chosen the BRL color based on the peak wavelength of the inhabited environment (e.g., Lomeli et al. 2020; Melli et al. 2018; Utne-Palm 1999). It should be noted that the bycatch animal may have visual pigments that do not match the spectrum of the background downwelling light to maximize contrast for detection of reflecting objects (e.g., prey) (Hawryshyn 1998; Loew and Lythgoe 1978; McFarland and Munz 1975).

5.1.3. Directionality

Because artificial lights can have directionality, BRL appearance could be greatly affected by small changes in attachment angle. As a result, the selected lights may affect the bycatch animal differentially depending on the direction from which the light source is approached or the size of the light field created. Therefore, the directionality of the BRL beam needs to be considered relative to animal movement when selecting the type and number of lights and when determining their placement on the gear (Melli et al. 2018). It should also be considered whether it is more effective to make gear components more visible or to use the light to make the component invisible (Kim and Wardle 1998; Wardle et al. 1991).

5.1.4. Flicker rate

When selecting a BRL that is strobed, the temporal acuity of the bycatch animal, specifically the flicker fusion threshold, is relevant (Meyer-Rochow 2001; see Section 4.1.1.4), as is the presence of naturally flickering light. At near-surface depths (ca. 10 m, depending on the cloud cover and water clarity), shallow-water fish are adapted to the natural flickering of light produced as waves on the water surface focus and defocus sunlight (Darecki et al. 2011; McFarland and Loew 1983; Meyer-Rochow 2001). Other animals may live in environments with flickering bioluminescence that is associated with behaviors for schooling (Gruber et al. 2019), avoiding predators (Goulet et al. 2020; Morin 1983), or acquiring prey (Hellinger et al. 2017; Morin 1983). In contrast, many animals have evolved under stable light regimes, so strobing BRL could create a more perceptible contrast with the background and, therefore, behavioral cue (Inger et al. 2014; Utne-Palm 1999). For example, artificial strobe lights have been investigated in the laboratory for their potential use as deterrents to guide migrating fish past artificial structures (e.g., Kim and Mandrak 2017, Patrick et al. 1985; Sager et al. 1987, 2000).

5.2. Measurement of BRL properties

Properties of BRL should be described to: (*i*) evaluate the spectrum relative to the spectral sensitivity of the bycatch animal and surrounding environment; (*ii*) investigate how the light level changes over the duration of use (i.e., as charge decreases); (*iii*) identify the relationship between BRL properties and observed behavioral responses; (*iv*) compare light properties with other BRL sources and the associated bycatch animal responses within or between studies; and (*v*) evaluate the influence of a BRL on the light environment during fishing. Specifications of the BRL are not always available from the supplier, but can be measured in the laboratory.

5.2.1. Radiometric and photometric measurement

There are two different forms of light measurements: radiometry and photometry. Photometric variables are based on human perception, whereas radiometric variables span the whole optical radiation spectrum: UV, visual, and infrared light (wavelength between 10 nm and 1000 m). Several radiometric metrics are available, each with a weighted photometric counterpart (Figure 7). Photon (quantum) counterparts can also be derived from each radiometric variable (see Section 5.2.2). Given that the visual pigments in an eye are photon counters (Figure 5), photon units should be reported in BRL studies.

Photometric variables are weighted according to the spectral sensitivity of the human eye and are, therefore, restricted to the visible part of the electromagnetic spectrum (CIE 1990). The values used to weigh the spectral data can be found in the International Commission on Illumination table for the photopic spectral luminous efficiency function (CIE 1990; Hunt 2004). It is important to note that when working with animal vision where spectral sensitivity differs from humans, radiometric rather than photometric variables should always be used (Johnsen 2012). If only photometric measurements are available, these can be related to radiometric units to enable comparison of light source color and light level between studies if the spectral distribution of the light source is known (Johnsen 2012). If a spectrum of the light is not available, conversions can be done for single values of known wavelength (e.g., peak value). Similarly, when relating the light level of a BRL to the photosensitivity of a species (which are often given in photometric units in older literature), a visual sensitivity curve for the animal is required.

Radiometric variables commonly include irradiance and radiance. Irradiance is the amount of light incoming to a receptor area (e.g., to a sensor) from all directions and describes the general light level. This is easy to measure, but depends on the distance between the light source and the sensor, which must be reported. A weak light source may have to be measured at a short distance to be detected by the sensor (Karlsen et al. 2021), while, at the same distance, a strong light source may saturate the sensor. For directional light sources, irradiance measurements would change depending on the location of the sensor relative to the center beam (see also Johnsen 2012). Radiance, on the other hand, is the amount of light reaching a point from a small set of directions (Johnsen 2012). It is independent of the angular size of and distance to the light source (unless it is a point source) or the light signal is being absorbed and scattered (as it is in water) (Johnsen 2012). Brightness is related to changes in radiance. This theoretically makes radiance the ideal unit to measure light; however, radiance is not as straightforward to measure as irradiance as illustrated in Figure 8.

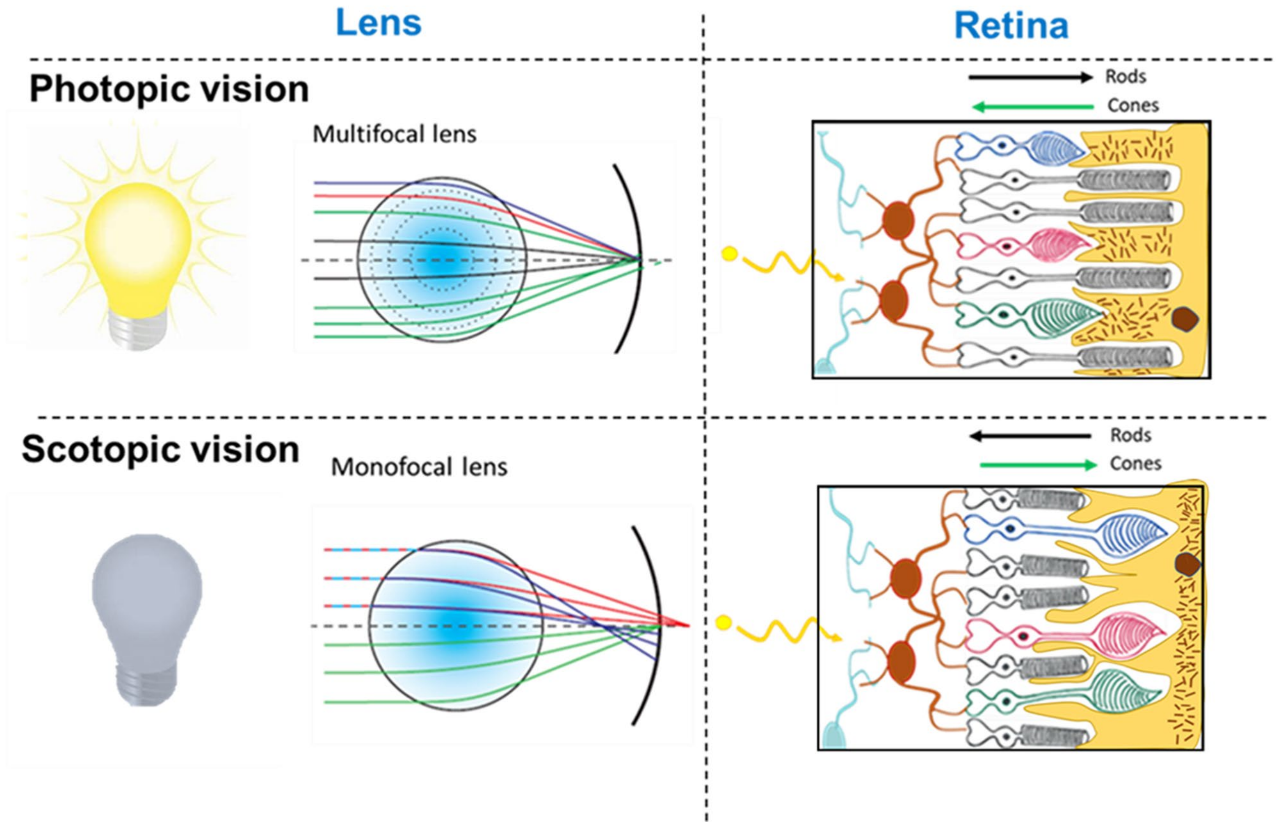

Figure 6. A simplified cartoon of two of the many examples of plasticity of the fish eye to changing light levels. Both lens and retina are plastic and change in structure from light (photopic; top imagine) to dark (scotopic; bottom image) vision (Burnside and Nagle 1983). The monofocal lens focuses each incoming wavelength at a different distance to the lens (green, blue, and red). With this lens, only a given wavelength (green light in this example) is focused correctly onto the retina. The multifocal lens corrects for chromatic blur by focusing each in a specific zone in the lens (concentric dashed lines) so that all wavelengths (red, blue, and green) are focused onto the retina. The fish lens possesses the flexibility to change from monofocal to a multifocal structure when going from dark to light conditions. In addition, the retina adapts to dark or light conditions by moving either rods (scotopic) or cones (photopic) closer to the incoming light. Drawings of the multifocal and monofocal lenses are taken from Gustafsson (2010); drawings by Anne Christine Utne-Palm.

5.2.2. Light level and spectrum

Light can be regarded both as an electromagnetic wave and as moving particles (photons). The shorter the wavelength (toward the purple end of the visible spectrum), the higher the energy of the photons. The energy, or power, of a light signal is the integral over all its spectral components. "Brightness" of a light source, which relates to the physiological sensation (i.e., the perceived light level), depends on the amplitude of the electromagnetic wave or the photon density (i.e., how many photons are received by the eye per unit area per time unit). The perceived color relates to the composition of the spectral components. Thus, the perceived BRL color and light level will be different for different species.

Most light meters (e.g., radiometers) can display the measured light in watts or milliwatts per area (i.e., mW m^{-2}), or the corresponding photon units (mol s^{-1}, μmol, μmol m^{-2} s^{-1}). Conversion to a photon variable can be done from a spectrum showing how much light energy there is at each wavelength (Johnsen 2012; Taiz et al. 2014). Therefore, it is recommended to always measure the whole spectrum of the light source (e.g., by using a spectroradiometer, Johnsen 2012) and avoid sensors that only give integrated values (i.e., total energy over the wavelength range). It is impossible to determine the spectrum from an integrated value; however, the integrated light energy can be found by adding the light level values for each wavelength, given that the energy or number of photons at each wavelength is known (Johnsen 2012). Due to the limited availability of suitable loggers, PAR sensors giving integrated values over the wavelength range 400–700 nm may have to be used to evaluate the influence on the light environment during fishing when adding the BRL (e.g., Lomeli et al. 2018a; Lomeli et al. 2018). It is important to note that these measurements cannot be used for comparison across

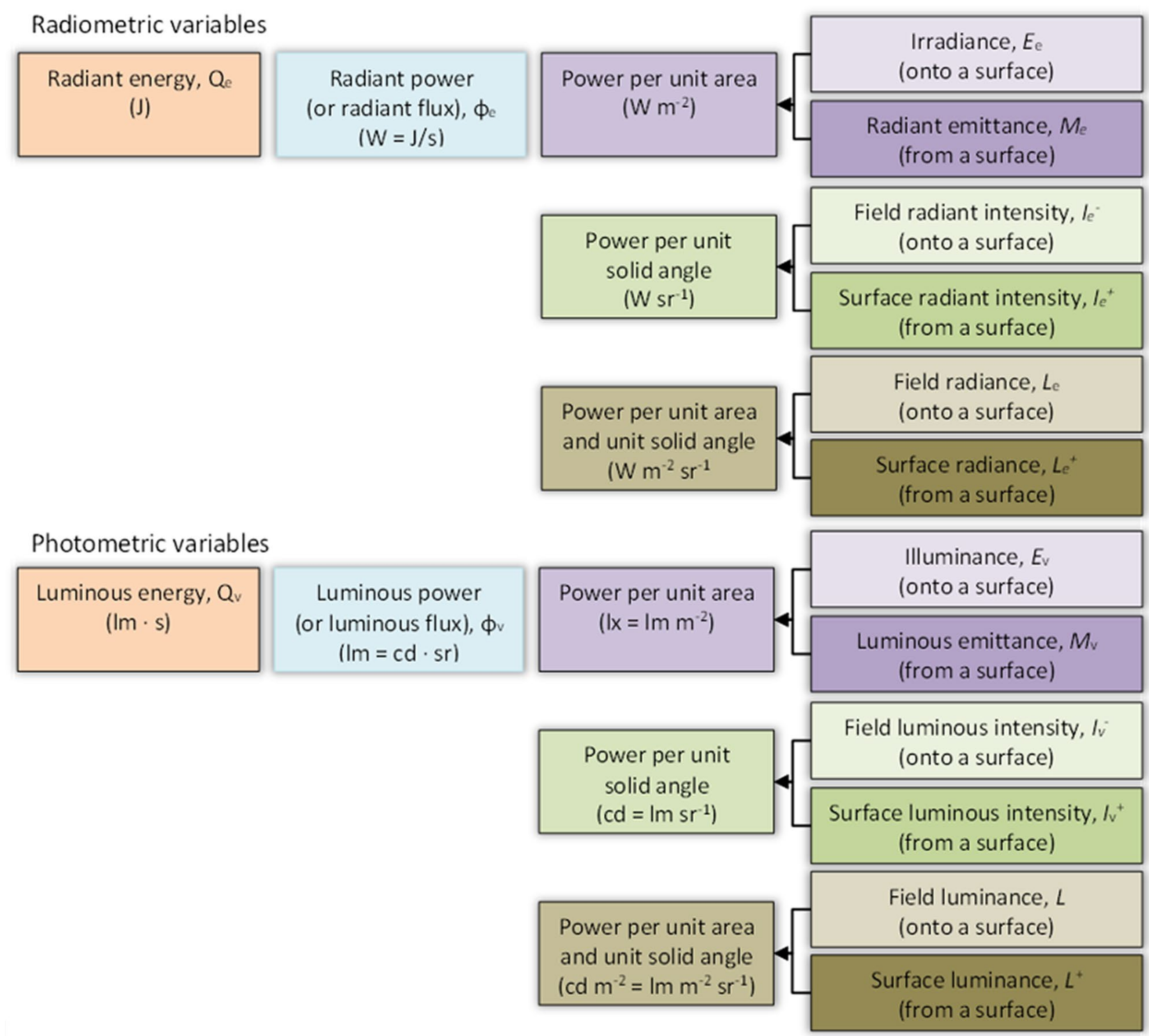

Figure 7. An overview of radiometric and photometric variables following the International System of Units (SI) (partially adapted from Mobley 1994).

conditions as the spectrum underlying the measurements is unknown.

The light emitted by a BRL is often not monochromatic (i.e., having a single wavelength; e.g., Nguyen et al. 2017; Utne-Palm et al. 2018; Yochum et al. 2022). The light should therefore be characterized by the wavelength range in addition to the peak wavelength. A standard method is to give the range as Full-Width-at-Half-Max (FWHM, Karlsen et al. 2021).

5.3. Background characteristics

Introducing a BRL to the environment changes the ambient light field and can influence the visibility of fishing gear components. Also, the underwater environment may not be as dark as expected at night or at depth when bioluminescence is present. Many marine species create their own light field (Martini and Haddock 2017; Widder 2010). Bioluminescence is most often blue (peak ~ 475 nm) in open water and green in coastal, more turbid waters. Violet, yellow, orange, and red bioluminescence are emitted by few organisms (Widder 2010). Bioluminescence can be an influential factor in the visibility of fishing gear (Jamieson et al. 2006). This is particularly true for fish species with well-developed visual systems that can detect low light-level bioluminescence (Arimoto et al. 2010).

Keeping in mind the background characteristics, a BRL should be selected considering how they will

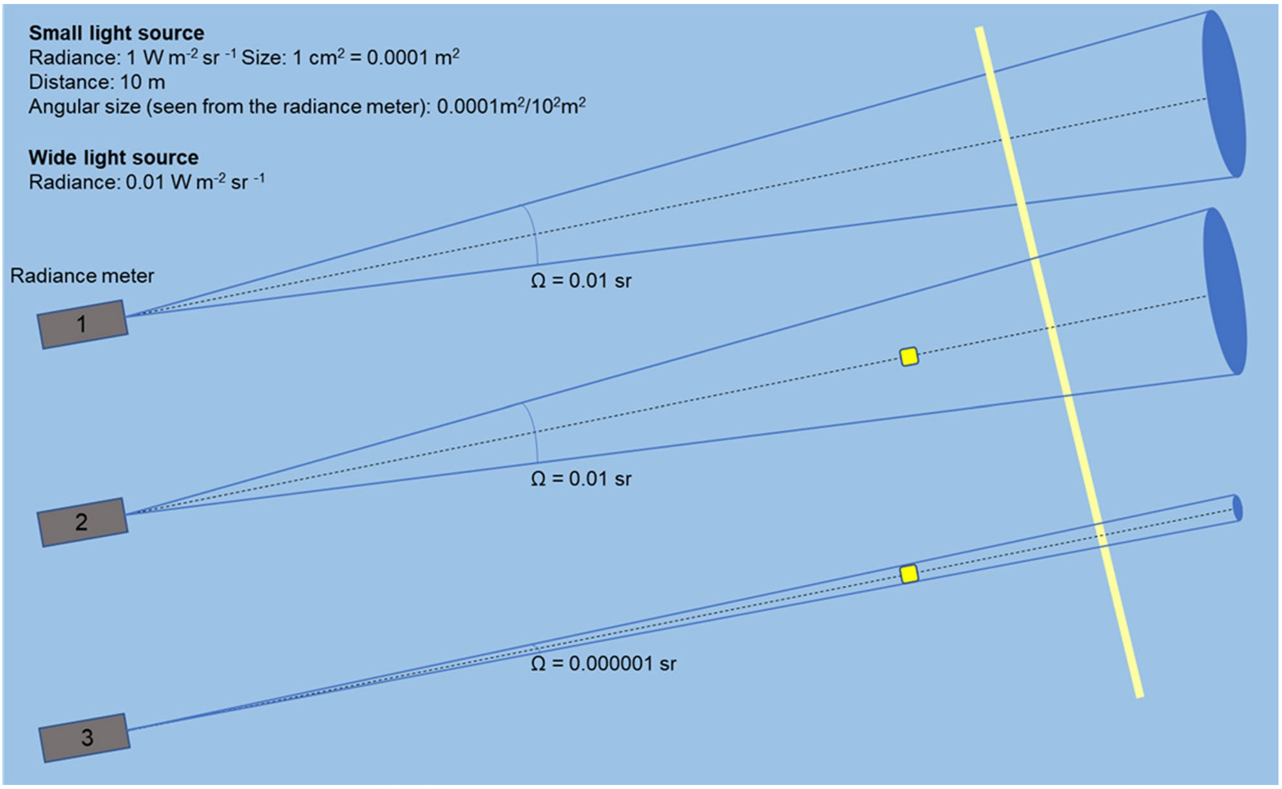

Figure 8. Radiance measurements (W $m^{-2}sr^{-1}$) depend on the angular size of the light source relative to the opening angle of the radiance meter. Ω is the 3D opening angle of the radiance meter (i.e., the solid angle). Radiance meter 1 measures 0.01 W $m^{-2}sr^{-1}$ regardless of distance to the light source and opening angle of radiance meter if the light source (yellow line) covers the whole opening angle. Radiance meter 2 measures 0.01 + 1 W $m^{-2}sr^{-1}$ * 0.000001 sr/0.01 sr = 0.0101 W $m^{-2}sr^{-1}$ as long as the small light source (yellow square) is located in the middle (dotted line) of the beam as the radiance meter is less effective in collecting light toward the lateral edges of the light beam. Furthermore, since the small light source does not cover the whole opening angle of the radiance meter, it is a point source. Therefore, measurements of light emitted from it depend on the distance as the field viewed by the radiance meter increases (corresponding to a decrease of the angular size of the light source) with the square of the distance. Radiance meter 3 measures 1 W $m^{-2}sr^{-1}$. The small light source (yellow square) covers the whole opening angle and so masks the effect of the wide light source (yellow line). This masking effect is independent of the light level of the small light source unless the light source is transparent (e.g., bioluminescent transparent organisms). The small opening angle increases the risk of displacing the light source outside the solid angle of the sensor by any movements in either radiance meter or light source. In an eye, each cone and rod correspond to a radiance meter. Given that the fish is looking at the light source, the chance is higher that most can detect the light similar to radiance meter 1 and 3. Drawing by Bo Lundgren, DTU Aqua.

affect the appearance of the fishing gear. The ability of aquatic animals to visually detect fishing gear depends on the perceived brightness (i.e., radiance), as well as the contrast created by differences in color and brightness of the fishing gear relative to the background (Kim and Wardle 1998; Wardle 1983). Contrast sensitivity, the threshold between the perceived visible and invisible, can be used to compare brightness between the fishing gear and background. Brightness contrast can be specified as Weber contrast (commonly used in cases where small features are present on a large uniform background), Michelson contrast (used for patterns that have both bright and dark features), or RMS contrast (for natural stimuli) (Pelli and Bex 2013). While Weber contrast has been used to describe some fishing gears (Arimoto et al. 2010), other contrast measures have yet to be employed. Regarding color contrast, it could be useful to consider how this has evolved for the bycatch animal in nature (e.g., for communication; Marshall 2000) or warning signals such as aposematic coloration (Arenas et al. 2014; Cortesi and Cheney 2010; Prudic et al. 2007).

6. Determining BRL placement on the fishing gear

Placement of the BRL should correspond with the objective of using the BRL (e.g., to deter passage: Grimaldo et al. 2018; to attract fish toward an opening: Lomeli and Wakefield 2019; or to guide fish using the optomotor response: Karlsen et al. 2021).

Placement determines the period in the fishing process when the animal will experience the BRL (e.g., fishing, gear retrieval), the duration of time the animal will experience the BRL, and how the light will be distributed through the gear (Table 2). The number and spacing of the lights affect the size of the light field and can create areas of reduced light levels between lights (Hazin et al. 2005; Wang et al. 2010). Placement considerations also include how attachment of the BRL onto the fishing gear may affect animal behavior (e.g., due to effects on water flow that the bycatch animal might detect) or fishing operations (e.g., time to attach, weight) and how buoyancy may affect light direction (Cerbule et al. in press).

Depending on the type of fishing gear and section of the gear (e.g., trawl mouth compared with codend) (Table 1), factors such as fatigue, stress, animal density, sediment clouds, size of the escape area, towing speed, and contrast between the gear and the surrounding environment need to be considered. For example, in large-body trawls, a BRL can be placed aft of the net in the extension sections where the circumference of the trawl is smallest to increase the likelihood that the animal will perceive the light. The angle of approach should also be considered, especially for more directional lights (see Section 5.1.3).

7. Selecting an appropriate method to evaluate the effect of the BRL

To better understand and evaluate to what extent a BRL reduces bycatch while maintaining catch rates of target animals, three key research approaches can be used (Figure 9): characterizing and cataloguing behavioral responses to a BRL (*i*) during the fishing process and (*ii*) in a laboratory setting; and (*iii*) quantifying changes in catch and catch rate when using a BRL relative to baseline or commercial fishing operation. While the research approach should be selected based on the objectives and circumstances (Figure 9), they complement each other when studied collectively. Combining methods increases the understanding of how a BRL affects behavior and, therefore, fisheries selectivity.

7.1. Characterization of behaviors during fishing

A key step in understanding how a bycatch animal responds to a BRL is to observe its behavior during the fishing process and around fishing gear. Behavioral data collected with standardized methodology can be used to improve the predictability of catch changes, inform BRL selection, and interpret results from BRL deployment.

7.1.1. Methods of observation

Behavior can be observed and characterized using: (*i*) video cameras (e.g., Grimaldo et al. 2018; Olla et al. 2000; Santos et al. 2020; Simon et al. 2020; Yochum et al. 2021); (*ii*) acoustic imaging systems (e.g., split-beam: Handegard and Tjøstheim 2005; imaging sonar: Rose et al. 2005); and (*iii*) tagging (e.g., acoustic transmitters: Engås et al. 1998; Løkkeborg et al. 2000). Selection of an observation method is often dictated by visibility at the study site, visual distance between the equipment and animals, species identification abilities, handling, and cost of equipment and labor to process the data (Figure 9).

Video cameras can be used to observe behaviors and gear interactions at high resolution and allow for length measurement and 3D representation when using stereo-cameras (e.g., Neuswanger et al. 2016; Shafait et al. 2017). Video camera observation range, though, is often limited by field of view, water clarity, obstructions, animal density, and ambient light levels. In low ambient light environments, additional illumination can be used, but the lights could affect the response of the bycatch animal (Lomeli and Wakefield 2019; Olla et al. 2000). The influence of camera lighting can be reduced by taking snapshots instead of continuous video (Glass and Wardle 1989); however, this limits observations of behavioral event chains and may itself be a cue for the bycatch animal (i.e., the effect of the flashing light). Another solution is to use illumination with wavelengths outside of the spectral sensitivity of the bycatch species, such as red (Favaro et al. 2012; Grimaldo et al. 2018; Olla et al. 1997; Yochum et al. 2022) or near-infrared (NIR) (Chladek et al. 2021; Olla et al. 2000; Wang et al. 2007). In comparison to visible light, NIR light rapidly attenuates in water and can only be used for observations up to ca. 2 m distance (Hermann et al. 2020). In addition, spectral sensitivity is species-specific and a fish may respond to red light (Yochum et al. 2022). This might be the case if it possesses only blue and green cones and there is a spectral overlap between the red light and the sensitivity range of the green cones (Widder et al. 2005), with the fish perceiving the red light as weak green. Likewise, some species may sense NIR light (Matsumoto and Kawamura 2005; Meuthen et al. 2012; Shcherbakov et al. 2013) using long-wavelength sensitive cones. Potential damage to the eyes of the animals needs to be considered when using NIR lights (Icnirp 2013). Beyond direct reactions to light, the

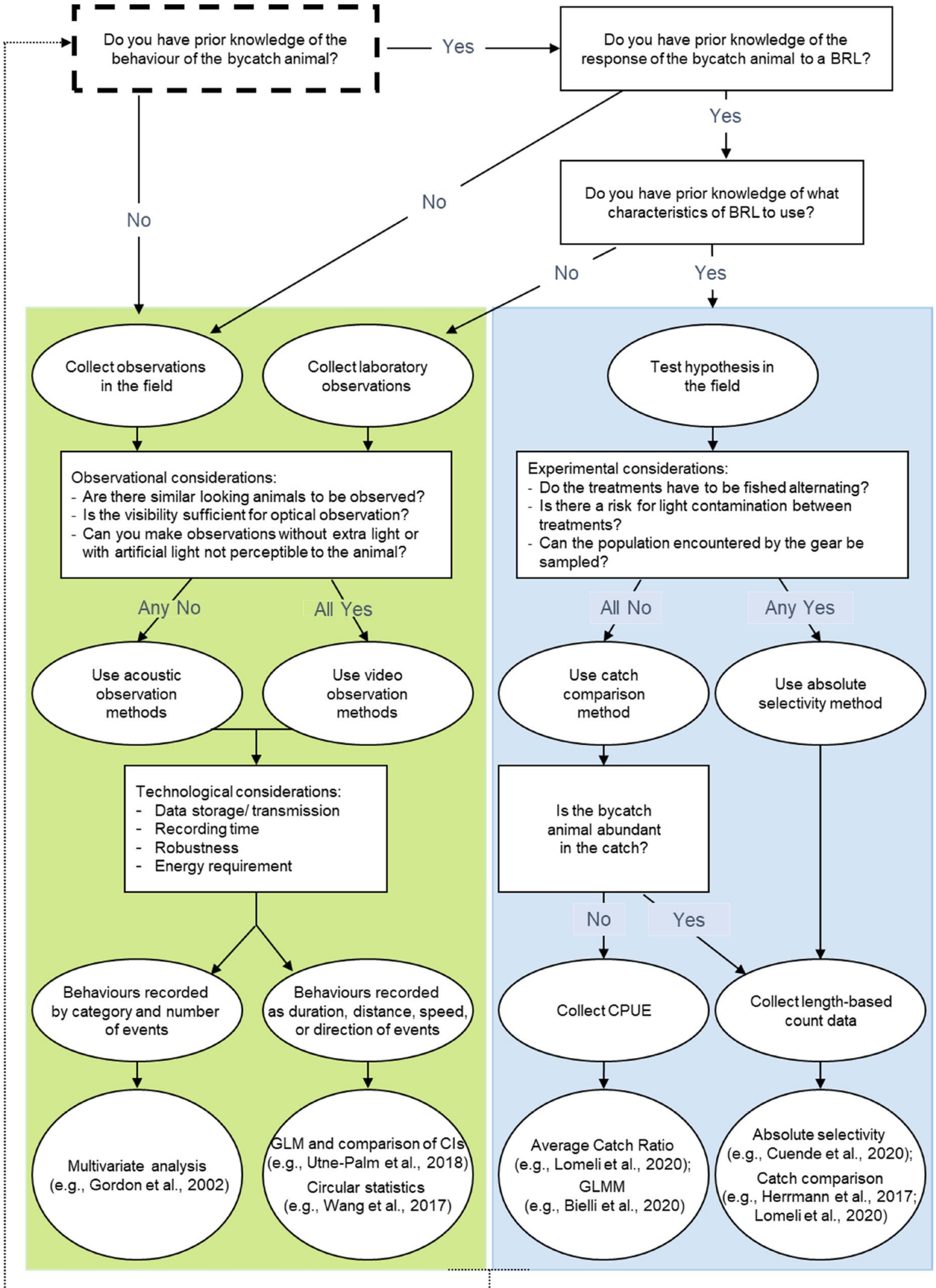

Figure 9. Decision tree to be used as guidance while planning experiments with BRL in relation to fishing gears. Squared steps include questions and considerations that the investigator should consider in addition to the resources available for the experiment. Circled steps represent methodology choices, including examples of statistical approaches or type of data to be collected. The green background includes guidance for observational experiments related to behavior; blue background includes guidance for quantification of BRL effect on gear selectivity. The three different experimental approaches can be combined or used as an iterative process (dotted line).

behavior of a bycatch animal could be influenced by other species reacting to the illumination (Hedgärde et al. 2016; Humborstad et al. 2018; Utne-Palm et al. 2018) and, depending on the configuration of the cameras and how they are deployed, the cameras could affect drag and water flow and, therefore, animal behavior (Bryan et al. in review).

Acoustic imaging systems ("acoustic cameras") can be used to observe behavior in and around fishing gear. Unlike video cameras, these systems can record data in both turbid and dark water without illumination (Moursund et al. 2003; O'Connell et al. 2014). This multi-beam sonar technology, which uses a higher frequency (2–3 MHz) for high-resolution images and a lower frequency (around 1 MHz) to detect fish at further ranges, has successfully observed species interactions with trawl gear (Handegard and Williams 2008; Rakowitz et al. 2012) as well as pots and hooks (Rose et al. 2005). Current development of this technology allows recording in 3D and includes semi-automated approaches to detect, count, and measure the size of fish and record their speed (e.g., Boswell et al. 2008; Schmidt et al. 2018). The resolution of acoustic camera systems, however, is low, and the cost high, as compared to optical cameras. Moreover, body coloring patterns are not visible in the acoustic camera images, and, depending on the frequency used, different species of similar morphology may not be distinguishable. Like the optical cameras, consequences of drag and water flow by the acoustic camera systems on fish behavior should be considered.

Acoustic camera imaging quality depends on animal density and orientation of the animal relative to the beam axes, which can make it difficult to observe individual species in a multispecies fishery and/or fisheries involving high fish densities. In addition, acoustic cameras are less effective in habitats with high physical relief, which will obstruct the acoustic signal through shadowing and backscatter (Rose et al. 2005). Similarly, interference from the fishing gear (e.g., groundgear, netting, and floats) must be addressed (Graham et al. 2004), and it is necessary to have a substantial distance between the acoustic camera and the desired area of observation due to near-field dead zones (Rose et al. 2005). To address this, acoustic observations close to the seabed (e.g., of demersal species) may reduce the near-bottom acoustic dead zone (Øvredal and Huse 1999). With acoustic cameras, a considerable volume of data is produced, which requires additional processing power and expertise, as well as efficient techniques for data display and analysis (Graham et al. 2004).

An echosounder system with a single or split-beam, narrow or broadband acoustic transducer can also be used to observe fish and crustacean behavior, for example, in the pre-trawl zone or between the sweeps of pelagic and demersal trawls (e.g., Michalsen et al. 1996, 1999; Rosen et al. 2012; Underwood et al. 2021, 2020). Collected acoustic data have been used to compare the distribution of fish under the vessel and over the net (Michalsen et al. 1999). Transducers can be mounted on vessels pointing downwards (e.g., Underwood et al. 2021), at the trawl mouth pointing forwards (Underwood et al. 2020) or upwards (Øvredal and Huse 1999), and in the trawl body pointing downwards (Rosen et al. 2012) or upwards (Krafft et al. 2023). On a submersible frame, these can be lowered from a vessel (Underwood et al. 2020) or used on remotely operated vehicles (ROVs; Øvredal and Huse 1999), autonomous underwater vehicles (AUVs; Fernandes et al. 2000), remotely operated catamarans (ROC; Dawson et al. 2022; Kotwicki et al. 2020), a rosette (Peña 2019), or (for passive fisheries) on moored (Ona and Godø 1990) or drifting buoys (Handegard et al. 2003; Handegard and Tjøstheim 2005).

Acoustic and radio telemetry are other options for recording data independent of turbidity and natural ambient light levels. Radio telemetry can be used in shallow, freshwater fisheries in distances up to a few meters, but the signal range is close to zero (< 1 m) in brackish and marine waters (Benelli and Pozzebon 2013; Thorstad et al. 2014) as radio signals are strongly attenuated in conducting media. Telemetry also requires applying tags internally or externally on the bycatch animal and having a receiving mechanism. The latter includes retrievable acoustic receivers (Engås et al. 1998; Løkkeborg 1998) or radio antennas (passive monitoring), or having to follow the individuals with hydrophones or radio antennas (active monitoring). These systems can give presence-absence data or positions of the animal over time in a small area, and have been utilized in both passive (Løkkeborg 1998) and active (Engås et al. 1998) gears. With this method, it is important to consider the impact of applying the tag on fish behavior and condition, and that multiple tags can result in colliding signals that block tag reception.

7.1.2. Behavioral units and ethograms

To enable a comparison of animal behavior in gear with and without a BRL, and between studies, behavioral units should be identified and described objectively from an analysis of recorded observations

(Lehner 1996). An ethogram is a catalogue of comprehensive, precise, and objective descriptions of observed and mutually exclusive behavioral units used to quantify behavior (Lehner 1996). Gear-specific ethograms are needed due to fundamental differences in the capture processes (e.g., active compared to passive gears). The behavioral units should be related to specific locations in or around the gear, the context in which they occur, and their consequences (Anders et al. 2017; Chladek et al. 2021; Ljungberg et al. 2016; Meintzer et al. 2017; Santos et al. 2020). Examples of ethograms for trawls, gillnets, pots, and longlines are provided in Table 3(a–d).

To evaluate behavior in response to a BRL, the ethogram should be made *a priori* and should inform the selection of BRL characteristics (see Section 5) and placement in the gear (see Section 6). Relevant behavioral mechanisms that might lead to changes in catch metrics include phototaxis (e.g., Larsen et al. 2017), photokinesis (e.g., Bielli et al. 2020; Grimaldo et al. 2018; Wang et al. 2010), and anti-predator response (Melli et al. 2018) (Table 4). Studies have also investigated if the optomotor response (Karlsen et al. 2021) and dorsal light response (Takayama 2019) may be used.

Behavioral accumulation curves (BAC), an asymptotic accumulation model of observed behavior units over the observation period, can be used to identify the completeness of the ethogram (Dias et al. 2009). Similar to studies on biodiversity (Soberón and Llorente 1993), the probability of observing a new behavioral unit can be estimated under the expectation that it decreases with increasing observational effort (i.e., the number of observation bins reviewed; Bolgan et al. 2016; Dias et al. 2009). When the BAC reaches an asymptote, the probability of observing a new behavioral unit approaches zero (Soberón and Llorente 1993), thus indicating a high degree of completeness of the ethogram. More details about the methodology, including models and software and an application for fish, can be found in Bolgan et al. (2016), Dias et al. (2009), and Soberón and Llorente (1993).

One of the more difficult aspects of describing behavioral units is distinguishing between the observed behavior and interpreting its potential function or consequences (i.e., its adaptive function). Anthropomorphizing (i.e., attributing human behavior to the animal) may predispose researchers to bias as human characteristics may not apply to fundamentally different animals. For example, “panic” in humans can be defined as sudden, uncontrollable fear or anxiety that produces irrational behavior, which often spreads quickly through a group. In fish, irregular changes in swimming behavior (e.g., sudden changes in swimming speed and direction) can be more appropriately labeled “erratic swimming.” Similarly, “calm” has been used to describe behavior of captured fish in pots once activity has decreased (Thomsen et al. 2010), or their behavior described as “aimless” swimming. These terms can be misleading, however, and ignore the underlying physiological state of the fish. For these behaviors, “inactive” or “cruising” would be more appropriate terms, respectively.

Capture by fishing gear is related to morphology (e.g., animal size and body shape), how the animal perceives the gear, and, consequently, their behavioral response to it (Winger et al. 2010). Observed behaviors are also often related to underlying physiological processes (see section 4.1) and may be important when interpreting responses to a BRL. For example, as fish increase swimming speed (observed as changes in tail beat frequency or gait changes; Winger et al. 2004), they switch from aerobic to anaerobic metabolic processes (e.g., at the trawl mouth). Higher swimming speed can aid escape, but also lead to fatigue (Beamish 1978; Hollins et al. 2019; Winger et al. 2000). Being “exhausted” or “fatigued” can be defined in less anthropomorphized terms as being depleted of glycogen resources (Beamish 1966; Winger et al. 2010; Xu et al. 1993).

Movement in trawls is often put in context with the swimming capacity of the individual (i.e., physiological responses such as fatigued); however, the response can be attributed to behavior (Breen et al. 2004; Peake and Farrell 2006). Thus, the falling back behavior of fish swimming in front of the trawl mouth, which is species-specific, could be described as “raising” or “turning,” for example. For passive gear, fish can approach the gear as individuals, pairs, or schools (High and Beardsley 1970). This can be sustained for a limited time while potentially enabling escape responses (Hollins et al. 2019). Cruising speed is synonymous with sustained swimming speeds (Beamish 1978) during which aerobic processes allow fish to maintain the observed speed for longer times without fatigue. Thus, observed changes in behavior at cruising speeds (e.g., entering the trawl) could be considered behavioral changes and not fatigue (e.g., density-dependent response; Godø et al. 1999). At higher swimming speeds, like “emphasised swimming” (which is synonymous with prolonged and critical swimming, Beamish 1978), a combination of aerobic and anaerobic processes is used. In contrast, purely anaerobic processes are used in burst swimming (Beamish 1978).

Table 3. An example of an ethogram for fish behaviors in relation to (a) trawls developed from Bolgan et al. 2016 unless otherwise noted; (b) gillnets (developed from He and Pol 2010); (c) pots; and (d) longlines (developed from Løkkeborg et al. 2010).

Behavior	Definition
(a) Trawls	
Locomotion	
Cruising	Rhythmic undulations of the body accompanied by rhythmic beats of the tail fin.
Emphasized swimming	Similar to cruising, but the body and tail movements are more conspicuous and faster (i.e., increase in tail beat frequency or change in gait).
Burst swimming (sprint)	An instantaneous and brief increase in swimming speed as a result of a further increase in tail beat frequency.
Gliding	Motionless movement through the water.
Erratic swimming	Sudden irregular changes in swimming speed and direction (Kim and Jang 2005).
Swimming backwards	Rhythmically beats of the tail fin while moving backwards, e.g., with the water flow (falling back) (Bublitz 1996).
Flipping	Turn upside-down or to a sideways orientation (Bublitz 1996).
Turning	While swimming, the fish changes direction in the plane with a vigorous tail beat.
Ascending	Lift head up, swimming upwards (Bublitz 1996; Main and Sangster 1981).
Descending	Lower head, swimming downwards (Sistiaga et al. 2018).
Stationary positions	
Swimming in place	Rhythmic beats of the tail fin without any horizontal or vertical change of position (holding) (Krag et al. 2009).
Inactive with tail movements	Similar to swimming in place, but, in this case, the tailbeats are less vigorous and occur with a really low repetition rate, usually at the bottom.
Inactive	The fish is in a stationary position, usually on the bottom. Movement is not detectable.
Interactions	
Avoiding	Movements away from an approaching obstacle (active) or maintaining a distance to an approaching obstacle (passive) (Colwill and Creton 2011).
Escaping	Rapid movements away from an approaching obstacle to evade an imminent collision (Colwill and Creton 2011), or successful mesh penetration (Grimaldo et al. 2018) or swimming out of an exit hole (Krag et al. 2009).
(b) Gillnets	
Locomotion in the vicinity of the net	
Swim speed	Speed of animal approaching the net (see different swimming modes in Table 3(a)).
Turning	The animal changes its movement in relation to the position of the net.
Orientation toward	The animal approaches the net (this could be measured in degrees relative to the net).
Orientation parallel	The animal swims alongside the net (this could be measured in degrees relative to the net).
Orientation away	The animal moves away from the net (this could be measured in degrees relative to the net).
Stopping/hold position	The animal is not moving in relation to the net.
Capture interactions with the net	
Gilling	Caught with the mesh behind the operculum.
Wedging	Caught by the largest point of girth of the body.
Snagging	Caught by small parts of the body (mouth, teeth, fins/flippers, etc.).
Entangling	Caught by partial or entire body intertwined with net, results in struggling.
Other behaviors	
Feeding behavior	The animal is actively feeding in the vicinity of the net, or on animals captured in the net.
(c) Pots	
Attraction	
Foraging behavior: Long range	Fish can be attracted from long distances, but may swim toward the gear and against the current following the bait plume, often in large, winding tracks to remain in contact with the bait plume (Løkkeborg et al. 2010).
Foraging behavior: Short range	Similar to long range, however, gear is within visual range (Thomsen et al. 2010).
Approach	
Netting bump	Fish bump against netting (Furevik 1994).
Slow approach	Fish approach pot with a slow swimming speed (Furevik 1994).
Zigzag swimming	Swimming back-and-forth to aid in bait location (Thomsen et al. 2010).
Guarding	Fish guard the entrance of the pot from others (Thomsen et al. 2010).
Ingress	
Ingress and egress	Large numbers of fish can be attracted and remain within a close proximity of a pot, with typically few contacting the gear, and entering, or exiting (Thomsen et al. 2010).
Inside pot	
Inactive	After pot entrance fish reduce their movements and mill around (Thomsen et al. 2010).
Active	Fish are very active upon first entering pot (Furevik 1994).
Aggressive	Larger individuals have been observed to chase, etc. smaller individuals (Cole et al. 2001).
(d) Longlines	
Contact	Fish comes into contact with the bait with their mouth or barbel.
Incomplete bite	Fish only takes part of the bait into the mouth or does not close its mouth (i.e., Atlantic cod); swordfish hits bait with sword, but does not take bait into the mouth.
Complete bite	Fish takes the entire bait into its mouth.
Jerk/Jerk series	Rapid, sideways movement with head while bait is in the mouth. Several jerks in a row.
Chewing	With the bait inside of the mouth, the fish opens and closes its mouth repeatedly.
Pulling	Fish pulls bait and against the attached snood.
Rush	Rapid, swimming burst with the bait in the mouth.
Expel	Fish spits out or regurgitates bait after having it in its mouth.
Escapement	Fish swims away, unhooked, after having the bait in its mouth.

7.1.3. Data analysis

Several automated tools have been used for identifying and analyzing behavior from video recordings (e.g., Albert et al. 2003; Simon et al. 2020), acoustic recordings (Handegard and Williams 2008), and tagging data (Hobson et al. 2007). For example, target tracking is a powerful method for quantifying behavior from echosounder data for which Multiple-Target Tracking algorithms are the standard tools (Blackman and Popoli 1999). Specialized software can conveniently log behavioral events from video recordings (e.g., Friard and Gamba 2016), even from a group of individuals (Delcourt et al. 2009, 2013). Some software can also include the possibility of extracting object lengths from stereo-synchronised video recordings (e.g., Neuswanger et al. 2016). Advancements in artificial intelligence (AI), especially the ability of deep learning models to handle large amounts of observations from images, will reduce the time burden and tedious work load to process voluminous data, including tracking of individuals from *in situ* video recordings (Abangan et al. 2023).

For statistical analysis, the occurrence of behaviors can be analyzed with multivariate techniques similar to those adopted to investigate differences in species composition (Gordon et al. 2002; Figure 9). These could be related to pertinent independent variables, such as operational, environmental, and biological factors (see Section 3). A flow chart matrix, where the start and end of the behavioral units are linked into sequences (e.g., "before pot funnel" can only end with "inside pot funnel" or "swimming away"), allows researchers to reveal interdependencies between the different units (Chladek et al. 2021; Ljungberg et al. 2016; Santos et al. 2020). Results can be presented in behavioral trees, with probability statistics and uncertainties estimated for each branch of the trees (Araya-Schmidt et al. 2022; Chladek et al. 2021; Santos et al. 2020).

7.1.4. Data interpretation

When studying animal behavior in relation to fishing gear there are considerations associated with the fundamentally different catching processes of different gear types, and it is important to disentangle a behavioral response to the BRL itself as compared with a response to the gear being illuminated (e.g., illuminating a pot entrance). Moreover, animals may respond in one way to a BRL in isolation, but another when the BRL is combined with other stimuli (with an additive or multiplicative effect). A systematic and quantitative approach to understanding how animals respond to multiple stimuli is provided by Hale et al. (2017). This approach involves classifying responses to the presence of a single stimulus (e.g., light) and multiple stimuli (e.g., light and water current) according to their direction and size. For passive gears using bait, for example, it is important to understand how

Table 4. Behaviors useful to study different aspects of visual capability in bycatch animals.

Behavior	Definition	Method	Visual capability studied
Phototaxis	The tendency to move toward (positive phototaxis) or away (negative phototaxis) from a light source (Pascoe 1990).	Observe directional movement of fish in the presence of a light source.	Visual thresholds and spectral sensitivity (Kawamoto and Konishi 1952; Harden-Jones 1956; Blaxter 1964, 1968, 1969) Color discrimination (Bauer 1910)
Optomotor response	Stabilize an image of the environment on the retina to remain stationary (Lyon 1904).	Observe the tendency of the bycatch animal to follow a series of stripes rotating around a circular aquarium (Arimoto et al. 2010; Douglas and Hawryshyn 1990; Harden-Jones 1963).	Spectral sensitivity (Grundfest 1932a,b; Cronly-Dillon and Müntz 1965; Cronly-Dillon and Sharma 1968; Bell 1982) Acuity (Carvalho et al. 2002; Douglas and Hawryshyn 1990) Temporal resolution (Carvalho et al. 2002; Douglas and Hawryshyn 1990) Photosensitivity (Carvalho et al. 2002) Light adaptation (Takahashi et al. 1968; Teyssedre and Moller 2010)
Dorsal light reflex	Maintain an appropriate orientation using input from eyes and vestibular system (Pfeiffer 1964). Normally, both gravity and the direction of highest light level indicate the vertical.	Artificially illuminate fish from the side and observe their degree of tilting around their longitudinal axis in comparison to the light source as they will take up a position somewhere between those specified by vestibular and ocular cues (von Holst 1935).	Sensitivity to a particular stimulus (Thibault 1949; Braemer 1957; Lang 1967; Silver 1974; Powers 1978)
Schooling	Group of fish swimming in the same direction in a coordinated manner.	Record the position and orientation of each fish and calculate the nearest neighbor distance and differences in compass headings (Hunter 1968; Glass et al. 1986).	Visual threshold, light level (Hunter 1968; Glass et al. 1986)
Feeding	Response to the presence of prey.	Record reactive distance (Meager et al. 2010)	Visual threshold (Meager et al. 2010)
Polarotaxis	The tendency to orient toward polarized light (Waterman and Forward 1972).	Observe orientation of fish to e-vector directions relative to the bearing of the sun at 0°)	Ability to see polarized light (Waterman and Forward 1972)

the combination of light, bait, and current affects how animals are attracted to and captured by the gear. In this scenario, the addition of light may change the attraction range of the gear, the efficiency of capture, or predator-prey dynamics. Therefore, a study looking at the effect of a BRL in a baited pot should include replicates without bait to aid in understanding how light and bait affect animals individually. In doing this, it is important to consider the influence of baited pots on unbaited pots that are in close proximity.

7.2. Characterization of behaviors from laboratory experiments

Laboratory studies can increase understanding of the response of an animal to a given BRL variable (e.g., wavelength and strobe; Yochum et al. 2022) in the absence of *a priori* base knowledge of the bycatch animal. It is important, however, to design the study under tightly controlled conditions. In doing this, particular aspects of the BRL can be isolated from potential confounding factors (e.g., conflicting stimuli from the capture process) and can allow a better understanding of the behavioral mechanisms that influence response to the BRL, such as orientation (Wang et al. 2007), phototaxis (Marchesan et al. 2005; Parsons and Foster 2007), photokinesis, optomotor response, dorsal light response (Takayama 2019), increased behavioral state, or a specific activity such as schooling (Glass et al. 1986; Yochum et al. 2022) (Table 4). Subsequently, variables that could affect the behavioral response during the capture process (e.g., temperature, water flow, turbidity) could be added one-by-one to understand their relationship to specific behaviors (Hale et al. 2017) and aid in interpreting observations from field experiments. While insights derived from these laboratory studies can inform and shape field trials, laboratory studies have limitations. Behaviors exhibited in a laboratory setting might not translate to the multi-stimulus setting of field-based studies or actual fishing operations.

A second use of laboratory experiments is to explore the visual capabilities of an animal (e.g., sensitivity to different wavelengths and spatial acuity) using behavior (Douglas and Hawryshyn 1990) (Table 4) as an alternative to retinal sampling using electroretinography and microspectrophotometry (Ali and Muntz 1975; Lythgoe 1984). Understanding the visual system is often a prerequisite for selecting the BRL characteristics and interpreting the responses to the BRL. Natural behaviors are relatively easy to use for this application, but data analysis often involves some degree of subjectivity, and the range of visual functions that can be studied could be limited by the small number of stimuli that elicit responses (Douglas and Hawryshyn 1990). Furthermore, natural behaviors are not present to the same degree in all species (e.g., the optomotor response; Jones 1963).

7.2.1. Experimental design considerations

Laboratory tests generally compare behavior in the presence and absence of light (Gless et al. 2008), in a light gradient (Krafft and Krag 2021), or to different light characteristics (wavelength: Sardo et al. 2020; Wang et al. 2007; light level: Parsons et al. 2012; multiple characteristics: Marchesan et al. 2005; Utne-Palm et al. 2018; Yochum et al. 2022). In a simulated fishery context, in contrast, it is often more appropriate to understand how an animal reacts to light in coordination with a section of fishing gear (or a proxy) (Gabr et al. 2007; Olla et al. 1997; Parsons et al. 2012; Ryer and Barnett 2006). Animals can alternatively be presented with a choice between alternatives (e.g., Y-maze: Ford et al. 2018).

When conducting laboratory studies, decisions must be made regarding the experimental design (e.g., conditioned or unconditioned responses), the type of conditioning (for conditioned studies; e.g., classical or operant; Douglas and Hawryshyn 1990), and the minimum sample size needed to be able to determine significance with the included covariates. It is also important to consider how to create conditions that are representative of the fishing environment (if appropriate), how reactions could vary by biological variable (e.g., size, sex), and whether an animal could become habituated to a light if exposed multiple times or over a long duration. Moreover, if multiple animals are used for a trial, it is important to consider how a response could be affected by the reaction of the other individuals.

Several replicate tanks could be included to account for any tank effects or response to the BRL housing (Hurlbert 1984) along with data on behavior in the tank without the BRL activated (e.g., Yochum et al. 2022). Single tanks are often used when adding fishing gear to the experiment, including netting (Gabr et al. 2007; Nambiar et al. 1970) or proxies that simulate the fishing gear (Parsons et al. 2012). Furthermore, the size and color of the tank should be considered, as well as if substrate is added to the tank, which can affect light reflection. The size of the tank and volume of water will determine the space available to respond to the BRL. Other variables related to animal husbandry should be noted and considered for influence on behavior (e.g., time of the trial relative to feeding and circadian rhythm, location fed in the tank, noise level in the laboratory, ambient or artificial light sources present other than the BRL, and how the light emitted is distributed). A mesocosm experiment may be considered if it is desirable to investigate the response to light in the natural environment.

7.2.2. Experimental animals

The use of captive-reared versus wild animals can be a key decision in laboratory-based experiments as there may be both subtle and distinct behavioral and visual adaptive differences, which should be considered when interpreting results and extrapolating to field conditions. Studies have tried to account for this issue by either using recently captured animals or animals grown to a similar size/age class to that typical in a natural setting. Regardless of origin, some consideration of the physiology of the animal should be made in terms of sensory organs, performance capacity, and circadian rhythms (Fry 1958; Yochum et al. 2022). Particularly, the functional state of their visual system should be regarded with respect to potential damage and the adaptive stage of their eyes. Moreover, the light condition under which the animals are reared should be considered as it could affect their photoreceptors and behavior (Kröger et al. 2003). Other factors to consider are endogenous rhythms (Bünning 1956), such as circadian or tidal (Gibson 2003) or lunar (Naylor 2001), that may influence the responsiveness of the experimental animal.

7.2.3. Data analysis

Similar to field observations (Section 7.1), automated software tools can be used to process footage and tag data in a laboratory setting (e.g., Yochum et al. 2022). Data from "choice" studies (e.g., Y-maze, Ford et al. 2018) can be analyzed with variables such as time until choice is made. Analysis of covariance (ANCOVA), a generalized linear model (GLM) that blends analysis of variance (ANOVA) and regression, has been used for statistical analysis of continuous variables (Ford et al. 2018; Gabr et al. 2007) and of binary data (Ford et al. 2018). These data can also be analyzed in the same way as for catch data (see Section 7.3).

Preferred techniques for data analysis are quantitative methods that lead to the determination of significance and enable the inclusion of covariate effects and interactions. The selection of the analytical approach depends on the type of data collected and what is chosen as the dependent variable. A dependent variable could be the "fate" of the animal (e.g., entrapped or escaped) after exposure to the fishing gear or a fishing gear section/device (Gabr et al. 2007), leaving the light treatment as an independent variable (Sardo et al. 2020). Animal response to light can also be evaluated as negative or positive phototaxis, demonstration of a behavior of interest, change in orientation or position relative to the light source, residence time, swimming speed, distance traveled from the light source (e.g., Yochum et al. 2022), or distance to conspecifics when near the light (i.e., schooling: Ryer et al. 2009). Data for analyzing changes in distance would consist of counts of predetermined distances, which can be considered proportions. Counts and proportions can be quantified using regression models such as a GLM (Utne-Palm et al. 2018). Distance could also be considered a continuous variable (Ryer et al. 2009), enabling linear modeling. Analytical techniques that quantify animal position or orientation include circular statistics (Batschelet 1981), a branch of statistics where data are measured on a circle in degrees or radians. This has been used, for example, to understand sea turtle orientation to light used in fisheries (Gless et al. 2008; Wang et al. 2007). Time-to-event analysis (e.g., parametric Weibull mixture model; Robert et al. 2020) can be used to evaluate residence time or time until a behavior (e.g., Hunter 1972; Parsons et al. 2012; Utne-Palm et al. 2018). Often called survival analysis, time-to-event analysis quantifies the time until an end point (e.g., Allison 1995).

7.2.4. Data interpretation

When interpreting laboratory results, it is important to evaluate consistency in observations and to keep in mind the context in which the animals experienced the light (see Section 3). Context should be used to limit the scope of inference. It is important to be aware that behaviors *in situ* will likely be different from those in the laboratory given different circumstances (e.g., motivation, stress) and given the influence of other variables/stimuli (e.g., turbidity, tow speed, crowding in the gear, ambient light levels, water current). It is also important to consider the biological information (e.g., age, sex, size) of the study animals relative to animals captured in the fishery. Researchers should focus their interpretation on what can be learned from a laboratory study to support experiments in the field. Laboratory studies can provide the necessary impetus to move the development process of BRL into field and fishery-based trials where catch comparisons will ultimately determine their efficacy (Nguyen et al. 2017; Parsons et al. 2012).

7.3. Quantification of BRL effects using catch data

Gear-based *in situ* experiments often have the primary goal of examining the efficacy of a BRL in conditions that are representative of the fishery by comparing the gear with a BRL (i.e., experimental gear) and without (i.e., control or baseline gear). Two different types of data can be collected to quantify the effect of the BRL (Figure 9): length-based count data (i.e., number of individuals per length class) and catch per unit effort (CPUE) (in either number of individuals or weight) for the bycatch and target animals. Additionally, escapes by way of a BRD with and without a BRL can be enumerated with a video or acoustic camera (e.g., Lomeli and Wakefield 2019; Yochum et al. 2021; see Section 7.1.1); however, results can be biased by the introduction of artificial light for camera illumination or by missing individuals that were either not recorded or undetected when reviewing the data (Krag et al. 2009). A recapture net can also be used for this application. The type of data collected should address the study objective (Section 2) and the context in which the BRL is applied (Section 3).

7.3.1. Length-based count data

Length-based counts are usually collected in size-selectivity experiments with both active and passive gears when the bycatch animal is abundant in the catch and when there is the capacity for onboard length measurements (e.g., Grimaldo et al. 2018; Karlsen et al. 2021; Melli et al. 2018). A length-based analysis allows for the detection of length-dependent differences in the effect of the BRL, which could be expected given differences in visual and swimming capacities by size and species (Arimoto et al. 2010; Videler and He 2010; Winger et al. 2004).

As retention probability is estimated for each length class, the analysis is population-independent for the length range represented in the data. Thus, the results are not influenced by proportional changes between length classes that may occur for different trials. If subsampling of the catch is necessary (e.g., due to limited time or excessive catch size), a subsampling fraction based on total catch weight can be calculated and included in the analysis as an offset in the model (e.g., Fryer et al. 2003; O'Neill and Summerbell 2019), or used to inform bootstrapping (e.g., Lomeli et al. 2020). Nonetheless, it is important to note that subsampling increases the uncertainty of selectivity estimates, which, in the case of subtle effects of the BRL, may result in inconclusive results (Veiga-Malta et al. 2018).

Two main statistical approaches can be used to determine if the BRL has a significant effect on the selectivity of a baseline gear: absolute- and relative-selectivity. The former is used when comparing the experimental gear to a nonselective gear, and the latter is used when comparing to a commercial gear that is also selective (e.g., a baseline gear) (Figure 9). Some study designs allow both analyses (e.g., Krag et al. 2016).

7.3.1.1 Absolute selectivity. Absolute selectivity is an approach to measure the selectivity of a gear in terms of catch probability at length (see Wileman et al. 1996 for more detail). It is used in cases where the population encountered by the gear can be sampled by a nonselective gear (i.e., by using small meshes or some mechanism to allow for full retention of catch in the relevant size range, e.g., Yochum and DuPaul 2008). The effect of a BRL is quantified in two steps: (*i*) estimating the mean absolute selectivity of the gear with and without a BRL and the associated uncertainty of both in terms of confidence intervals (Section 7.3.2); and (*ii*) inferring the BRL effect by superimposing the two selectivity curves. When the confidence intervals of the two selectivity curves do not overlap, there is a significant difference in selectivity from the BRL (e.g., Cuende et al. 2020). Compared to a direct experimental comparison between the gear with and without a BRL (i.e., relative selectivity; see Section 7.3.1), this approach has the advantage of allowing future comparisons of catch probability with other gear configurations (e.g., BRL applied in different positions, different light intensities, etc.).

Depending on the location of the BRL on the gear, some considerations are required regarding the appropriate experimental design to collect absolute selectivity data. For example, the covered-codend method used for active gears requires the presence of a small mesh cover capturing all escapees from the codend (or other opening) (e.g., Cuende et al. 2020). When using artificial lights inside a test codend, the cover on the outside could be illuminated by the BRL and thus influence the escape behavior of the bycatch animal and target catch. When this is a risk, a paired gears approach could be preferable (for a description of the two methods, see Herrmann et al. 2007).

For passive gears, an analysis of absolute selectivity is also possible. Gillnets are highly size-selective and can be set in pairs with less selective control gears like trammel nets (e.g., Kurkilahti and Rask 1996). Alternatively, nets with different mesh sizes can be deployed concurrently or with short sections of different mesh sizes tied together. One can also use tie downs or "suspenders" that connect the float line to the sink line and thus result in loose bags of monofilament net that increase entanglement (e.g., Senko et al. 2022). In the case of longlines, knowledge of the true population fished can be obtained using other gear that is nonselective in the size range of interest (e.g., a trawl) (Dickson et al. 1995; Hovgård and Riget 1992). In using that approach, it is important to consider spatio-temporal variability in catch composition.

7.3.1.2. Relative selectivity. In estimating relative selectivity both the baseline (no BRL) and experimental (with BRL) gears are selective. This analysis tests whether the experimental gear catches more or less than the baseline gear at a given body length. It expresses the probability of catching an individual of a given length class in the experimental gear, given that it was caught in either gear (e.g., Lomeli et al. 2020). Similar analysis can be done for trawl gears with more than one compartment (e.g., O'Neill and Summerbell 2019). Relative selectivity analysis allows the effect of the BRL to be directly quantified if it is the only difference between the two gears tested (e.g., Geraci et al. 2021; Lomeli et al. 2020; Wang et al. 2010). Estimated confidence intervals are used to determine if there is a significant difference in selectivity between the gears (Section 7.3.2). When bycatch rates are low (e.g., endangered animals), it is especially important to conduct a power analysis prior to initiating the study to ensure that there can be sufficient data to determine significance (e.g., Methven and Schneider 1998).

Relative selectivity/catch-comparison analysis can be conducted with paired or unpaired data. Paired data are typically collected by fishing the experimental and baseline gears simultaneously and in similar environmental conditions and habitat. Alternate deployments can also be treated as paired (e.g., Field et al. 2019; Lomeli et al. 2018). When using a paired set-up, light contamination to the baseline gear must be avoided. For example, with passive gears, the paired data can be collected by alternating experimental and baseline gear (e.g., alternating pots in a string, Humborstad et al. 2018; using two gillnets, Bielli et al. 2020; Ortiz et al. 2016; or alternating hooks on a longline, Hazin et al. 2005). When testing a BRL, the distance between gear (e.g., strings, pots) should be a tradeoff between avoiding light contamination to the baseline gear and minimizing environmental and operational differences between the two gears. A buffer section can be included between the experimental and baseline sections (Bielli et al. 2020). Care should also be taken when determining placement of the BRL to avoid bias (e.g., due to consistent differences in catch rates for the end pots of a string). Also, the baseline gear should include deactivated lights to control for the effect of the added weight and interruption of water flow by the BRL (e.g., Wang et al. 2010).

Unpaired data can result from broad-scale testing of BRL in commercial fisheries (e.g., Nguyen et al. 2019). In these cases, deployments of the baseline and experimental gears are often not equal or cannot be paired on the basis of geographic and/or temporal overlap. With unpaired data, a double bootstrap procedure is conducted independently for the test and baseline gears (e.g., Herrmann et al. 2017), which increases the data required (relative to absolute selectivity analysis) to determine significance.

7.3.2. CPUE data

CPUE data are frequently used when there are low capture rates of the bycatch animal or when length-based counts are impractical. The unit of effort can be related to gear deployment in terms of haul, gillnet set, pot, or number of hooks (e.g., Diaz 2008; ICES 2021; Woll et al. 2001) or to area and time (e.g., net length and soak time, Bielli et al. 2020; Ortiz et al. 2016; Wang et al. 2010, 2013). An approach is to use twin-rig data collection methods with the experimental and baseline gears towed in parallel by the same vessel (which can also be used for length-based analysis).

One important caveat of using CPUE is that it does not take into account possible size-dependent responses. This could make interpreting results more difficult if a bycatch animal has different responses to the BRL based on size, and the results cannot be compared across fishing situations (e.g., areas, seasons) where the size distribution of the fished population may be different. If, however, the BRL successfully reduces bycatch (based on changes in CPUE), and similar population structures or size-independent responses can be assumed, a comparison of CPUEs provides an average percentage reduction in bycatch, which may be informative and intuitive for management purposes.

Three statistical approaches have been used to determine the effect of a BRL based on CPUE data (Figure 9). The first approach is similar to catch comparison, but uses an average catch ratio based on the number of individuals in each gear (Lomeli et al. 2020). The second approach is to use a generalized linear mixed-effects model (GLMM) on CPUE data of the target and bycatch animals (Bayse et al. 2016; Bielli et al. 2020; Nguyen et al. 2019; Underwood et al. 2018).

The choice of model distribution is determined by the dispersion of the data. If equidispersed, a Poisson distribution is used (e.g., Nguyen and Winger 2019b; Ortiz et al. 2016); if overdispersed a negative binomial is used (e.g., Nguyen et al. 2019); and a quasi-poisson can be used for either over- or under-dispersion (e.g., Bayse and Grant 2020). The GLMM approach can include several predictor variables as fixed (e.g., treatment and effort) and random effects (e.g., season, vessel, fishing trip). Notably, the GLMM approach allows comparison of multiple treatments (e.g., different colors of BRL; Martínez-Baños and Maynou 2018). A third approach is to use the Wilcoxon signed-ranks test, a non-parametric equivalent of the paired *t*-test, to test for a difference between paired observations of CPUE from the experimental and baseline gears (Senko et al. 2022; Wang et al. 2010, 2013).

7.3.3. Independent variables

Any variable likely to influence the strength or type of observed response to the BRL can also affect catch data. Therefore, collecting such data during the experiment and including them in the analysis as independent variables is relevant if the number of gear deployments provides sufficient analytical power (Ortiz et al. 2016; Southworth et al. 2020; see Section 3). Operational, environmental, and biological variables may influence the ability of the animal to react to the BRL (e.g., temperature influence on swimming performance) or may affect the perception of the BRL or the background (e.g., the netting). Some variables can be kept consistent between the experimental and baseline gears (e.g., towing the two gears in parallel) so that differences in the response of the bycatch animal can be attributed to the presence of the BRL.

7.3.4. Data interpretation

Selectivity studies can help formulate hypotheses on how BRL changes behaviors (e.g., Cuende et al. 2020); however, it is ultimately behavioral studies, either in the laboratory or in the field, that give direct information about how behavior is affected by the introduction of a BRL and how that introduction of light might lead to changes in catch rate (Santos et al. 2020). Over-extrapolation of selectivity studies might lead to incorrect conclusions, highlighting the importance of considering the scope of the study (e.g., spatio-temporal aspects, vessel characteristics; see Section 3.2) and having a sufficient sample size. One should also consider the potential for habituation of animals to light, and if external factors influence catch rates (e.g., animals seeking out the gear as shelter; Nguyen et al. 2017).

Regardless of the experimental approach used to estimate the effect of the BRL (e.g., absolute or relative selectivity), uncertainty in the data could arise from confounding effects such as changes in operational and environmental variables. Uncertainty in terms of confidence intervals can be estimated using double-bootstrapping that takes between- and within-gear deployment (i.e., haul or gear line) variation into account (methodology: Millar 1993; trawl: Cuende et al. 2020; gillnet: Savina et al. 2022). If uncertainty in the data is too large (e.g., due to few individuals in the catch or large inter-specific differences in the response) it could prevent drawing conclusions regarding the effect of the BRL on the bycatch and target animals. Moreover, operational and environmental variables should be kept as consistent as possible throughout the experiment unless the aim of the study is to investigate the consistency in the effect of the BRL under different conditions. In the latter case, modeling of size selectivity can include covariates of interest (e.g., depth, catch size, towing speed; Brooks et al. 2022), but this requires a larger number of gear deployments. Compared with active gears, passive gear studies may be prone to wider confidence intervals due to the patchy distribution of animals.

7.4. Combined methods

When testing hypotheses about behavioral responses to BRLs, the methods previously described should be considered as complementary rather than alternatives. In field experiments testing a BRL, when a difference in selectivity is detected the behavioral mechanisms leading to the change in catch are usually inferred. If selectivity data are combined with direct observations of behaviors (e.g., using video and/or acoustic cameras; see Section 7.1.1) in the field or the laboratory, the effect of the artificial lights can be quantified in terms of selectivity (Parsons et al. 2012; Santos et al. 2020) and qualified based on behavioral mechanisms (Nguyen et al. 2017; Takayama 2019). For example, Utne-Palm et al. (2018) suggested that increased catch of Atlantic cod in illuminated pots was due to predatory behavior by cod on prey attracted to the artificial lights. In the laboratory, they demonstrated that krill (*Meganyctiphanes norvegica*) was positively phototactic to artificial light, while cod was generally indifferent. A related study confirmed the increased catch rates of cod in illuminated pots and demonstrated, using cameras and stomach content analysis, that the increase in cod presence was due to feeding on krill and other light-attracted prey rather than exhibiting positive phototaxis (Humborstad et al. 2018).

8. Evaluating BRL practicability

At the completion of data collection and analysis for a BRL study, evaluation of study results will inform whether the BRL was successful based on the metrics defined at the start of the study (see Section 2) (e.g., change in gear selectivity or consistency in BRL performance) and the scope (e.g., spatio-temporal, vessel characteristics) will inform the extent to which the findings can be extrapolated (see Section 3).

If the objective of testing the BRL is to lead to fishery-wide adoption (either through voluntary uptake or regulatory action) it is important to consider the feasibility and potential unintended social consequences of using the lights (see Jenkins et al. 2022). Moreover, voluntary BRL adoption will likely be determined by exposure of the fishermen to the technology (Kakai 2019), their engagement in BRL selection and testing (Jenkins et al. 2022), reliability of the BRL effect (or a clear understanding of the uncertainty), changes in catch (e.g., decrease of the bycatch and target proportion of the catch), and relative change in the ex-vessel value of the catch (Bielli et al. 2020; Ortiz et al. 2016; Wang et al. 2010, 2013). These considerations will likely be weighed against the benefits of applying the BRL (Gilman et al. 2005, 2006, 2007). Adoption will also be influenced by logistic considerations and operational efficiency (Kakai 2019; Senko et al. 2022), such as cost of integrating the lights into operations (including interruptions to fishing operations), handling time (e.g., attaching the BRL or replacing batteries), availability of the lights, and their power requirements (e.g., cable linked, or rechargeable or disposable batteries) relative to the capability and resources of the fleet, and durability of the lights.

For regulated adoption, BRL use will likely be influenced by its efficacy as well as enforcement capability and industry engagement. The likelihood that the BRL will accomplish defined management goals will be tied to the ability of the researchers to describe how the BRL should be used (e.g., light properties, placement, number) as well as efforts to socialize fishery managers to BRL technology (Gautama et al. 2022).

In considering fishery-wide BRL use, it is also important to evaluate the unintended biological and environmental consequences of the lights. This includes potential damage to animals' visual systems and interference with communication or natural behaviors (e.g., fish foraging and schooling, spatial distribution, migration, reproduction; Nguyen et al. 2019), especially when animals can be expected to respond to subtle changes in light levels (Berge et al. 2020). The lights could also alter predator-prey relationships, affect catch composition (e.g., increase catch of other non-target animals), or artificially select for individuals in a population that are more reactive to the light (i.e., fishery-driven evolution). The design, production processes, material selection, and power supply of the lights will determine the level of greenhouse gas emissions emitted in the fabrication of the BRL (e.g., Mills et al. 2014; Nguyen et al. 2019; Senko et al. 2020). The lights and their components (e.g., power source) that fall into the water (either intentionally or accidentally) also contribute to marine/plastic pollution (Nguyen et al. 2019; Oliveira et al. 2014). Lights using renewable energy, such as solar-powered lights (e.g., Senko et al. 2020) and photoluminescent twine (Karlsen et al. 2021; Nguyen et al. 2019), are rechargeable options that may reduce the environmental footprint of the BRL.

Measurements of efficacy using predefined metric(s) for success (see Section 2) will inform subsequent action. This could include conducting laboratory experiments to evaluate the vision of the bycatch animal or the effect of light properties on behavior (e.g., Yochum et al. 2022; see section 7.2), repeating field trials, broadening the scope of the research, or moving toward uptake or terminating investigation of BRL for that fishery. It would also be appropriate to investigate alternative light types from those used in the trials based on the needs and constraints of the fishery (e.g., availability, integration into the gear). At the end of a study, it is important to provide feedback to the base knowledge (Figure 1), including using the results to make inferences about behavior and vision, as well as fishermen perspective on BRL use.

9. Conclusions and future directions

The goal for writing this paper was to provide guidelines to support researchers, fishermen, and managers aiming to mitigate bycatch by modifying animal behavior using artificial light. Needed base knowledge was highlighted; the importance of understanding the context in which the BRL is applied was emphasized; and considerations for designing a BRL study, analyzing the data, and interpreting results were described. Regarding data interpretation, it is important to look not only at the study results, but to be aware of the mechanisms driving a change in behavior with the introduction of a BRL. There are many stimuli that aquatic animals experience when interacting with fishing gear, and these can confound or prevent a response to the BRL. Along these lines, it is important to be aware of the influence of the study design on behavior (e.g., introduction of camera lights; e.g., Weinberg and Munro 1999). Caution is advised against anthropocentric driven interpretations of behavior, recognizing that the bycatch animal will not perceive light as a human would. Both data interpretation and study design can be improved by employing a multidisciplinary and collaborative approach given the diverse expertise required to effectively assess BRL efficacy at appropriate ecological, socioeconomic, and technological scales and the importance of industry engagement (Geraci et al. 2021).

Additional research is needed on the efficacy of BRL, on the visual systems of commercially significant and common bycatch species, and on the factors that drive uptake of BRL in a fishery. For the former, one aim of this paper is to provide a mechanism for standardizing data collection that will support meta-analyses in the future. With studies following the described guidelines, opportunities will arise for a broader examination of the influence of BRL on animal behavior and fisheries selectivity, and it will lead to a better understanding of potential community and even ecosystem-scale effects of BRL (Senko et al. 2022).

While there is an increasing body of literature on the use of BRL to affect fisheries selectivity and an increase in producers of artificial lights and luminous netting, there remain gaps in research and technology. For the latter, BRL research would benefit from *in situ* light sensors that are more affordable, light sensitive, robust, and readily accessible (Ortiz et al. 2016; Senko et al. 2020, 2022; Wang et al. 2010). There is also a need for the development of lights that both incentivize the prevention of disposal at sea (e.g., rechargeable, renewable-powered devices) and integrate more easily into existing gear (e.g., lighted gillnet buoys; Senko et al. 2020).

With the improvement and increased affordability and availability of BRL technology, coupled with research increasing our understanding of the effects of light on animal behavior in and around fishing gear, BRL will likely be a more effective and better-understood tool in our fisheries research and management toolbox.

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